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REVIEW

Biology and management of sarcoptic mange in wild Caprinae populations

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ABSTRACT

1. Sarcoptic mange is a cosmopolitan disease affecting the skin of domestic and wild mammalian species and humans as well. In Eurasia, sarcoptidosis (also known as sarcoptic mange or scabies) affects mountain ungulates (Caprinae) among other wild hosts, and epizootic outbreaks induce variable mortality rates. This fact, coupled with the important ecological and socio-economic values of such mammalian hosts, resulted in many research projects being focused on addressing ecological, physiological, behavioural, genetic, and pathological effects of the disease.
2. Nevertheless, information about management of sarcoptic mange in free-ranging populations is scarce and scattered, with contradictory results and a lack of consensus on basic aspects of the disease.
3. In this review, we summarise knowledge on the effects of sarcoptic mange in wild Caprinae, at individual, pathological and population epidemiological levels, as well as on the current tools and management strategies for its detection, diagnosis, prevention, and control.
4. Disease spread in naïve populations is ca. 6 km year^{-1}, and the mortality rate can be >95%. Tools for monitoring the disease include visual diagnosis, photographic traps, trained dogs, thermography, immunodiagnostics, molecular tools, radiocollars, and epidemiological modelling. Options for management

include eradication, control, and prevention of the disease; biosecurity and prevention of spread to humans can be achieved by careful hygiene methods.

5. Sarcoptic mange is a natural, biological factor controlling host population numbers and dynamics in Caprinae, so goals and strategies for its management in wild populations must be set accordingly.
6. Specific management programmes for preventing and controlling sarcoptic mange in wild Caprinae populations must be based on reliable epidemiological data. More research is needed to provide evidence-based policies. The efficacy and safety of various management approaches remain to be tested experimentally.

INTRODUCTION

Animal diseases are a topic of concern, firstly, because animals can act as reservoirs or vectors of pathogens which can affect humans (zoonoses). Secondly, wild mammals and livestock share a number of diseases; this poses an indirect zoonotic risk and causes economic losses (Gortázar et al. 2016). Finally, but importantly, wildlife diseases can affect host densities. This is particularly relevant for small populations of threatened species (Peterson & Ferro 2012). Moreover, information obtained when monitoring wildlife diseases is pivotal for the adaptive management of wild populations.

Wild caprines (subfamily Caprinae), as large herbivores, are keystone and umbrella species of mountain habitats (Found 2016), as well as valuable game species. In addition, they represent a potential source of new genetic material for improving livestock or to ensure its adaptation to less productive conditions. However, more than 70% of wild caprine species face some degree of threat, and more than 30% are considered Endangered or Critically Endangered, due to overexploitation (hunting); alteration, loss, and fragmentation of habitats; and competition with domestic species (Schackleton 1997).

During the last few decades, a number of mange outbreaks caused by the mite *Sarcoptes scabiei* have been reported in wild free-ranging populations of different Caprinae species. Sarcoptic mange has also been reported affecting animals kept in captivity in zoological gardens (Yeruham et al. 1996). The reported mortality rates induced by mange vary significantly among host species and populations (Fernández-Morán et al. 1997, Rossi et al. 2007), and for most outbreaks, there is a lack of information about such rates. Despite some reported mortality rate values exceeding 95 % (Fandos 1991), the complete extinction of a host population by *Sarcoptes scabiei* has not been reported.

Such high levels of induced mortality mean not only the loss of renewable natural resources, but also a threat for some host species or populations, which, in turn, may have potential impact on the dynamics of mountain ecosystems. Within this context, we reviewed the biology and management of sarcoptic mange in wild Caprinae populations. Our review will serve as a reference for managers as well as for biologists.

METHODS

We conducted a search in the ISI Web of Science using several keywords, such as sarcoptic mange, ungulates, Caprinae, and management. Some references focussed on the management of sarcoptic mange in other types of hosts (e.g. carnivores) were also considered. This primary source of information was complemented with abstracts and proceedings of specialised congresses (e.g. World Conference on Mountain Ungulates, European Congress on Genus *Capra*, and Rencontres du Groupe d'Etudes sur l'Ecopathologie de la Faune Sauvage de Montagne).

