9. Diseases of Free-ranging Snow Leopards and Primary Prey Species

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Abstract

Although a wide range of diseases have been reported in captive snow leopards, very little is known about those affecting the species in the wild. However, the potential threat that disease represents for wild snow leopards must not be underestimated as a consequence of the lack of health surveillance throughout the inaccessible terrain that they occupy. As a felid, the snow leopard is likely to be susceptible to most infectious agents affecting the domestic cat, and here we provide an overview of those that are potentially fatal for free-ranging snow leopards. In contrast to the health of snow leopards themselves, a great deal is known about the diseases affecting their primary prey species. We present these cases and highlight the importance of livestock as the main source of disease spillover to natural prey species. Further studies are required to understand the impact of infectious agents on intra- and inter-specific population dynamics of snow leopards and associated prey.

Key words: Infectious disease, wildlife disease, livestock disease, disease spillover

Introduction

This review aims to present the major infectious diseases that may affect free-ranging snow leopards, and those that may impact the abundance of their natural ungulate prey. It is beyond the scope of this review to cite the numerous studies of captive animals that have documented neoplasia, inflammatory and degenerative diseases, and congenital malformations, ailments that have so far not been detected in free-ranging snow leopards (Esson et al., 2019; Shannon Kachel personal communication, Stephane Ostrowski personal observation). In addition, the chapter should not be considered as a comprehensive review of infectious diseases, as it concentrates only on those with a perceived lethality in the wild.

Snow leopards and their ungulate prey inhabit cold arid environments. Because microbial abundance in soil correlates negatively with precipitation (Blankinship et al., 2011), it is likely they are less exposed to microbes than their more mesic, temperate or tropical-living counterparts, and may have evolved correspondingly lower immune indices. This may have conservation implications as it could render the species particularly vulnerable to the emergence of pathogens disseminated by fast-spreading populations of domestic species that they may prey upon, and to changes in pathogen distribution resulting from climatic change and globalization. The present review shows that at least for snow leopard prey species, disease is already a significant local threat and may be increasing, whereas data deficiencies prevent a full evaluation of the disease threat to the snow leopards themselves.

Diseases in free-ranging snow leopards

Causes of mortality in snow leopards

There are no publications that provide a comprehensive account of mortality of free-ranging snow leopards. Natural deaths due, for example, to starvation or natural accidents are rarely observed. Human-induced casualties due to poaching, traffic accidents or poisoning are almost never reported in time for efficient forensic investigation. Surveillance of wild populations for infections, based on *ante-mortem* testing of blood and feces, has been limited to one population in Mongolia (Esson et al., 2019; Johansson et al., 2020). Incidental reports tend to suggest that non-infectious causes likely constitute a significant proportion of deaths in free-ranging snow leopards, which concurs with comprehensive mortality studies carried out in other non-domestic cats (e.g. Schmidt-Posthaus et al., 2002). Hussain Ali who conducted extensive surveys of the Khunjerab area in northern Pakistan, reports in his diary to have examined 14 dead snow leopards between 2000 and 2008. Two had been poached, 4 were found dead alongside uneaten carcasses of Siberian ibex (*Capra sibirica*) and fallen rocks and presumably died accidentally in the course of chases in steep terrain, 3 had fallen over cliffs with no dead prey around and possibly as a result of avalanche or rock slide, 1 was found on the Karakoram Highway and was possibly a road casualty or had fallen over a cliff, 3 (an adult female with her 2 subadult cubs) could have been poisoned, and 1 odd case was found dead on top of a juniper tree. Interestingly, of the 7 animals that had fallen off cliffs (with or without prey), 5 were young animals (< 2 years-old) suggesting possible misadventure. Snow leopards can also be victims of poisons, either placed intentionally as retaliation for livestock depredation, or unintentionally during indiscriminate poisoning campaigns. However, the nature of poisons, extent of use, and impact on snow leopard populations remain largely unstudied. Poaching is usually underestimated because it is rarely reported or is mischaracterized (e.g. in the case of individuals that were assumed to have starved or "fallen-from-cliffs", Figure 1), but it has been confirmed in some snow leopard mortalities (Nowell et al., 2016). Infectious diseases are not common in adult animals in captivity (Womble et al. 2021) and have almost never been reported or successfully verified by *post-mortem* evaluations in free-ranging snow leopards (Figure 2; Batzorig et al., 2011). However, as in poaching this cause of mortality could easily be underestimated because of the difficulty in detecting and/or investigating cases in the inaccessible terrain that they occupy. Infectious diseases may be a normal feature of an otherwise healthy snow leopard population, but effects may be exacerbated by increased stress, occur at unnaturally elevated exposure due to spillover from domestic animals, or where populations are already compromised by declining numbers.

Infectious diseases

Selected viral diseases

A wide variety of viral agents have been found in captive felids, including snow leopards, of which some have severe and sometimes fatal consequences for the host. Clinical disease has rarely been recorded in free-ranging wild felids, with a poorly documented account of rabies infection from 1940 (Heptner and Sludskii, 1992), representing the only clinically significant report of viral disease in a free-ranging snow leopard. However, the true incidence of viral infections in wild snow leopards is hampered by the lack of surveillance in the remote locations they occupy, and the species is likely to be susceptible to a range of pathogens found in other free-ranging felids (Table 1). A recent study using next-generation sequencing reported the presence of nucleic acids of potentially harmful viruses in rectal swabs and serum from 7 clinically healthy free-ranging snow leopards in Mongolia (Johansson et al. 2020) (Table 1). Still more recently, pathological examinations and positive RNA recovery confirmed that SARS-CoV-2, the agent of COVID-19 pandemic, was a contributing factor or primary reason for demise of four snow leopards in two zoological collections in the US in October 2021 (Karen A. Terio, University of Illinois, personal communication). In the current stage of the pandemic the highest risk of exposure of free-ranging snow leopards would probably result from direct contacts with infected humans such as during research activities.

Viral infections will only have a negative impact on population viability if they reduce reproductive output either directly, or by increasing host mortality that is additive to other causes of death. Contributory risk factors include increased pathogenicity of circulating viruses, the presence of a more abundant reservoir population (domestic or wild), and an increased susceptibility of the host such as in case of co-infection, chronic stress or decreased genetic variability.

One viral pathogen of particular importance to populations of other *Panthera* species is canine distemper virus (CDV). In 1994, populations of lions (*P. leo*) in the Serengeti National Park declined by two thirds during an outbreak of CDV, equating to the loss of over 1,000 animals (Roelke-Parker et al., 1996). More recently, CDV has been identified in Amur tigers in the Russian Far East, where it has contributed to local population declines (Seimon et al., 2013). Snow leopards are susceptible to CDV infection, with 3 cases recorded in captive animals (Fix et al., 1989; Silinski et al., 2003, Chinnadurai et al 2017), although 2 of these were concurrent with other pathogens. In one case, CDV infection in 2 leopards was assumed to be a sequel to prior infection with feline panleukopenia virus, whereas in the other immunosuppression related to CDV was thought to have predisposed to an acute infection with *Toxoplasma gondii*. Co-infections have also been associated with outbreaks of CDV in free-ranging lions, with climatic conditions promoting high tick burdens and *Babesia* infection contributing to the high mortality recorded during CDV outbreaks in Serengeti in 1994, and Ngorongoro in 2001 (Munson et al., 2008). This may explain the occurrence of so-called 'silent' outbreaks among lions in Eastern and Southern Africa, where infection is evident without apparent sickness or mortality (Munson et al., 2008). However, at least some captive and wild outbreaks appear to have been uncomplicated by co-infections (Seimon et al., 2013), and so other factors may contribute to clinical severity, such as strain virulence or additional external stressors.

