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10 **Development of resistance to sarcoptic mange in ibex**

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ABSTRACT Sarcoptic mange affects mammal host species worldwide and, particularly, wild Caprinae throughout much of Eurasia. In the Iberian Peninsula, several outbreaks of sarcoptic mange in Iberian ibex (*Capra pyrenaica*) have been reported since the 1980s. Using data from a period of long-term monitoring and a seasonal autoregressive integrated moving average (SARIMA)-generalized autoregressive conditional heteroscedasticity (GARCH) model approach, we performed a time-series analysis of the monthly prevalence of sarcoptic mange in the Iberian ibex population in Sierra Nevada Natural Space (S Spain). In January 2003–March 2021, we documented a significant negative trend in sarcoptic mange prevalence, albeit with some interannual peaks. These findings can only be explained if a certain level of resistance to sarcoptic mange exists in hosts that, along with other factors, could provoke this reduced prevalence. Prevalence values varied seasonally, with maximum values in spring and minimum values at the end of summer, which may be due to factors linked to climate, host behavior, and endocrine activity. Our model predicts that the prevalence of sarcoptic mange in the Iberian ibex will continue to decrease over the next 2 years. Despite the inherent challenges involved, the diagnosing and monitoring of wildlife diseases remain a pivotal part of obtaining reliable epidemiological data and designing appropriate management strategies.

KEYWORDS epidemiology, Iberian ibex, management, prevalence, sarcoptic mange, wildlife diseases

Diseases are one of the main justifications for wildlife management (Gilbert and Dodds 1992) given the significant effects they can have on population dynamics – particularly in small and threatened populations – and the risk that they will also spread to domestic animals and humans (zoonoses). In addition, diseases are indicators of poor states of health (Broom 1991). The management of wildlife diseases involves the selection of

objectives and methods and, then, their application, either through inaction, prevention, control or eradication, to minimize their impact on populations (Wobeser 2002).

Sarcoptic mange affects the skin of wild Caprinae such as the Iberian ibex (*Capra pyrenaica*; León-Vizcaino et al. 1999) and other mammal host species throughout Eurasia (Rossi et al. 2019, Pérez et al. 2021), This catabolic disease, caused by the scabies mite (*Sarcoptes scabiei*), exerts a certain degree of control on ibex populations as a result of induced mortality, which can reach >95% (Fandos 1991), and has negative effects on male (Sarasa et al. 2011) and female (Espinosa et al. 2017*a*) reproductive performance. Although sarcoptic mange can lead to the death of hosts, there is evidence that both naturally and experimentally infested Iberian ibex can develop resistance to this disease (Alasaad et al. 2013, Castro et al. 2018). Epidemiological research in humans and wild hosts have revealed persistence (endemisation) of sarcoptidosis in affected populations and a typical dynamic pattern consisting of periodic waves with 10–30-year cycles and falling disease-induced mortality rates (Arlian 1989, Rossi et al. 1995, Guberti and Zamboni 2000).

The epidemiology of sarcoptic mange and the variety of hosts affected seem to differ between different regions of the world (Bornstein et al. 2001). In North America, this disease affects mainly wild canids (Niedringhaus et al. 2019), while another sarcoptiform mite, *Psoroptes ovis*, infests bighorn sheep (*Ovis canadensis*) and also mule deer (*Odocoileus hemionus*), white-tailed deer (*Odocoileus virginianus*), elk (*Cervus canadensis*) and bison (*Bison bison*) (Ramey et al. 2000). Psoroptic mange is also a highly contagious disease and the lesions caused by psoroptic mites resemble those produced by *Sarcoptes scabiei*. Regarding the epidemiology of psoroptic mange, both epizootics leading severe morbidity and mortality in bighorn sheep, and examples

of relatively benign mite infestations have been reported (Welsh and Bunch 1983; Boyce and Weisenberger 2005).

In view of this, management decisions require reliable diagnostic methods based on intensive monitoring to obtain accurate epidemiological data. In the field, visual diagnosis is the most commonly employed diagnostic method for detecting sarcoptic mange (Pérez et al. 2011; Figure 1). Nevertheless, despite its reasonably good sensitivity (> 85%), its specificity is low (~ 60 %) (Valldeperes et al. 2019) and so, the digestion of skin samples and the detection of mites and eggs (direct method) is still considered as the gold-standard method of diagnosis.