RESULTS AND DISCUSSION

Sarcoptic mange affects a number of wild Caprinae species throughout Eurasia (Table 1), but there is a striking absence of similarly affected species in other continents. A recent review of sarcoptic mange affecting North American wildlife (Niedringhaus et al. 2019b) included bighorn sheep *Ovis canadensis* as a host for *Sarcoptes scabiei* (Cowan 1951). This was possibly a case of mite misidentification, since this host is affected by psoroptic mange *Psoroptes ovis* throughout North America (Lange et al. 1980, Ramey et al. 2000). In North America, sarcoptic mange affects mainly carnivores, such as red foxes *Vulpes vulpes*, wolves *Canis lupus*, coyotes *Canis latrans,* and black bears *Ursus americanus* (Niedringhaus et al. 2019a,b).

Spatio-temporal dynamics of sarcoptic mange in mountain ungulates

Rossi et al. (2007) described the spatial advance of mange in a northern chamois *Rupicapra rupicapra* population from

Table 1. Checklist of Eurasian Caprinae host species affected by sarcoptic mange

Host species	Location	References
Aoudad *Ammotragus lervia*	Zoological garden (Israel)	Yeruham et al. 1996
	Sierra Espuña (southeastern Spain)	González et al. 2004
Alpine ibex *Capra ibex*	Eastern Alps (Italy, Austria, Slovenia)	Rossi et al. 2007
Iberian ibex *Capra pyrenaica*	South and eastern Spain	León Vizcaino et al. 1999
Nubian ibex *Capra nubiana*	Zoological garden (Israel)	Yeruham et al. 1996
Asiatic ibex *Capra sibirica*	Tien-Shan (Kazakhstan, former Soviet Union)	Vyripaev 1985
	Xinjiang (China)	Li et al. 2018
Blue sheep *Pseudois nayaur*	Karakoram (Pakistan)	Dagleish et al. 2007
Goral *Naemorhedus goral*	Sichuan (China)	Li et al. 2018
Formosan serow *Capricornis swinhoei*	Central Mountain Range (Taiwan)	Chen et al. 2012
Himalayan serow *Capricornis thar*	Uttarakhand (India)	Khanyari et al. 2017
	Sichuan (China)	Li et al. 2018
Japanese serow *Capricornis crispus*	Japan (several prefectures)	Matsuyama et al. 2019
European mouflon *Ovis aries musimon*	Cazorla Segura y Las Villas Natural Park (southern Spain)	León Vizcaino et al. 1992
	Eastern Alps (Italy)	Rossi et al. 2007
Southern chamois *Rupicapra pyrenaica*	Cantabrian mountain range (northern Spain)	Fernández-Morán et al. 1997
Northern chamois *Rupicapra rupicapra*	Eastern Alps (Germany, Austria, Slovenia, Italy)	Miller 1985, Rossi et al. 2007

the Dolomite Alps during a 10-year period. Mange spread like an 'oil spot', combined with 'jumps' at speeds of 9–20 km year^{-1}. On average, these authors estimated that the disease frontline advanced at a speed of 5.5 ± 7.1 km year^{-1} (mean ± standard deviation; range 0 – 22.8 km year^{-1}). A similar advance speed (6-7 km year^{-1}) was reported by Fernández-Morán et al. (1997) for the initial phase of a sarcoptic mange outbreak affecting a population of southern chamois *Rupicapra pyrenaica*. In the Sierra Nevada Natural Space, southern Spain, the first scabietic Iberian ibex *Capra pyrenaica* was observed in 1992, and, ten years later, the disease had spread throughout the whole mountain range and surrounding areas, giving an estimated mean mange front speed of around 9 km year^{-1} (Granados et al. 2007).