Classically transmission of CDV is thought to require direct contact between an infected animal and a susceptible host, as it is inactivated by ultraviolet radiation, drying and moderate temperatures (Green and Appel, 2006). Longer survival at low temperatures raises the possibility of indirect transmission in cold environments (such as viral contamination of carcasses attended by scavengers). However, the most likely source of infection in solitary *Panthera* species is assumed to be direct transmission when predating infected animals (Gilbert et al., 2020). During the early stages of infection, the virus replicates in the respiratory epithelium, leading to respiratory signs and often, purulent oculonasal discharge. The virus spreads systemically by infecting leucocytes, resulting in immunosuppression related to lymphopaenia. Infected animals may die at this stage, or improve in condition if the immune system is able to overcome the systemic infection. However, in a proportion of animals the virus infects the central and peripheral nervous system, leading to degenerative neurological signs. For these animals, death is probably inevitable, either from the effects of the disease, or as a result of secondary sequelae such as inappropriate behavior. In wild tigers, CDV infections are most evident in these later stages, when neural deficits manifest as aberrant behavior, with a reduced aversion to people leading to observations of tigers in villages or along roadsides. Whether this is evident in all cases, or is an effect of observation bias is unknown. It is unknown whether snow leopards would show similar behavioral signs, but CDV should be considered in any cases where snow leopards present with respiratory infection, ocular and/or nasal discharge, or aberrant behavior, fearlessness, muscle twitching and/or convulsions.

Populations of large felids are too small and occur at densities that are too low to maintain CDV circulation in the long term. Therefore, infections in free-ranging large felids are the result of spillover from more abundant reservoir hosts, and possibly short chains of infection among conspecific contacts. Most terrestrial carnivore species are thought to be susceptible to CDV, and so the exposure of snow leopard populations will depend on the presence of the virus in the wider carnivore community within their habitat. A more abundant susceptible host with high population turnover could act as a reservoir species, or several epidemiologically connected species could act as a reservoir community (Haydon et al., 2002; Viana et al., 2015). In areas that are sparsely settled and poorly connected, numbers of domestic dogs may be insufficient to maintain CDV on their own, but the virus could persist if it were to circulate among more abundant carnivores (such as wild canids and/or mustelids), either in concert with or independent from domestic dogs. Modeling has also shown that CDV circulation occurs over very wide spatial scales (Almberg et al., 2010), and so the status of CDV in snow leopard habitat could be influenced by transmission in distant locations (such as urban centers), if these are epidemiologically connected to remote carnivore communities.

<u>Selected bacterial and rickettsial diseases</u>

Several bacterial agents have the potential to be lethal to free-ranging snow leopards (Table 1). However, as in many nondomestic cats, clinical diseases due to bacterial agents are probably most commonly due to ubiquitous bacteria associated with accidental injuries, gingival and dental lesions and infected wounds (Schmidt-Posthaus et al., 2002). These bacterial infections self-resolve in most cases or remain benign in immunocompetent individuals.

A recent serologic study of 20 free-ranging snow leopards in Mongolia found prior exposure to *Coxiella burnetii*, the agent of zoonotic Q fever, and to *Leptospira* spp. (Esson et al., 2019), two infectious agents of unknown adverse effects on the health and reproduction of wild carnivores. The origin of these pathogens and the role played by snow leopards in their life cycles is unknown.

In contrast, mycobacterial infections and particularly tuberculosis due to *Mycobacterium bovis* have caused significant morbidity and mortality in large free-ranging felids including lions and leopards (*P. pardus*; Michel et al., 2006). In wild felids the disease seems to be primarily acquired from feeding on an infected carcass. Assessing the presence of *M. bovis* in natural prey species and livestock is therefore a crucial indicator of the risk that tuberculosis poses to free-ranging felids. In captivity, snow leopards infected by *M. bovis* have been found with symptoms of weight loss, persistent cough and lesions of granulomatous inflammation of the lungs (Helman et al., 1998). This disease should therefore be considered in abnormally thin and emaciated free-ranging snow leopards with clinical signs or lesions of pulmonary disease.

Anthrax, caused by *Bacillus anthracis*, has been associated with the death of free-ranging felids in Africa, infected after eating an infected carcass (Jager et al., 1990). The disease has been reported from most states of the snow leopard distribution range. A radio-collared snow leopard found dead in the Gobi Desert in April 2011 with marked neck edema, a common sign of anthrax in felids (Jager et al., 1990), and unclotted bloody discharge from the nostrils, was suspected of anthrax (K. Smimaul, personal communication), although no confirmatory test was carried out and the disease is not known to be endemic in this part of Mongolia (Odontsetseg et al., 2007).

Nondomestic felids are known to succumb to other bacterial infections, usually as incidental hosts (Table 1), yet the extent to which snow leopards are susceptible and the occurrence of responsible agents across their range are largely unknown. The exception to this is *Yersinia pestis,* the agent of plague, which is potentially dangerous to any carnivore it would infect, and occurs in enzootic or epizootic cycles in marmot populations across snow leopard habitat (e.g., Sariyeva et al., 2019).

Selected parasitic infections

There have been several reports of ectoparasite infestations in free-ranging felids including cases of highly debilitating mange caused by the mite *Sarcoptes scabiei* in the Himalayan lynx (*Lynx lynx isabellinus*) from Chitral District, Pakistan (Hameed et al., 2016). The responsible mites are fairly host-specific, yet most will parasitize humans. Animals affected by these mites can have hair loss and various degrees of encrusting dermatitis affecting the head, feet and tail most prominently. Monitoring of lynx populations in Europe has however shown that the disease does not constitute a threat to the long-term survival of this species and persists only in areas where it is endemic in co-existing red fox (*Vulpes vulpes*) populations (Ryser-Degiorgis et al., 2005). The snow leopard is susceptible to sarcoptic mange (Peters and Zwart, 1973) but to date the disease has not been documented with certitude in free-ranging animals, although debilitated individuals with hair loss suggestive of mange have been recorded locally (Pamir Times 2011). Anecdotal cases of notoedric mange and facial demodicosis, caused by *Notoedres cati* and *Demodex cati*, respectively, have been recorded in captive snow leopards, and manifested as localized hair loss (Fletcher, 1978, 1980).

Hemoparasites such as piroplasms including *Babesia*, *Hepatozoon, Trypanosoma* and *Cytauxzoon* spp. appear to be common in free-ranging felids. However, except in a few rare instances (see above for *Babesia* spp.), most cases of infections in wild felids are subclinical. Hemoparasites associated with clinical disease have yet to be documented in captive or free-ranging snow leopards.