Our objective was to characterize the general trend of prevalence of sarcoptic mange in Iberian ibex, analyze seasonality and interannual fluctuations, and test the predictive capacity of the model. Based on previous results (Alasaad et al. 2013), we hypothesized that a host population may develop a certain level of resistance to the disease after a long period of coexistence with the parasite. Thus, using data from a long-term monitoring program for sarcoptic mange in the Iberian ibex population in the Sierra Nevada Natural Space (SNNS, S Spain), we obtained information about the monthly prevalence of mange from January 2003 to March 2021.

STUDY AREA

We conducted our study on the Iberian ibex population in SNNS; 36°00′–37°10′ N, 2°34′–3°40′ W, S Spain, an area of almost 1,700 km^2. This alpine massif holds the highest peak in the Iberian Peninsula (Mulhacén, 3,481 m) and 11 other peaks >3,000 m. The core area lies above 2,000 m and is protected as a national park, with a surrounding buffer zone designated as a natural park. Due to its latitudinal position (36º N) and its proximity to the Mediterranean Sea, this protected space has a Mediterranean

climate with important altitudinal gradients of temperature and rainfall, and all the bioclimatic stages or thermotypes described for this climate are present (Rivas-Martínez 1984). During the dry season (May–Oct) rainfall is very low (~79 mm) but reaches 180 mm during the wet season (Nov–Apr), almost exclusively in the form of snow >2,000 m (Raso Nadal 2011).

The Iberian Ibex is the most iconic animal in this mountain range in numbers (Pérez et al. 2002; >15 000 individuals estimated in 2021) and genetic variability (Márquez et al. 2020); this ibex population is the most important in the south of the Iberian Peninsula. The ibex in the SNNS has been monitored since 1992 (Granados et al. 2020) and is endemically affected by sarcoptic mange. In recent years, the first cases were reported in 1992 (Pérez et al. 1997) and a management plan designed to control the spread of this disease was instigated in 2000. Initially, all detected scabietic animals or their carcasses were removed and cremated. A few years later, after the detection of the first cases of spontaneous recovery from the disease (Arenas et al. 2002), only those animals with >50% of their skin surface affected by mange were selectively euthanized (mainly for humanitarian reasons) and removed. Several researchers focusing on the epidemiology and pathology of mange and other parasites initiated studies, one of whose main findings was that mange-induced lesions of skin and inner organs are reversible (Espinosa et al. 2017*c*). Additionally, a captive ibex population consisting of several dozen ibex in an enclosure of 30 ha was established as a stock reservoir at El Toril in the SNNS (Espinosa et al. 2017*b*). This genetic pool could be used for restoring the ibex population if a demographic collapse occurs. Due to the ease of access to animals for sampling, this reservoir has been used for many research activities and over the past 25 years 129 animals from this enclosure have been donated to diverse research centres and authorities for scientific and reintroduction purposes.

Red deer (*Cervus elaphus*), which have recently colonised the SNNS (Palomares and Amaya 2014), and wild boar (*Sus scrofa*) are both abundant. Foxes, badgers, martens, wild cats and raptors including the golden eagle (*Aquila chrysaetos*), Bonelli's eagle (*A. fasciata*), common kestrel (*Falco tinnunculus*), little owl (*Athene noctua*) and Eurasian eagle-owl (*Bubo bubo*; and >60 other bird species) all breed in the area. The SNNS harbours a diversity of insects and, for instance, twenty butterfly and moth species are endemic to this natural area. Despite the continuous alteration to the natural vegetation due to human activity, around 2,100 plant species are present in the SNNS, some of which (>60; e.g. mountain chamomile [*Artemisia granatensis*], Sierra Nevada daffodil [*Narcissus nevadensis*] and snow star [*Plantago nivalis*]) are endemic (Valle 1985). Historically, iron, copper and lead have been mined in the SNNS, although land-use today is more focussed on agriculture, animal husbandry and tourism. The monthly prevalence of sarcoptic mange was monitored from January 2003 to March 2021.

METHODS

Field Sampling and Prevalence Estimation

We obtained data on the abundance and demographic structure of the ibex population in SNNS using distance sampling methodology (Buckland et al. 2004) during 3 decades (Granados et al. 2020). We estimated the monthly prevalence of mange visually on walked transects or from a vehicle (Pérez et al. 2011, Valldeperes et al. 2019). Throughout the monitoring period, we confirmed all visually inconclusive cases at the laboratory after the digestion of skin pieces in 5% KOH and mite counts (Castro et al. 2016). Then, we calculated the prevalence of mange as the percentage of scabietic animals out of the total number of observed animals (Margolis et al. 1982, Bush et al. 1997).