Epidemiological surveys in humans and wild animals reveal a remarkable persistence (endemisation) of scabies in affected populations, and a common pattern consisting of periodic fluctuations ('waves') with cycles ranging between 10 and 30 years (Orkin 1975, Arlian 1989, Rossi et al. 1995). When naïve populations experience their first contact with the mite, they can suffer high rates of mange-induced mortality. However, in later waves, lower levels of mortality are registered due to selection of resistant individuals and strengthening of herd immunity (Rossi et al. 1995, Guberti & Zamboni 2000).

The monthly prevalence of sarcoptic mange shows a seasonal pattern linked to the social and breeding behaviour of hosts, which influence mite transmission and load

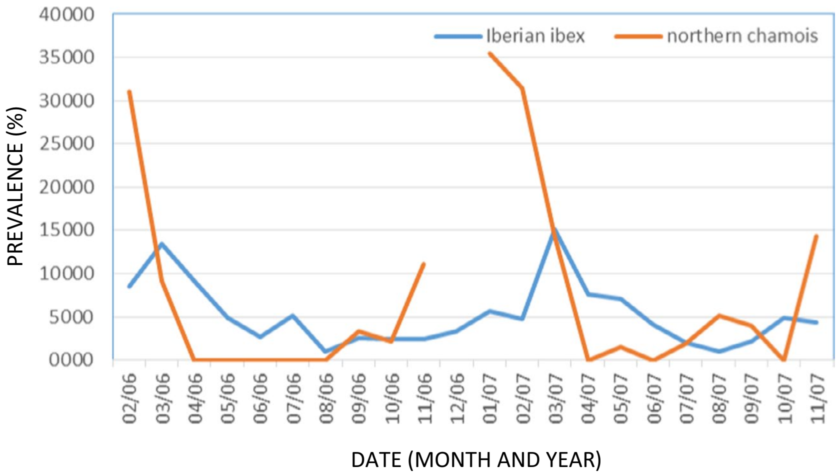

Fig. 1. Comparative dynamics of monthly prevalence of sarcoptic mange (percentage of individual hosts affected) in Iberian ibex *Capra pyrenaica* in the Sierra Nevada Natural Space (southern Spain), and northern chamois *Rupicapra rupicapra* in the Italian Alps during the period 2006–2007. [Colour figure can be viewed at wileyonlinelibrary.com]

(Pérez et al. 2017). The seasonal pattern is also likely to be related to temperature and rainfall during the previous months (Pérez et al. 1997). In northern chamois populations from the Alps, the highest prevalence is reached in January (Rossi et al. 2007), while in the Iberian ibex population in the Sierra Nevada Natural Space, prevalence peaks in March (Granados et al. 2007; Fig. 1). In both populations, a second smaller peak occurs in September.

Parasite–host relationships: pathophysiology of sarcoptic mange

Sarcoptic mange is a catabolic process triggered by the arrival of mites (either through direct contact with infected animals or from inanimate objects—*fomites*) on the host's skin. All the developmental mite stages (larvae, nymphs, and adults) are able to penetrate host skin and excavate galleries in the superficial epidermic layers (Bornstein et al. 2001). Within these galleries, mites move, breed, and deposit eggs, excrement, exuviae, and other products with antigenic properties. In scabietic Iberian ibex, the deriving typical skin lesions include acanthosis, hyperkeratosis, rete ridges, spongiotic oedema, serocellular and eosinophilic crusts, exocytosis foci, apoptotic cells, and sebaceous gland hyperplasia with inflammatory infiltrate consisting mainly of lymphocytes, macrophages, and eosinophils (Oleaga et al. 2012, Espinosa et al. 2017c). Scabietic Iberian ibex also show anaemia and suffer secondary infections by opportunistic bacteria penetrating the damaged skin (Pérez et al. 2015, Espinosa et al. 2017c). Histopathological evaluation of non-dermal tissues reveals structural changes in specific organs, including lymphoid hyperplasia, leucocytosis, congestion, and amyloid deposits (Espinosa et al. 2017c). Sarcoptic mange also induces systemic inflammation. In Iberian and Alpine ibex *Capra ibex*, serum concentration of acute phase proteins, such as alpha-1-acid glycoprotein, serum amyloid A and, to a lesser extent, haptoglobin, and ceruloplasmin, increases with the severity of the disease (Rahman et al. 2010, Ráez-Bravo et al. 2015). In addition, sarcoptidosis increases the oxidative stress and decreases antioxidant status of Iberian ibex, which may contribute to the pathogenesis (Espinosa et al. 2017a). Sarcoptic mange is also a stressful factor for scabietic animals, which may have faecal glucocorticoid metabolite concentrations up to 60 times higher than healthy Iberian ibex (Pérez et al. 2019).