Toxoplasma gondii is a protozoal parasite that infects most species of warm-blooded animals. Felids are the only known definitive hosts for this parasite, and therefore serve as the main reservoir. Free-ranging snow leopards are exposed to the parasite without described negative effects (Esson et al., 2019). Cats rarely develop clinical toxoplasmosis, although captive Pallas's cats (*Otocolobus manul*) have been reported susceptible to the infection, resulting in high neonatal mortality (Kenny et al., 2002). A mortality case has also been reported in a captive snow leopard (Ratcliffe and Worth, 1951).

Metazoan parasites whether nematodes, cestodes, or trematodes are common in free-ranging felids and do not generally cause clinical disease. Infestations with ascarids such as *Toxascaris leonina* and *Toxocara cati* seem common in free-ranging snow leopards (Mozgovoi, 1953 cited in Ganzorig, et al. 2003), and all fresh feces from a sample of 8-9 adult animals collected in Afghanistan (5), Pakistan (2) and China (1-2) between 2008 and 2013 had eggs of *Toxascaris* spp (Stéphane Ostrowski, personal observation). A case of mortality due to a ruptured aortic aneurysm caused by larvae of *Spirocerca lupi* was reported in a snow leopard 3 months after being brought into captivity, but authors suggested that the infection was acquired during captivity (Kelly and Penner, 1950).

Diseases in snow leopard natural ungulate prey species

Sarcoptic mange in blue sheep and other prey species

The blue sheep (*Pseudois nayaur*) is an important prey species for snow leopards (e.g. Bagchi and Mishra, 2006). In 2007, an outbreak of sarcoptic mange was reported among blue sheep in extreme northern Pakistan (Figure 3), and caused hundreds of fatalities (Dagleish et al., 2007). The disease was first reported by local herders in 1996 and occurred throughout the year, affecting both sexes and all age groups, and reduced the species' population over the ensuing decade. Infected animals were in very poor condition, presenting with severe and extensive skin lesions, especially on the forelegs and chest, and were reluctant to flee when approached (Figure 4). Dagleish et al. (2007) suggested that the severity of lesions in blue sheep could have been the result of protein/energy malnutrition, and perhaps also weak immune response due to a lack of previous exposure to the ectoparasite. Although the origin of the initial infection was not determined with certainty, the authors believed that the most likely source was infected domestic livestock encroaching into blue sheep habitat. The gregarious social behavior of blue sheep may have promoted the dissemination of this novel parasite, which may have been aided by malnutrition due to food competition with livestock (e.g., Mishra et al., 2004). The consequences of this mange outbreak were severe for blue sheep, but potentially also for snow leopards, which rely on this species as an important food source. The prevalence of mange in blue sheep appeared to have decreased by 2010-11 (Hussain Ali, personal communication. 2012), possibly as a result of host adaptation, or selection of more tolerant animals. However, the corollary impacts on the snow leopard population size or dynamics remain unknown. This outbreak and the emergence of similar reports from Nepal in 2020 (Martin Gilbert, personal communication) raise concerns that mange may affect blue sheep populations at a wider scale.

Mange has a long history of affecting populations of Siberian ibex, possibly the main prey species for snow leopards rangewide. Outbreaks can lead to considerable local mortality, such as in the Aksu-Dzhabagly Reserve in Kazakhstan (where ca. 80% of the population was infected in 1968-71), in the Chatkal Range, Uzbekistan, and in Kyrgyzstan. The disease also seems to be endemic in ibex in Khovd Province of the Mongolian Altai (Figure 3). Clinically sarcoptic mange in ibex is similar to that described in blue sheep, with front legs and thorax being affected first, yet the neck and head also appear to be affected at a later stage. Mortality of infected ibex is particularly high during years of heavy snow (Fedosenko and Blank, 2001). Further studies are required to understand the impact of this infectious agent on intra- and inter-specific population dynamics of snow leopards and associated prey.

Mycoplasmosis in markhor and other prey species

Throughout its range, the markhor (*Capra falconeri*) often forages in close proximity to domestic goats (Woodford et al., 2004), and is therefore prone to infections transmitted by these animals. In autumn 2010 an outbreak of *Mycoplasma capricolum* pneumonia killed at least 64 markhor in the southwest of the Hazratishoh Range in Tajikistan (Figure 3; Ostrowski et al., 2011). Several live specimens were observed with clinical signs of labored breathing, with relevant necropsy findings including an abundant serous to mucopurulent nasal discharge; and internally, severe pneumonia associated with a variable level of yellow pleural fluid (Figure 5). The clinicopathologic features of the disease resembled contagious caprine pleuropneumonia (CCPP) caused by *Mycoplasma capricolum* subsp. *capripneumoniae* (Frey, 2002), a highly fatal disease affecting goats in the Middle East, Africa, and Asia. However, a closely related species; *Mycoplasma capricolum* subsp. *capricolum* associated with respiratory diseases in domestic ruminants was identified, using sensitive molecular techniques, as the most probable causative agent of the fatal pneumonia outbreak in the markhor (Ostrowski et al., 2011). Although the origin of the infection remained unknown, occasional contact with domestic goats may have been the source of the markhor outbreak. A survey carried out 8 months after the outbreak confirmed a CCPP serological prevalence of 10.1% (95% CI: 6.3–15.2%) in sympatric domestic goats (Peyraud et al., 2014). The susceptibility of ruminants to *Mycoplasma* infections can be exacerbated by environmental and nutritional stresses. The disease appeared in autumn, when livestock and guard dogs force markhor to retreat to suboptimal pastures (Woodford et al., 2004). It was also the end of the dry season, when contact between markhor and livestock increases around dwindling water sources. The consequences of this pneumonia outbreak appeared to be locally severe for markhor but potentially also for the snow leopard, which preys on this species.

Community guards swiftly implemented control measures, including burning of carcasses and disinfecting contaminated grounds with slaked lime. Shepherds were also asked to avoid using water sources concomitantly to wild ungulates (Stefan Michel, personal communication). As a possible consequence, the markhor population recovered from the outbreak, increasing from an estimated 145 specimens in March 2011 to ca. 400 animals in February 2017 (Broghammer, 2018).

The 2010 outbreak highlighted the general risk posed by mycoplasmas to ungulate prey species throughout snow leopard range. Although there have been no similar reports involving markhor populations since 2010, there is a relative lack of disease surveillance, and access to diagnostic laboratories is limited. Primary outbreaks of diseases caused by various *Mycoplasma* species, including *M. conjunctivae*, the cause of infectious keratoconjunctivitis have had serious consequences for wild Caprinae in Europe. Mortality occasionally occurs due to the disease, and more frequently from associated starvation, or falls due to disease-induced behavioral modifications (Giacometti et al., 2002). In Asia, the presence of *M. conjunctivae* has recently been confirmed among domestic sheep and goats in Central Karakoram, Pakistan, (Fernandez-Aguilar et al., 2017) and may pose a risk of infection for sympatric Siberian ibex and markhor. In China *Mycoplasma ovipneumoniae* (an important pathogen for wild *Ovis* spp. in other parts of the world) has apparently been associated with respiratory disease in captive argali (*Ovis ammon*) (Leng et al., 2014), and would be worth further researching in free-ranging argali with and without symptoms. The confirmation of a massive CCPP outbreak that claimed the lives of ca. 2,400 endangered Tibetan antelopes (*Pantholops hodgsonii*) during September-December 2012 (Figure 3; Yu et al., 2013), raises the specter of an increasing risk of *Mycoplasma* *capricolum* outbreaks in susceptible prey species, which include blue sheep, Siberian ibex, argali, markhor and Himalayan tahr (*Hemitragus jemlahicus*).