144 **Statistical Analyses**

145 Seasonal autoregressive integrated moving average (SARIMA) model

146 The ARIMA models can be transformed to accommodate a time-series with a seasonal
147 time-lapse cycle. The seasonal autoregressive integrated moving average expects either
148 data that are not seasonal or data whose seasonal components have been removed (e.g.,
149 seasonally adjusted via methods such as seasonal differencing). An alternative is to use
150 a seasonal autoregressive integrated moving average (SARIMA) model, which we used
151 (Box and Jenkins 1976) to model the prevalence of sarcoptic mange in the Iberian ibex
152 (*Capra pyrenaica*) in the SNNS. A SARIMA time-series model can be written as a
153 combination of both seasonal and non-seasonal parameters (Wang et al. 2005):

154 $$Y_t = (1 - B^d)(1 - B^S)^D e_t$$

155 where Y_t is the percentage time-series data values for prevalence, t the integer index,
156 $(1 - B^d)$ is the d order of the difference of the non-seasonal part of the model,
157 $(1 - B^S)^D$ is the D order of the difference of the seasonal part of the model, e_t is the
158 error term with zero mean and unit standard deviation, B the backshift operator
159 (operating on Y_t has the effect of shifting the data back 1 period, that is: $BY_t = Y_{t-1}$),
160 and S the seasonal length (Modarres and Ouarda 2013, Rahman and Lateh 2015). Each
161 SARIMA competing model is named as SARIMA(p,d,q)(P,D,Q)[m], where p, d, and q
162 are non-negative integers parameters, p is the order (number of time lags) of the
163 autoregressive term, d is the degree of differencing (the number of times the data have
164 had past values subtracted), q is the order of the moving-average term, the uppercase
165 P,D,Q refer to the autoregressive, differencing, and moving average terms for the
166 seasonal part of the model, and m refers to the number of periods in each season. The
167 randomness of the model residuals is used to ensure the adequacy of the fitted model.

Testing the heteroscedasticity: the SARIMA-generalized autoregressive conditional heteroscedasticity (GARCH) model

In some cases, the squared residuals of the SARIMA model show significant serial correlation or time-dependent variance, commonly known as heteroscedasticity, which can invalidate the standard errors and the forecast confidence bands. Generalized autoregressive conditional heteroscedasticity (GARCH) models are very useful for modelling the serial correlation in the second moment of the underlying time series (Engle 1982, Bollerslev 1986, Tsay 2005). The GARCH model is denoted by GARCH (k, l) and the variance equation of the process takes the form

$$e_t = \sigma_t z_t \ , \sigma_t^2 = \omega + \sum_{i=1}^{k} \alpha_i \, e_{t-i}^2 + \sum_{j=1}^{l} \beta_j \, \sigma_{t-j}^2$$

where *k* is the order of the ARCH terms, e_t^2 l is the order of the ARCH terms σ_t^2, e_t is the error term of the SARIMA model, σ_t^2 is the conditional variance of e_t, z_t is a random variable often required to satisfy $z_t \sim \mathcal{N}(0,1)$, and ω, $\alpha_1, \alpha_2, \ldots, \alpha_k$ and $\beta_1, \beta_2, \ldots, \beta_l$ are the parameters of the GARCH (k, l) model.

This heteroscedasticity can be taken into account in the model and the resulting SARIMA-GARCH model was obtained as:

$$\begin{cases} Y_t = (1 - B^d)(1 - B^S)^D e_t \\ e_t = \sigma_t z_t \\ \sigma_t^2 = \omega + \sum_{i=1}^{k} \alpha_i e_{t-i}^2 + \sum_{j=1}^{l} \beta_j \sigma_{t-j}^2 \end{cases}$$

All the parameters of this model were simultaneously estimated using the maximum likelihood method.

To evaluate the performance of the candidate SARIMA or SARIMA-GARCH models regarding the accuracy of the forecasting model, we used the following multi-criteria metrics: mean error (ME), root mean squared error (RMSE), mean absolute

error (MAE), mean percentage error (MPE) and mean absolute scaled error (MASE) (Hyndman and Koehler 2006, Hyndman and Athanasopoulos 2018).

The flowchart of the hybrid SARIMA-GARCH methodology for conducting the forecasting analysis shows all the steps followed (Figure 2). In the first 4 steps, we fitted the SARIMA part of the hybrid model. Once the model satisfied these steps, we tested whether or not there was conditional heteroscedasticity in the series. If conditional heterocedasticity was not found, the process ended here and we made the predictions using only a SARIMA model. If conditional heteroscedasticity was confirmed, we proceeded to build the GARCH part of the hybrid model (steps 5–8). If this was successful, we proceeded to make the predictions with the full SARIMA-GARCH model. More details regarding the model design, selection and testing, and parameter estimation are provided in the Supporting Information.