Scabietic Iberian ibex usually lose weight (Pérez et al. 2015), since the disease prevents infected animals from taking advantage of higher food availability during periods of vegetative growth of plants due to its chronic catabolic consumptive nature (Carvalho et al. 2015). A delay in the rhythm of ossification during the skeletal growth period in mangy male Iberian ibex has been reported (Serrano et al. 2007), and mange affects male Iberian ibex more severely than females (López-Olvera et al. 2015). While sarcoptic mange can cause death in affected hosts, there is clear evidence that resistance to the disease may develop in both naturally infected (Alasaad et al. 2013) and experimentally infested Iberian ibex (Castro et al. 2018). Increasing immunoglobulin G concentrations against *Sarcoptes scabiei* seemed to constitute a protective response in southern chamois but not in Iberian ibex (Lastras et al. 2000). In experimentally infested Iberian ibex, a lower clinical severity of sarcoptic mange and subsequent recovery from the disease has been associated with a higher local (skin-level) activation of genes modulating antigen presentation, therefore leading to a lower systemic immune and inflammatory response (Ráez-Bravo 2019).

The effects of sarcoptic mange on the demography of affected populations of Iberian ibex may go beyond the immediate induced mortality (Table 2), since downregulation of the reproductive performance may occur in parallel, through a reduction of testicular mass in males (Sarasa et al. 2011) and negative effects on follicular maturation and ovulatory capacity of females (Espinosa et al. 2017b). Future studies on effects of the disease on the recruitment rate of affected populations are needed, in order to increase our understanding of how the parasite influences demographic trends in its host populations.

Tools for monitoring sarcoptic mange in wild ruminant hosts

Sarcoptes mites are difficult to maintain *in vitro*; this has limited our knowledge of their biology, host–parasite relationships, resistance to drugs, and other topics and has prevented the development of vaccines (Mounsey et al.

Table 2. Mortality rates related to sarcoptic mange outbreaks found in the literature

Host species	Location	Mortality rate and period	References
Aoudad *Ammotragus lervia*	Sierra Espuña (SE Spain)	86% (1991–1995)	González et al. 2004
Iberian ibex *Capra pyrenaica*	SCSLVNP* (S Spain)	97% (1987–1991)	Fandos 1991
Asiatic ibex *Capra sibirica*	Tien-Shan Mount Range (Central Asia)	58% (1974–1978)	Vyripaev 1985
Southern chamois *Rupicapra pyrenaica parva*	Asturias (NW Spain)	81% (1993–1994)	Fernández-Morán et al. 1997
Northern chamois *Rupicapra rupicapra*	Dolomite Alps (Italy)	9.3 – 88% (1995–2004)	Rossi et al. 2007

*SCSLVNP: Sierras de Cazorla, Segura y Las Villas Natural Park.

2012). Moreover, research on free-ranging wildlife models is also difficult, which further restricts access to samples and complicates surveillance. Various methods for monitoring have been developed, however.