Peste des petits ruminants in primary prey species

Peste des petits ruminants (PPR) is a highly infectious viral disease that can cause high mortality of domestic and wild artiodactyls, and has propagated across continental Asia via infected livestock for at least two decades (e.g. Muniraju et al., 2014). By 2021 it has been documented in all countries of the snow leopard range, except Russia. Owing to the wide susceptibility of wild artiodactyls (Fine et al., 2020), it is unsurprising that fatal outbreaks have occurred in three of the most important prey species for snow leopards; the blue sheep in Tibet in October 2007 (Bao et al. 2011), the Siberian ibex and argali in Xinjiang in 2013-2016 (Li et al., 2017) and in western Mongolia in 2016-2017 (Pruvot et al., 2020) (Figure 3). Outbreaks of PPR affecting Asian mountain ungulates have always been significant, with high morbidity and mortality (> 50%, with population declines >80% reported during an outbreak affecting saiga antelope, *Saiga tatarica* Pruvot et. al. 2020). PPR often involves several susceptible species (Fine et al., 2020) suggesting that it could also have significant impacts on wild ungulate communities in the longer term. Several studies have shown that PPR infections are not self-sustaining in wildlife and require spillover from livestock (Fine et al., 2020). Similarly, it was suggested that the closely related rinderpest morbillivirus affected argali in the Pamirs prior to its eradication (Figure 3) (Meklenburtsev, 1948), with infections attributed to spill-over contamination, whilst sharing pastures or water sources with infected livestock (Barrett et al., 2006). The control of the disease in livestock is therefore crucial to protect the natural prey basis of snow leopards.

Conclusions

The current lack of baseline information on the health of free-ranging snow leopards prohibits an assessment of the potential for infectious disease to impact their populations directly. The remote and inaccessible habitat occupied by the species limits opportunities to detect disease-related mortality, and complicates access to laboratories for diagnostic testing. To address these information deficits, researchers should be encouraged to include at least minimal sample collection protocols (appropriate to local circumstances) whenever opportunities arise to handle a snow leopard (e.g. through research projects, conflict situations or when responding to a debilitated or dead individual). A description of minimal sampling protocols is beyond the scope of this review; therefore, researchers are encouraged to seek the advice of a veterinarian with relevant wildlife experience when planning for these situations. The population impact of infectious disease should not be dismissed, despite the relatively low rate of contact among conspecifics, and comparatively low densities of other domestic and wild carnivore species occupying snow leopard habitat. Modeling of another wide-ranging solitary felid, the Amur tiger has shown profound impacts on population viability, even when opportunities for disease exposure are infrequent (Gilbert et al., 2020). These effects may be exacerbated by other physiological stressors, such as food availability, climate-related habitat changes, or by the genetic stresses of inbreeding depression. Domestic dogs and cats represent a potential source of pathogens to which snow leopards are susceptible and their introduction and free-ranging behaviour should be discouraged. Ultimately, a population's ability to withstand the pressures of disease will be maximized by maintaining snow leopards in numerically large subpopulations that are as interconnected as terrain and land use permit.

Snow leopards prey on a range of mammals of varying size. However, large ungulates (including blue sheep, Siberian ibex, argali, markhor and Himalayan tahr) account for more than 40% of their diet and are essential to their survival. Monitoring the health of these species is therefore of crucial importance to support snow leopard conservation at local and global scales. Livestock are increasingly encroaching into wild habitats across Asia, and as the most likely source of disease spillover to snow leopard prey are the prime target for disease surveillance. Moreover, livestock can be responsible for upslope range-shift of mountain ungulates into less suitable, stressful foraging habitat, exacerbating the climate-driven impacts on their ecology (Mason et al., 2014). Therefore, controlling the risk of disease outbreaks in snow leopard prey requires a complex and holistic approach that enforces prevention of disease spillover from livestock to wild ungulates and implements multifaceted controls over livestock numbers and their range use. Limiting other controllable stressors (such as human disturbance), and whenever possible maximizing genetic variability of small, fragmented populations through enhanced subpopulation connectivity, are also recommended to reduce disease susceptibility (Lafferty and Gerber, 2002). Vaccination of livestock is frequently not available (e.g. sarcoptic mange) or inefficacious (e.g. CCPP vaccination in Pakistan; Samiullah, 2013), and when efficiently implemented, may lead to further livestock encroachment into wild ungulate habitat, as a consequence of increased survival and productivity. Therefore, prophylactic-based interventions should always be associated to more comprehensive livestock management strategies that maintain production through smaller healthier herds where wild ungulate contact is limited.

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References

Almberg, E.S., Cross, P.C., Smith, D.W., 2010. Persistence of canine distemper virus in the Greater Yellowstone Ecosystem's carnivore community. Ecological Applications 20, 2058-2074.

Bagchi, S., Mishra, C., 2006. Living with large carnivores: predation on livestock by the snow leopard (*Uncia uncia*). Journal of Zoology 268, 217-224.

Bao, J., Wang, Z., Li, L., Wu, X., Sang, P., Wu, G., Ding, G., Suo, L., Liu, C., Wang, J., Zhao, W., Li, J., Qi, L., 2011. Detection and genetic characterization of peste des petits ruminants virus in free-living bharals (*Pseudois nayaur*) in Tibet, China. Research in Veterinary Science 90, 238-240.

Batzorig, B., Tserenchimed, S., Sugir, S., Purevjat, L., Lhagvasumberel, T., 2011. A case of snow leopard mortality in Mongolia. Annual Proceedings of the State Central Veterinary Laboratory, Unpublished Report, Ulaanbaatar, Mongolia, pp. 109-110 (in Mongol).

Barrett, T., Pastoret, P.-P., Taylor, W.P., 2006. Rinderpest and peste des petits ruminants: virus plagues of large and small ruminants. Academic Press, London.

Blankinship, J.C., Niklaus, P.A., Hungate, B.A., 2011. A meta-analysis of responses of soil biota to global change. Oecologia 165, 553-565.

Broghammer, T., 2018. Assessment of population status and trophy hunting in Heptner's markhor. MSc Thesis, BOKU, Vienna.

Chinnadurai, S.K., Kinsel, M.J., Adkesson, M.J., Terio, K. 2017. Canine distemper in a vaccinated snow leopards (*Panthera uncia*). Journal of Zoo and Wildlife Medicine 48, 1200-1203.

Dagleish, M.P., Qurban, A., Powell, R.K., Butz, D., Woodford, M.H., 2007. Fatal *Sarcoptes scabiei* infection of blue sheep (*Pseudois nayaur*) in Pakistan. Journal of Wildlife Diseases 43, 512-517.