Comparison of monthly prevalence

We also analyzed the evolution of the year-by-year prevalence of the disease, (i.e., monthly throughout the study). For this, the monthly values were plotted together with their standard deviations, and then the monthly means were compared to check whether or not there were significant differences between them. To perform this comparison, we used the Shapiro-Wilk test and Levene's test of homogeneity of variances to test whether or not the monthly data followed a normal distribution and were homoscedastic. Given that the monthly data did not fit a normal distribution, we used the Kruskal-Wallis test. This nonparametric test was used to perform a comparison between the distributions of the different groups to detect significant differences between months. We conducted multiple comparisons after the Kruskal-Wallis test using Dunn's test. We used R software 3.3.2 (R Development Core Team 2017) to

conduct all the statistical analyses. More details regarding statistical analyses can be found in the Supporting Information.

Forecasting

To check the reliability of the predictions carried out with the SARIMA-GARCH model, we first fitted the model to all the data (Jan 2003–Mar 2021) once we had identified the optimal SARIMA-GARCH model. Then, we reduced the size of the data series by removing 24 entries starting at the end of the series, thereby creating a fresh database starting in January 2003 but ending in March 2019. Finally, we fitted the selected model to this new smaller database and made predictions for the following 24 months to coincide with the end (Mar 2021) of the original time series.

Welfare statement

Our study complied with all regional and national regulations on animal welfare. Our research activities are covered by the Agreement of the Mixed Commission for the Management of the National Parks of Andalusia (2000), Decree 238/2011, and were approved by the Department of Agriculture, Livestock and Rural Development of the Junta de Andalucía (Project 15/12/2018/163).

RESULTS

SARIMA-GARCH model

The adapted series for the prevalence of mange in the Iberian ibex seems to show non-stationary behaviour, characterized by an overall negative trend with inter-annual peaks (Figure 3C) about every 5 years. The SARIMA (1,1,1)(0,0,2)[12] model was selected as the best of several competing models. All the parameters of the SARIMA-GARCH model were significant ($p<0.05$; Tables 1-2).

Seasonal trend

We found significant differences in mange prevalence between several months, particularly when August and September were compared with winter and spring months, as revealed by the Dunn's test (Table 3). Prevalence shows a clear seasonal trend (Figure 4) that peaks in March–April that falls in August–September (Figure 5).

Forecasting

According to the estimated coefficients shown in Tables 1 and 3, the final equation of the hybrid SARIMA-GARCH model can be written as follows:

$$\begin{cases} (1-0.460B)\nabla Y_t = (1-0.974B)(1+0.226B^{12}+0.256B^{24})e_t \\ \sigma_t^2 = 0.154 + 0.210e_{t-1}^2 + 0.575\sigma_{t-1}^2 \end{cases}$$

We used this equation to forecast monthly prevalence values for the following 24 months (Apr 2021–Mar 2023). The predicted trend of the prevalence values continues to fall over the following 2 years (Figure 5). The predicted and observed values do not deviate from each other (Figure 6), which indicates that the model has good predictive ability.

DISCUSSION

As expected, the results obtained in this study highlight the endemic character of the sarcoptic mange affecting the ibex population in the SNNS. Several populations of northern chamois (*Rupicapra rupicapra*), another mountain-dwelling caprine, have also experienced high mortality rates (>80%) after an initial contact with this mite, followed by a rapid regression of the disease and a consequent recovery of the host population. New epizootic waves occur at 10–15-year intervals but generally with ever-less severity as the host population gradually acquires resistance to the disease (Miller 1985, Rossi et al. 1995). In the studied host population, a similar trend or dynamics were observed,

260 although epizootic waves or peaks tended to occur more frequently (~5 yrs; Figure 3C).
261 Iacopelli et al. (2020) report high cluster-rates for the number of sarcoptic mange cases
262 in Iberian ibex from the neighbouring Sierras de Cazorla, Segura y Las Villas Natural
263 Park (S Spain), with peaks every 5 years that differed from the periodicity of mange
264 peaks in the red deer present in this park. These differences are possibly due to the
265 climatic, behavioral or demographic differences (e.g., host density) between the 2 study
266 areas or between the susceptibility to disease in host species (Iacopelli et al. 2020).
267 Differences in the exposure or contact with infested livestock could also explain, at least
268 in part, the observed trends. According to Pence et al. (1983), several potential sources
269 play an important role in epizootic processes: the introduction of a pathogenic strain of
270 *Sarcoptes scabiei* of external origin, the mutation of an established but previously less
271 virulent mite strain, or an increase in the susceptibility of the host population.