Visual diagnosis

Visual diagnosis of sarcoptic mange is the reference field diagnostic method (Pérez et al. 2011). However, it may generate false negatives, particularly in the early stages of the disease, when skin lesions may be small, hidden by fur, and/or located in areas that are particularly difficult to observe from a distance (e.g. axillar or inguinal areas). False positives may also occur, because of other skin diseases (e.g. lice infestation or dermatophilosis) or conditions such as moulting. While the sensitivity of visual diagnosis high (87%), the specificity is low (61%; Valldeperes et al. 2019), and both sensitivity and specificity are affected by factors such as age, sex, and time of year. Due to these limitations, the combination of visual diagnosis with the detection of mites and their eggs in skin scrapings or in skin digested with potassium hydroxide is considered the gold standard method (Valldeperes et al. 2019).

However, the diagnosis of scabies in skin scrapings can be complicated in cases of suboptimal sampling technique, limited skin tissue availability, suboptimal preservation of samples, and/or low mite burdens (Rambozzi et al. 2004, Mounsey et al. 2012). Difficulties in identifying affected individuals correctly under field conditions have prompted studies on alternative diagnostic methods.

Photographic traps

Camera trapping, widely used for wildlife research, conservation, and documentation purposes worldwide, has proved useful for mange surveillance in the wolf *Canis lupus* (Oleaga et al. 2011), red fox *Vulpes vulpes* (Carricondo-Sánchez et al. 2017), coyote *Canis latrans* (Brewster et al. 2017), racoon dog *Nyctereutes procyonoides* (Saito & Sonoda 2017), wild boar *Sus scrofa* (Haas et al. 2015), white-tailed deer *Odocoileus virginianus*, and nilgai *Boselaphus tragocamelus* (Brewster et al. 2017).

Moderate-to-severe cases of mange are readily identifiable in photographs and videos; however, seasonal changes in coat patterns (e.g. moult) may confound diagnostics (Brewster et al. 2017).

Trained dogs

Trained detector or sentinel dogs (Fig. 2) have proved to be effective in detecting dead or moribund scabietic northern chamois in the Alps (Alasaad et al. 2012). Over 15 months of study, these dogs allowed the collection of 292 carcases and the localisation and capture of 63 sick individuals, with apparently no false positive cases.

Thermography

The hair loss induced by sarcoptic mange results in heat loss (Cross et al. 2016). Under these conditions, the energetic cost of infection may become critical, especially in cold climates, which characterise high-elevation mountain habitats. Moreover, dermatitis due to mange produces a local temperature increase in the skin areas affected. Both factors make thermography a promising surveillance method for mange (Fig. 3). Although the first assessments of thermographic cameras suggested that their sensitivity was impaired at distances over of 100 m (Arenas et al. 2002), currently available devices allow photography and surveillance from distances of over 1000 m.

Fig. 2. Trained dogs proved to be very useful in following and finding live, but sick (a), and dead (b) northern chamois affected by sarcoptic mange. Photos courtesy of Roberto Permunian. Fig. 2a was previously published by Alasaad et al. (2012). [Colour figure can be viewed at wileyonlinelibrary.com]

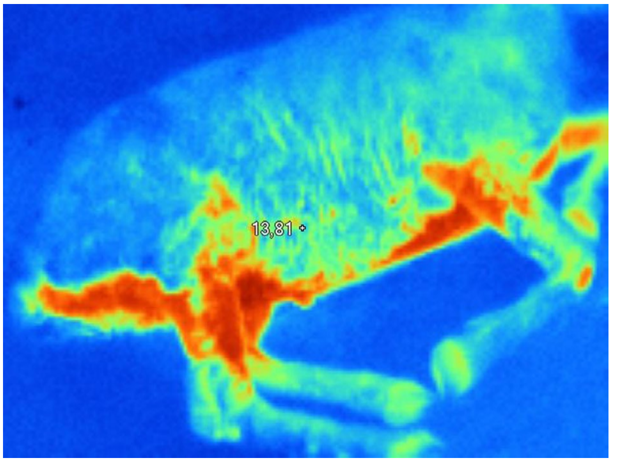

Fig. 3. Thermography of a male Iberian ibex with scabietic lesions in the abdominal region. [Colour figure can be viewed at wileyonlinelibrary.com]

Immunodiagnostics

An increase in immunoglobulin G specific to *Sarcoptes scabiei* has been reported in scabietic animals of several species (Wooten et al. 1986, Bornstein et al. 1995, Arlian et al. 1996, Lastras et al. 2000, Sarasa et al. 2010). This has led to the development, evaluation, and validation of various in-house and commercial enzyme-linked immunosorbent assays to detect specific antibodies to *Sarcoptes scabiei* in wild species, reaching sensitivity and specific values of over 90% (Rambozzi et al. 2004, Haas et al. 2015, Ráez-Bravo et al. 2016).