Esson, C., Skerratt, L.F., Berger, L., Malmsten, J., Strand, T., Lundkvist Å., Järhult, J.D., Michaux, J., Mijiddorj, T.N., Bayrakçismith, R., Mishra, C., Johansson, Ö. 2019. Health and zoonotic infections of snow leopards *Panthera uncia* in the south Gobi desert of Mongolia. Infection Ecology and Epidemiology 9, 1604063.

Fedosenko, A.K., Blank, D.A., 2005. *Ovis ammon*. Mammalian Species 773, 1-15.

Fernandez-Aguilar, X., Rossi, L., Cebezon, O., Giorgino, A., Llopis, I.V., Frey, J., Lopez-Olvera, J.R., 2017. Infectious keratoconjunctivitis and occurrence of *Mycoplasma conjunctivae* and *Chlamydiaceae* in small ruminants from Central Karakoram, Pakistan. Veterinary Record 181(9): 237.

Fine A.E., Pruvot, M., Benfield, C.T.O., Caron, A., Cattoli, G., Chardonnet, P., Dioli, M., Dulu, T., Gilbert, M., Kock, R., Lubroth, J., Mariner, J.C., Ostrowski, S., Parida, S., Fereidouni, S., Shiilegdamba, E., Sleeman, J. M., Schultz, C., Soula, J.-J., Vand der Stede, Y., Tekola, B.G., Walzer, C., Zuther, S., Njeumi, F. 2020. Eradication of peste des petits ruminants virus and the wildlife-livestock interface. Frontiers in Veterinary Science 7, 50.

Fix, A.S., Riordan, D.P., Hill, H.T., Gill, M.A., Evans, E.B., 1989. Feline panleukopenia virus and subsequent canine distemper virus infection in two snow leopards (*Panthera uncia*). Journal of Zoo and Wildlife Medicine 20, 273-281.

Fletcher, K.C., 1978. Notoedric mange in a litter of snow leopards. Journal of the American Veterinary Medical Association 173, 1231-1232.

Fletcher, K.C., 1980. Demodicosis in a group of juvenile snow leopards. Journal of the American Veterinary Medical Association 177, 896-898.

Frey, J., 2002. Mycoplasmas of animals. In: Razin, S., Herrmann, R., (Eds.) Molecular biology and pathogenicity of mycoplasm. Kluwer Academic/Plenum Publishers, New York, pp. 73-90.

Ganzorig, S., Oku, Y., Okamoto, M., Kamiya, M., 2003. Specific identification of a taeniid cestode from snow leopard, *Uncia uncia* Schreber, 1776 (Felidae) in Mongolia. Mongolian Journal of Biological Sciences 1, 21-25.

Giacometti, M., Janovsky, M., Jenny, H., Nicolet, J., Belloy, L., Goldschmidt-Clermont, E., Frey, J., 2002. *Mycoplasma conjunctivae* infection is not maintained in alpine chamois in eastern Switzerland. Journal of Wildlife Diseases 38, 297-304.

Gilbert, M., Sulikhan, N., Uphyrkina, O., Goncharuk, M., Kerley, L., Hernandez Castro, E., Reeve, R., Seimon, T., McAloose, D., Seryodkin, I.V., Naidenko, S.V., Davis, C.A., Wilkie, G.S., Vattipally, S.B., Adamson, W.E., Hinds, C., Thomson, E.C., Willett, B.J., Hosie, M.J., Logan, N. McDonald, M., Ossiboff, R.J., Shevtsova, E.I., Belyakin, S., Yurlova, A.A., Osofsky, S.A., Miquelle, D.J., Matthews, L., Cleaveland, S. 2020. Distemper, extinction, and vaccination of the Amur tiger. Proceedings of the National Academy of Sciences 117, 31954-31962.

Green, C.E., Appel, M.J., 2006. Canine Distemper. In: Green, C.E. (Ed.) Infectious diseases of the dog and cat, third ed. Elsevier, St Louis, MO, pp. 25-41.

Hameed, K., Angelone-Alasaad, S., Din, J.U., Nawaz, M. A., Rossie, L., 2016. The threatening but unpredictable *Sarcoptes scabiei*: first deadly outbreak in the Himalayan lynx, *Lynx lynx isabellinus*, from Pakistan. Parasites & Vectors 9, 402.

Haydon, D.T., Cleaveland, S., Taylor, L.H., Laurenson, M.K. 2002. Identifying reservoirs of infection: a conceptual and practical challenge. Emerging Infectious Diseases 8, 1468-1473.

Helman, R.G., Russel, W.C., Jenny, A., Miller, J., Payeur, J., 1998. Diagnosis of tuberculosis in two snow leopards using polymerase chain reaction. Journal of Veterinary Diagnostic Investigation 10,89-92.

Heptner, V.G., Sludskii, A.A., 1992. Mammals of the Soviet Union. Vol. 2 Part 2 (Carnivores: Hyaenas and Cats). Amerind Publishing, New Delhi, India.

Jager, H.G., Booker, H.H., Hubschle, O.J., 1990. Anthrax in cheetahs (*Acinonyx jubatus*) in Namibia. Journal of Wildlife Diseases 26, 423-424.

Johansson, Ö., Ullman, K., Lkhagvajav, P., Wiseman, M., Malmsten, J., Leijon, M. 2020. Detection and genetic characterization of viruses present in free-ranging snow leopards using next-generation sequencing. Frontiers in Veterinary Science 7: 645.

Kelly, A.L., Penner, L.R., 1950. *Spirocerca* from the snow leopard. Journal of Mammalogy 31, 462.

Kenny, D.E., Lappin, M.R., Knightly, F., Baier, J., Brewer, M., Getzy, D.M., 2002. Toxoplasmosis in Pallas' cats (*Otocolobus felis manul*). Journal of Zoo and Wildlife Medicine 33, 131-138.

Lafferty, K.D., Gerber, L.R., 2002. Good medicine for conservation biology: the intersection of epidemiology and conservation biology. Conservation Biology 16, 593-604.

Leng, Q., Li, Z., Lu, H., Jin, Y., Wang, J., Yan, G., 2014. Isolation and identification of *Mycoplasma ovipneumoniae* in argali. Chinese Journal of Preventive Veterinary Medicine 36(3), 197-200 (In Chinese).

Li, J., Li, L., Wu, X., Liu, F., Zou, Y., Wang, Q., Liu, C., Bao, J., Wang, W., Ma, W., Lin, H., Huang, J., Zheng, X., Wang, Z. 2017. Diagnosis of peste des petits ruminants in wild and domestic animals in Xinjiang, China, 2013-2016. Transboundary Emerging Diseases 64, e43-7.

Mason, T.H.E, Stephens, P.A., Appolonio, M., Willis, S.G., 2014. Predicting potential responses to future climate in an alpine ungulate: interspecific interactions exceeds climate effects. Global Change Biology 20, 3872-3882.

Meklenburtsev, R.N., 1948. Pamir argali *Ovis polii polii* Blyth. Bulletin of the Moscow Society of Naturalists, Biology Department 53, 65-84 (In Russian).

Michel, A.L., Bengis, R.G., Keet, D.F., Hofmeyr, M., de Klerk, L. M., Cross, P.C., Jolles, A.E., Cooper, D., Whyte, I.J., Buss, P., Godfroid, J., 2006. Wildlife tuberculosis in South African conservation areas: Implications and challenges. Veterinary Microbiology 112, 91-100.

Mishra, C., Van Wieren, S.E., Ketner, P., Heitkönig, I.M.A., Prins, H.H.T., 2004. Competition between domestic livestock and wild bharal *Pseudois nayaur* in the Indian Trans-Himalaya. Journal of Applied Ecology 41, 344-354.

Muniraju, M., Munir, M., Parthiban, A.R., Banyard, A.C., Bao, J., Wang, Z., Ayebazibwe, C., Ayelet, G., El Harrak, M., Mahapatra, M., Libeau, G., Batten, C., Parida, S., 2014. Molecular evolution of peste des petits ruminants virus. Emerging Infectious Diseases 20, 2023-2033.

Munson, L., Terio, K.A., Kock, R., Mlengeya, T., Roelke, M.E., Dubovi, E., Summers, B., Sinclair, A.R.E., Packer, C., 2008. Climate extremes promote fatal co-infections during Canine Distemper epidemics in African lions. *Plos ONE* 3, e2545.

Nowell, K., Li, J., Paltsyn, M., Sharma, R.K., 2016. An ounce of prevention: snow leopard crime revisited. TRAFFIC, Cambridge, UK.

Odontsetseg, N., Tserendorj, S., Adiyasuren, Z., Uuganbayar, D., Mweene, M.S., 2007. Anthrax in animals and humans in Mongolia. Revue Scientific et Technique (Office International des Epizooties) 26, 701-710.

Ostrowski, S., Thiaucourt, F., Amirbekov, M., Mahmadshoev, A., Manso-Silván, L., Dupuy, V., Vahobov, D., Ziyoev, O., Michel, S. 2011. Fatal outbreak of *Mycoplasma capricolum* pneumonia in endangered markhor. Emerging Infectious Diseases 17, 2338-2341.

Pamir Times, 2011. Sick snow leopard captured by villagers in Skardu, dies. Available from: <http://pamirtimes.net/2011/02/27/sick-snow-leopard-captured-by-villagers-in-skardu-dies/>. [6 February 2015].

Peyraud, A., Poumarat, F., Tardy, F., Manso-Silván, L., Hamroev, K., Tilloev, T., Amirbekov, M., Tounkara, K., Bodjo, C., Wesonga, H., Gacheri Nkando, I., Jenberie, S., Yami, M., Cardinale, E., Meenowa, D., Reshad Jaumally, M., Yaqub, T., Shabbir, M. Z., Mukhtar, N., Halimi, M., Ziay, G. M., Schauwers, W., Noori, H., Rajabi, A.M., Ostrowski, S., Thiaucourt, F. 2014. An international collaborative study to determine the prevalence of contagious caprine pleuropneumonia by monoclonal antibody-based cELISA. BMC Veterinary Research 10, 48.

Peters, J.C., Zwart, P. 1973. Sarcoptesräude bei Schneeleoparden. Erkrankungen der Zootiere. Verhandlungsbericht des XV Symposium uber die Erkrankungen der Zootiere 15, pp. 333-334.

Pruvot, M., Fine, A.E., Hollinger, C., Strindberg, S., Damdinjav, B., Buuveibaatar, B., Chimeddorj, B., Bayandonoi, G., Khishgee, B., Sandag, B., Narmandakh, J., Jargalsaikhan, T., Bataa, B., McAloose, D., Shatar, M., Basan, G., Mahapatra, M., Selvaraj, M., Parida, S., Njeumi, F., Kock, R., Shiilegdamba, E. 2020. Outbreak of Peste des Petits Ruminants virus among

Critically Endangered Mongolia Saiga and other wild ungulates, Mongolia, 2016-2017. Emerging Infectious Diseases 26, 51-62.

Ratcliffe, H.L., Worth, C.B. 1951. Toxoplasmosis of captive wild birds and mammals. American Journal of Pathology 27, 655-667.

Roelke-Parker, M.E., Munson, L., Packer, C., Kock, R., Cleaveland, S., Carpenter, M., O'Brien, S.J., Pospischil, A., Hofmann-Lehmann, R., Lutz, H., Mwamengele, L.M., Mgasa, M.N., Machange, G.A., Summers, B.A., Appel, M.J.G. 1996. A canine distemper virus epidemic in Serengeti lions (*Panthera leo*). Nature 379, 441-445.

Ryser-Degiorgis, M.-P., Bröjer, C., Hård af Segerstad, C., Bornstein, S., Bignert, A., Lutz, H., Uggia, A., Gavier-Widén, D., Tryland, M., Mörner, T. 2005. Assessment of the health status of the free-ranging Eurasian lynx in Sweden. Proceedings of the 1st workshop on lynx veterinary aspects, Doñana, 4-6 November 2005, Ministry of the Environment, Spain.

Samiullah, S. 2013. Contagious caprine pleuropneumonia and its current picture in Pakistan: a review. Veterinarni Medicina 58, 389-398.

Sariyeva, G., Bazarkhanova, G., Maimulov, R., Abdikarimov, S., Kurmanov, B., Abdirassiliva, A., Shabunin, A., Sagiyav, Z., Dzhaparova, A., Abdel, Z., Mussagaliyeva, R., Morand, S., Motin, V., Kosoy M., 2019. Marmots and *Yersinia pestis* strains in two plague endemic areas of Tien Shan Mountains. Frontiers in Veterinary Science 6, 207.

Schmidt-Posthaus, H., Breintenmoser-Wursten, C., Posthaus, H., Bacciarini, L., Breitenmoser, U., 2002. Pathological investigation of mortality in reintroduced Eurasian lynx (*Lynx lynx*) populations in Switzerland. Journal of Wildlife Diseases 38, 84-92.

Seimon, T.A., Miquelle, D.G., Chang, T.Y., Newton, A.L., Korotkova, I., Ivanchuk, G., Lyubchenko, E., Tupikov, A., Slabe, E., McAloose, D., 2013. Canine Distemper Virus: an emerging disease in wild endangered Amur tigers (*Panthera tigris altaica*). mBio 4, e00410-13

Silinski, S., Robert, N., Walzer, C., 2003. Canine distemper and toxoplasmosis in a captive snow leopard (*Uncia uncia*) – a diagnostic dilemma. Verhandlungsbericht Erkrankungen der Zootiere 41, 107-111.

Viana, M., Cleaveland, S., Matthiopoulos, J., Halliday, J., Packer, C., Craft, M.E., Hampson, K., Czupryna, A., Dobson, A. P., Dubovi, E.J., Ernest, E., Fyumagwa, R., Hoare, R., Hopcraft, J.G. C., Horton, D.L., Kaare, M.D., Kanellos, T., Lankester, F., Mentzel, C., Mlengeya, T., Mzimbiri, I., Takahashi, E., Willett, B., Haydon, D.T., Lembo, T., 2015. Dynamics of a morbillivirus at the domestic-wildlife interface: Canine distemper virus in domestic dogs and lions. Proceedings of the National Academy of Sciences 112, 1464-1469.