In contrast to other diagnostic methods, the detection of antibodies allows retrospective epidemiological studies on stored samples, permitting comparison within and among areas (Haas et al. 2018). Immunodiagnostic methods have been a key tool in revealing the presence of *Sarcoptes scabiei* in hosts and zones where it was only suspected or not confirmed by mite identification (Haas et al. 2018). This is particularly relevant for host species that are elusive and difficult to detect visually in the field and in host species where mange may be asymptomatic or cause only mild lesions.

Molecular tools

Methods for collecting single *Sarcoptes scabiei* mites for DNA extraction have been recently revised and improved (Alasaad et al. 2008, Alasaad et al. 2009, Soglia et al. 2009). Recent results from molecular genetics allow a better understanding of the epidemiology of mange (e.g. gene flow between different hosts and between *Sarcoptes* populations; Walton et al. 1999, Zahler et al. 1999, Rasero et al. 2010). These molecular techniques can also be used for diagnostic purposes, especially when working with small skin samples (Angelone-Alasaad et al. 2015). The internal transcribed spacer 2 region in nuclear rDNA is the most frequently used gene for *Sarcoptes scabiei* diagnosis (Peltier et al. 2018). However, Angelone-Alasaad et al. (2015) reported universal, conventional, and real-time polymerase chain reaction diagnosis tools for *Sarcoptes scabiei* based on mitochondrial DNA.

The complete mitochondrial genome of *Sarcoptes scabiei* has been recently elucidated (Ueda et al. 2019), and results support the possibility of transmission of *Sarcoptes* mites between different host species. In the near future, knowledge on the complete genome of the mite species may become a powerful tool for designing a vaccine and effective treatments against mange.

Radiocollars

Monitoring animals with conventional radio-tracking is a challenging task in mountainous habitats, since topography limits fast displacement and, therefore, triangulation and location of marked animals. Such problems disappear with the use of global positioning system or global system for mobile communications radiocollars, which allow researchers to monitor the location and activity of animals virtually in real time. This technology also facilitates the estimation of survival rates (Alasaad et al. 2013) and the definition of home ranges (Viana et al. 2018), as well as allowing the location, capture, sample, and data collection and, eventually, treatment of selected animals, which could become the basis of a strategy for the management of mange in wild populations.

Epidemiological modelling

Modelling the dynamics of a disease affecting a wild species helps researchers to explore relationships between epidemiology and host demography and to identify both empirical and theoretical subjects and topics requiring further attention (Leung & Grenfell 2003). Modelling also allows reductions in the number of experimental animals (Mounsey et al. 2010).

Several model-based studies focused on northern chamois have been used to estimate key parameters regarding mange epidemiology, such as a threshold host density below which the outbreak would become extinct or would not be able to propagate, and to explore the effect of mass or selective killing at various intensities, to control the demographic impact of the disease in naïve host populations (Guberti & Zamboni 2000, Lunelli 2010, Turchetto et al. 2014). In a long-term study of northern chamois mange in the endemically infected Austrian Alps, temporal and spatial analysis of a large number of cases resulted in the detection of clusters with seasonal and interannual occurrence (Fuchs et al. 2000).

Linking climate and host density with scabies epidemiology, estimating first wave and re-infection outcomes at the population level, analysing the optimal timing for treatment and/or the application of complementary or alternative control measures for the disease, including *laissez-faire*, or exploring scabies epidemiology within a multihost species scenario are topics which can be addressed through simulation or modelling.