Womble, M., Georoff, T.A., Helmick, K., Carpenter, N. A., Joslin, J., Tupa, L., Tetzloff, J., and McAloose D., 2021. Mortality review for the north American snow leopard (*Panthera uncia*) zoo population from January 1999 to December 2019. Journal of Zoo and Wildlife Medicine 52, in press.

Woodford, M.H., Frisina, M.R., Awan, G.A., 2004. The Torghar conservation project: management of the livestock, Suleiman markhor (*Capra falconeri*) and Afghan urial (*Ovis orientalis*) in the Torghar Hills, Pakistan. Game Wildlife Science 21, 177-187.

Yu, Z., Wang, T., Sun, H., Xia, Z., Zhang, K., Chu, D., Xu, Y., Cheng, K., Zheng, X., Huang, G., Zhao, Y., Yang, S., Gao, Y., Xia, X., 2013. Contagious caprine pleuropneumonia in endangered Tibetan antelope, China, 2012. Emerging Infectious Diseases 19, 2051-2052.

Figure captions

Figure 1. Determining with accuracy the genuine cause of death of free-ranging snow leopards (*P. uncia*) could prove a daunting task. This specimen was found dead at the base of a steep cliff over which local people alleged it had accidentally fallen. However, a thorough necropsy of the animal revealed the presence of bullet fragments in the radius bone (A) (arrow), and an hemorrhagic track through shoulder muscles with additional fragments of a 0.22 caliber rimfire bullet (B), supporting that the fall was consecutive to a gunshot. Wakhan District, Afghanistan, December 2010. *Source: Photo courtesy of S. Ostrowski and Inayat Ali*.

Figure 2. A veterinarian saws the skull of a dead radio-collared snow leopard (*P. uncia*) in order to collect brain tissue for laboratory investigations. Snow leopards are susceptible to a range of neurotropic infectious agents, such as the viruses responsible of rabies and canine distemper. Tost Mountains, South-Gobi Province, Mongolia, August 2011. *Source: Photo courtesy of T. Lhagvasumberel*.

Figure 3. Geographical locations of reported disease outbreaks in natural ungulate prey species plotted over snow leopard distribution range (in pink). Details of outbreaks are provided hereinafter (disease name / date of outbreak / mountain range / country / reference). A. Rinderpest and anthrax / 1895-1898 / Pamir Mountains / Tajikistan / Meklenburtsev, 1948; B.

“Goats pleuropneumonia disease” / 1940s’ / Pamir Mountains / Tajikistan / Heptner, V.G., Nasimovich, A.A., Bannikov, A.G., 1961. Mammals of the Soviet Union. Artiodactyla and Perissodactyla. Vyssahya Shkola, Moscow, USSR (in Russian); C. Sarcoptic mange / late 1960’s / Pamir-Alai Mountains / Uzbekistan / Vyrypaev, V.A., 1973. The status of the Siberian ibex population in the west part of the Chatkal Range (Central Asia). In: Sokolov, V.E. (Ed.) The rare mammal species in the USSR and their conservation. Nauka, Moscow, USSR (in Russian); D. Sarcoptic mange / 1968-1971 / Pamir-Alai Mountains / Kazakhstan / Fedosenko, A.K., Savinov, E.F., 1983. The Siberian ibex. In: Gvozdev, E.V., Kapitonov, V.I. (Eds.), Mammals of Kazakhstan. Nauka of Kazakh SSSR, Alma-Ata, pp. 92-143. (in Russian); E. Sarcoptic mange / late 1960’s / Tien Shan Mountains / Kyrgyzstan / Yanushevich et al., 1972, cited in Fedosenko, A.K., Blank, D.A., 2001. *Capra sibirica*. Mammalian Species 675, 1-13.; F. Peste des petits ruminants / 2014-2016 / Xinjiang / China / Li et al., 2017; G. Tuberculosis / 1989 / Altai Mountains / Russia / Fedosenko and Blank, 2005; H. Peste des petits ruminants / 2016-2018 / Khovd and Gobi-Altai / Mongolia / Pruvot et al., 2020; I. Sarcoptic mange / ongoing / Altai Mountains / Mongolia / E. Shiilegdamba pers. comm., 2014; J. Contagious caprine pleuropneumonia / 2012 / Tibetan Plateau / China / Yu et al., 2013; K. Peste des petits ruminants / 2007-2008 / Tibetan Plateau / China / Bao et al., 2011; L. Sarcoptic mange / 1997-2007 / Karakoram Mountains / Pakistan / Dalgleish et al., 2007; M. Foot and mouth disease (??) / 2011 / Hindu Kush Mountains / Pakistan / Shabbir Mir, 2011. Deadly disease kills 12 markhors in Chitral. The Express Tribune, April 9, 2011. Available from: <http://tribune.com.pk/story/146166/deadly-disease-kills-12-markhors-in-chitral>. [6 February 2015]; N. Caprine mycoplasmosis / 2010 / Pamir-Alai Mountains / Tajikistan / Ostrowski et al., 2011.

Figure 4. An adult male blue sheep (*Pseudois nayaur*) presenting severe and extensive skin lesions on the forelegs and chest due to *Sarcoptes scabiei*, the ectoparasite responsible of sarcoptic mange. Debilitated and indifferent to humans, this animal was easily handled by yak herders. Shimshal area, Gilgit-Baltistan Province, Pakistan, July 2000. *Source: Photo courtesy of D. Butz*.

Figure 5. An adult male Heptner's markhor (*Capra falconeri heptneri*) found dead in the south-west of the Hazratishoh range, Tajikistan. *Mycoplasma capricolum* subsp. *capricolum* associated with respiratory diseases in domestic ruminants was identified as the most probable causative agent of the fatal pneumonia which killed this markhor, along with at least 63 others, in September 2010. *Source: Photo courtesy of State Veterinary Department of Tajikistan*.

Table 1. Selected microbial diseases potentially responsible of morbidity and mortality in free-ranging snow leopards

Disease	Symptoms in felids	Mode of transmission	Perceived lethality	Reference (captive snow leopard)	Reference (free-ranging large nondomestic cats)
Virus[1]					
Rabies	CNS disease; death	Bite injury; saliva	High	-	(Pfukenyi et al., 2009)[a]
Canine distemper	CNS disease, pneumonia ; death	Ingestion ; inhalation	High	(Fix et al., 1989)	(Seimon et al., 2013)
Feline immunodeficiency	Pneumonia; diarrhea; death	Bite injury	Possibly high	(Barr et al., 1989)[b]	(Roelke et al., 2006)[c]

[1] SARS-CoV-2 the coronavirus responsible of the COVID-19 human pandemic has affected snow leopards in zoological collections in October 2021 (see text). It is currently not known whether an infection with the virus could adversely impact wild snow leopard populations.

Bluetongue	Lethargy; pneumonia; death	Ingestion; mosquito bite	Possibly high	-	(Alexander et al., 1994)[d]
Feline panleukopenia	Fever ; diarrhea ; vomition ; death	Ingestion ; transplacentally	Moderate	(Fix et al., 1989)	(Schmidt-Posthaus et al., 2002)
Feline leukemia	Anemia; immunosuppression; death	Bite injury; body fluids	Moderate	-	(Meli et al., 2009)[e]
Feline papillomavirosis	Oral warts (PV-1); cutaneous neoplasia (PV-2)	Damaged oral mucosa	Low	(PV-1 and PV-2; Sundberg et al., 2000)[f]	(PV-2; Johansson et al., 2020)
Feline coronavirosis	Enteritis; diarrhea ; peritonitis	Ingestion	Low	(Kennedy et al., 2002)[g]	(Heeney et al., 1990)[h]
Feline calicivirosis	Upper respiratory tract disease	Inhalation	Low	-	(Hofmann-Lehmann et al., 1996)[i]

Feline herpesvirosis	Upper respiratory tract disease, ocular lesions	Inhalation, conjunctival contact	Low	-	(Johansson et al., 2020)
Bacteria					
Tuberculosis	Lower respiratory tract disease; emaciation; death	Inhalation	High	(Helman et al., 1998)	(Michel et al., 2006)
Plague	Pneumonia ; death	Ingestion ; flea bite	High	-	(Wild et al., 2006)[j]
Anthrax	Sudden death	Ingestion	Moderate	-	(Jager et al., 1990)
Pseudotuberculosis	Diarrhea ; vomition; lethargy ; anorexia;	Ingestion	Moderate	-	(Ryser-Degiorgis and Robert, 2006)[k]
Tularemia	Lethargy; oral ulcers; enlarged lymph nodes	Ingestion; Inhalation; insect bite	Low	-	(Girard et al., 2012)[l]
Protozoa					

Babesiosis	Fever; anemia; jaundice	Tick bite	Low	-	(Munson et al., 2008)
Hepatozoonosis	Anemia; emaciation	Tick bite	Low	-	(Khoshnegah J. et al., 2012)[m]
Toxoplasmosis	CNS disease, pneumonia	Ingestion	Low	(Ratcliffe and Worth, 1951)	(Smith et al., 1995)[n]
Fungi					
Dermatophytosis	Focal/coalescing skin lesions; alopecia;	Skin contact	Low	-	(Rotstein et al., 1999)[o]

[a] Pfukenyi, D.M., Pawandiwa, D., Makaya, P.V., Ushewokunze-Obatolu, U., 2009. A retrospective study of wildlife rabies in Zimbabwe between 1992 and 2003. Tropical Animal Health Production 41, 565-572.

[b] Barr, M.C., Calle, P.P., Roelke, M.E., Scott, F.W., 1989. Feline Immunodeficiency Virus infection in nondomestic felids. Journal of Zoo and Wildlife Medicine 20, 265-272.

[c] Roelke, M.E., Pecon-Slattery, J., Taylor, S., Citino, S., Brown, E., Packer, C., VandeWoode, S., O'Brien, S.J., 2006. T-Lymphocyte profiles in FIV-infected wild lions and pumas reveal CD4 depletion. Journal of Wildlife Diseases 42, 234-248.

[d] Alexander, K.A., MacLachlan, N.J., Kat, P.W., House, C., O'Brien, S.J., Lerche, N.W., Sawyer, M., Frank, L.G., Holekamp, K., Smale, L., McNutt, J.W., Laurenson, M.K., Mills, M.G.L., Osburn, B.I., 1994. Evidence of natural bluetongue virus infection among African carnivores. American Journal of Tropical Medicine and Hygiene 51, 568-576.

[e] Meli, M.L., Cattori, V., Martínez, F., López, G., Vargas, A., Simón, M.A., Zorrilla, I., Muñoz, A., Palomares, F., Lópes-Bao, J.V., Pastor, J., Tandon, R., Willi, B., Hofmann-Lehmann, R., Lutz, H., 2009. Feline Leukemia Virus and other pathogens as important threats to the survival of the critically endangered Iberian Lynx (*Lynx pardinus*) PloS ONE 4, e4744.

[f] Sundberg, J.P., Van Ranst, M., Montali, R., Homer, B.L., Miller, W.H., Rowland, P.H., Scott, D.W., England, J.J., Dunstan, R.W., Mikaelian, I., Jenson, A.B., 2000. Feline papillomas and papillomaviruses. Veterinary Pathology 37, 1-10.

[g] Kennedy, M., Citino, S., McNabb, A.H., Moffatt, A.S., Gertz, K., Kania, S., 2002. Detection of feline coronavirus in captive Felidae in the USA. Journal of Veterinary Diagnostic Investigation 14, 20-522.

[h] Heeney, J.L., Evermann, J.F., McKierman, A.J., Marker-Kraus, L., Roelke, M.E., Bush, M., Wildt, D.E., Meltzer, D.G., Colly, L., Lukas, J., Manton, V.J., Caro, T., O'Brien, S.J., 1990. Prevalence and implications of feline coronavirus infections of captive and free-ranging cheetahs (*Acinonyx jubatus*). Journal of Virology 64, 1964-1972.

[i] Hofmann- Lehmann, R., Fehr, D., Grob, M., Elgizoli, M., Packer, C., Martenson, J.S., O'Brien, S.J., Lutz, H., 1996. Prevalence of antibodies to feline parvovirus, calicivirus, herpesvirus, coronavirus and immunodeficiency virus, and feline leukemia antigen and the interrelationships of these infections in free-ranging lions in East Africa. Clinical and Vaccine Immunology 3, 554-562.

[j] Wild, M.A., Shenk, T.M., Spraker, T.R., 2006. Plague as a mortality factor in Canada lynx (*Lynx canadensis*) reintroduced to Colorado. Journal of Wildlife Diseases 42, 646-650.

[k] Ryser-Degiorgis, M.-P., Robert, N., 2006. Causes of mortality and diseases in free-ranging Eurasian lynx from Switzerland - an update. Proceedings of the Iberian Lynx. *Ex situ* conservation seminar series. Sevilla and Doñana, Spain, pp. 36-41.

[l] Girard, Y.A., Swift, P., Chomel, B.B., Kasten, R.W., Fleer, K., Foley, J.E., Torres, S.G., Johnson, C.K., 2012. Zoonotic vector-born bacterial pathogens in California mountain lions (*Puma concolor*), 1987-2010. Vector-borne and zoonotic diseases 12, 913-921.

[m] Khoshnegah, J., Mohri, M., Mirshahi, A., Mousavi, S. J., 2012. Detection of *Hepatozoon* sp. in a Persian leopard (*Panthera pardus ciscaucasica*). Journal of Wildlife Diseases 48, 776-780.

[n] Smith, K.E., Fischer, J.R., Dubey, J.P., 1995. Toxoplasmosis in a bobcat (*Felis rufus*). Journal of Wildlife Diseases 31, 555-557.

[o] Rotstein, D.S., Thomas, R., Helmick, K., Citino, S.B., Taylor, S.K., Dunbar, M.R. 1999. Dermatophyte infections in free-ranging Florida panthers (*Felis concolor coryi*). Journal of Zoo and Wildlife Medicine 30, 281-284.