From prevention to eradication: options for managing the disease in the wild

Managing a disease in a wild mammal population requires the application of initiatives in order to restrict or limit the effects caused by the disease, or other management options, in the population. Several approaches or strategies can be used to accomplish objectives such as eradication, control, and prevention (Wobeser 1994).

Eradication consists of completely clearing an affected population of a disease. In the real world, this goal is hard to reach, due to logistic, cultural, and economic constraints, though there are rare exceptions (Freuling et al. 2012, Rossi et al. 2015). Eradication is not advisable in several cases, since native pathogens exert a pivotal role in naturally controlling host populations, significantly contribute to biodiversity, and have their own evolutionary value (Rózsa 1992, Windsor 1995).

Control of sarcoptic mange involves implementing targeted actions to increase the mortality rate and/or reduce the reproductive rate of *Sarcoptes* mites. In Iberian ibex populations in the Sierra Nevada Natural Space, control in the 1990s consisted of the identification and removal of infested and dead hosts, coupled with the disinfection of carcass locations, in order to reduce the probability of mange transmission (Pérez et al. 1996). Currently, due to the poor success of these measures registered under field conditions, and the high (unattainable) effective killing rates predicted to be required by simulation models, the selective removal of infested animals is recommended to be limited to individuals in the generalised chronic phase of the disease, mainly for ethical and welfare reasons (Espinosa et al. 2020).

Control of sarcoptic mange in domestic livestock is also an important issue for preventing the transmission of the disease to wild mammals. In the Iberian Peninsula, all major outbreaks of sarcoptic mange in free-ranging Caprinae reported during the last decades originated from contact with scabietic poorly managed livestock (Leon-Vizcaino et al. 1999, Lavin et al. 2000).

Of the feasible control actions that can be considered, treatment of infested animals is particularly controversial. One issue is the best antiparasitic drug or class of drugs to use in the field (Fang 2016, Rowe et al. 2019). So far, the macrocyclic lactone, ivermectin, has largely been used for treating captive and free-ranging scabietic southern chamois (Lavin et al. 2000) and Iberian ibex (León-Vizcaíno et al. 2001, Sánchez-Isarria et al. 2008b), although its usefulness in wild free-ranging populations has not been unambiguously demonstrated. Other drugs (pyrethroids, formamidines, organophosphates, phenylpyrazoles, isoxazolines [e.g. fluralaner], and botanical extracts) may help control mange. In general, drugs achieving long active periods would be recommended (Van Wick & Hashem 2019), but treatment of game animals that may be hunted for consumption should be done in accordance with recommended withdrawal times, which may prevent the use of long-acting drugs.

Promising results have been obtained in relation to the biological control with *Bacillus thuringiensis* toxins of various mites, including *Acarus siro*, *Tyrophagus putrescentiae*, *Dermatophagoides farinae* and *Lepidoglyphus destructor* (Erban et al. 2009, Ahmed et al. 2016), *Varroa destructor* (Alquisia-Ramírez et al. 2014, Alquisia-Ramírez et al. 2017), and *Psoroptes cuniculi* (Dusntand-Guzmán et al. 2017). Moreover, the extensive use of *Bacillus thuringiensis* toxins seems to be safe for the environment (Addison et al. 2006). This method of control deserves attention, and experimental research is required to assess its usefulness in sarcoptic mange control.

The extent of control actions is important, and the best option was considered to be treatment of a large proportion of the population (Wobeser 1994, Pérez et al. 1996). However, large-scale treatment of free-ranging wild mammal populations can be unaffordable, from economic and logistic viewpoints. On the other hand, the natural recovery of a number of scabietic animals (Alasaad et al. 2013, Castro et al. 2018) suggests that capture and treatment of selected specimens may be the best option in terms of cost-effectiveness. More studies are needed to address the efficacy and safety of mass treatment programmes in comparison with programmes taking a selective approach. Finally, the season in which control measures are most effective must be investigated (Pérez et al. 1996).

Preventing the occurrence of sarcoptic mange in naïve wild Caprinae populations involves reducing their probability of encountering infected individuals (including asymptomatic ones) of any host species that may harbour *Sarcoptes* mites. To achieve this, physical and immunological barriers may be considered, as well as restriction or modification of management or conservation activities, such as wildlife relocations (Pérez et al. 1996).

Immunisation may become an effective method for managing mange (Van Neste 1986, Arlian et al. 1994), since immunised animals are able to produce antibodies to a higher number of *Sarcoptes scabiei* antigens than infested animals (Morgan & Arlian 1994). A recent study reported a 74% recovery rate in experimentally infested rabbits after vaccination with a chitinase-like protein from *Sarcoptes scabiei* (Shen et al. 2018). Potential benefits and costs should be addressed when designing vaccination programmes to be implemented in free-ranging wild mammal populations.

Fences can be used to prevent or limit the spread of diseases and, in general, can contribute to achieving conservation benefits, but they also have costs. For example, fences have been used to keep captive breeding stock reservoirs of *Capra pyrenaica* free of mange (Espinosa et al. 2017d). However, wildlife mobility and landscape connectivity are pivotal in conservation and management, so fencing should be a last-resort action (Woodroffe et al. 2014).

Other measures to prevent the spread of sarcoptic mange that deserve attention include: (1) management at the wildlife–livestock interface to reduce possible cross-transmission to the detriment of naïve wildlife; (2) the veterinary control of livestock; (3) in translocations, the exhaustive surveillance of source populations coupled with the exhaustive quarantine (including a twofold antiparasitic treatment) of individuals to be translocated; (4) avoiding introduction of alochtonous species (wild ruminants and other mammal game species); and (5) regulating access of domestic animals to natural spaces in which the disease is endemic and where epizootic events have been experienced (Pérez et al. 1996, Sánchez-Isarria et al. 2008a, Arenas-Montes et al. 2009).

As well as Caprinae, other sympatric wild and domestic mammalian species may act as maintenance hosts of mange, confirming a multispecies scenario (León-Vizcaino et al. 1999, Iacopelli et al. 2020). This has implications for the management of scabies and for monitoring programmes as well.

Biosecurity and biosafety

Humans can become infected when handling scabietic animals (e.g. during capture, sampling, transport, or carcass management; Menzano et al. 2004). To minimise the risk of transmission of *Sarcoptes scabiei* between such individuals and other animals, including people, we must apply biosecurity and biosafety protocols. Carcasses with evident or suspected mange should be buried, incinerated, frozen, or placed in approved landfills (Niedringhaus et al. 2019a,b). Capture devices and vehicles used for the transportation of carcasses or infested animals must be cleaned and disinfected. Handling equipment (e.g. blindfolds, stretchers, leg snares for physical restraint, backpacks) must also be frozen overnight, thoroughly washed or treated with disinfectant. It is also advisable to warn members of the public of the transmission risks in areas where risks exist (Niedringhaus et al. 2019a,b). If possible, research staff must use personal protective equipment (Fig. 4), and exterior clothing should be changed and treated in the same way as contaminated handling equipment.

Fig. 4. The use of personal protective equipment reduces the risk of *Sarcoptes scabiei* transmission to research personnel involved in handling infested samples, animals or carcasses. [Colour figure can be viewed at wileyonlinelibrary.com]

CONCLUSIONS

Sarcoptic mange is a natural, biological factor controlling host population numbers and dynamics in Caprinae. Accordingly, goals and strategies for the management of this disease in wild populations must be quite different to those applicable in humans or domestic animals.

Independently of contexts and views, intensive surveillance in mange outbreak areas is pivotal to generating reliable datasets on the main epidemiological variables (such as prevalence, intensity, and mortality rate) and to understanding the disease dynamics and temporal trends. Based on this information, specific management plans should be implemented for each population of susceptible hosts, consisting of preventive and control measures (including a *laissez-faire* option, when applicable). These measures should also take into account the available human and material resources and should be reviewed periodically for efficacy and sustainability, using meaningful indicators.

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