272 In small domestic ruminants, immunoglobulin E (IgE) responses seem to be
273 related to the development of acquired resistance to scabies mites (Tarigan and Huntley
274 2005, Rodríguez-Cadenas et al. 2010). In accordance with findings reported from
275 naturally (Alasaad et al. 2013) and experimentally infested ibexes (Castro et al. 2018),
276 the ibex population in the SNNS seems to have acquired resistance to mange through
277 long-term exposure to the disease because no high induced mortality rates have been
278 reported and the number of spontaneously recovering animals (i.e., without treatment) is
279 continuously increasing (J.E. Granados, Sierra Nevada Natural Space, unpublished
280 data). In the absence of other factors (e.g., less severe winters as a consequence of
281 climate warming or interference due to competition with other parasitic species) that
282 could result in reduced prevalence or mite survival, a progressive decrease in
283 prevalence, coupled with low induced mortality rates may indicate greater resistance to

sarcoptidosis. Further genetic and immunological studies of hosts, combined with an analysis of mite virulence and climate data, are still required to test this hypothesis.

The observed seasonal dynamics of the monthly prevalence of sarcoptic mange fits the patterns reported in Iberian ibex and red deer in Sierras de Cazorla, Segura y Las Villas Natural Park (Iacopelli et al. 2020). Like the monthly dynamics of mite counts, these temporal patterns seem to be related to host breeding cycles (Pérez et al. 2017): if mite counts peak in November (i.e. during the rutting season, when mixed groups increase in number and so favor mite transmission), a few months later (Mar–Apr) prevalence values peak (Figure 4). Progesterone and testosterone concentrations in the peripheral blood of ibexes peak in December–January and October–November, respectively (Santiago-Moreno et al. 2003, Toledano-Díaz et al. 2007) and, due to their immunosuppresive effect (Schust et al. 1996, Wyle and Kent 1977), could help explain the dynamics of monthly prevalence.

This disease affects animals for 1–4 months (León-Vizcaino et al. 1999), with an average survival time for non-resistant ibexes of 121 ± 71 days (Alasaad et al. 2013) and a mean estimated recovery time for resistant animals of 245 ± 277 days (Alasaad et al. 2013). Therefore, a certain margin of time exists for capturing and treating scabietic animals (e.g., specimens with rare genotypes, ibex prized by hunters, or those intended to be translocated) and for implementing actions aimed at controlling the disease.

The incidence of wildlife diseases is usually difficult to estimate because it requires intensive monitoring of marked or recognizable individuals. A monitoring program of a group of 35 Iberian ibex was conducted in the mating season in a neighbouring ibex population (Sierras de Cazorla, Segura y Las Villas Natural Park). At the end of the mating season, 81% of individuals within the group had become infested

and the accumulated incidence had increased from 6 to 100% in 4 months (León-Vizcaino et al. 1999).

As observed for prevalence, the monthly mean parasitation intensity (e.g. mite counts) also has a high associated standard deviation, but drops significantly in October (Pérez et al. 2017). Therefore, August–October is probably the most appropriate period for performing actions aimed at controlling sarcoptic mange since during this period the mite population appears to be at its lowest interannual point. Action during these months could avert a peak in numbers of mite larvae, which occurs in November, and so prevent the appearance of a new generation of mites (Pérez et al. 2017).

Mortality induced by sarcoptic mange varies between host Caprinae species and populations (Pérez et al. 2021) but it is probably still the most severe disease affecting wild Caprinae in Europe (Rossi et al. 2019, Turchetto et al. 2020). Despite being intensively studied in recent decades, several aspects of the disease remain unclear. An example is its effect on host behavior and its detection probability during field surveys. Hence, it would be useful to perform specific sampling work (e.g., in caves or other cavities) aimed at detecting the carcasses of dead animals (León-Vizcaino et al. 1999). In addition, long-term monitoring of the main epidemiological variables (e.g., prevalence and induced mortality rate) must be continued if adequate preventive and control measures are to be implemented during the most appropriate time period in terms of the severity of mange epizootics.

Observed and forecasted (predicted) values given by the model were reasonably similar and had similar trends (Figures 6-7). If the model's predictive capacity is good, a decrease of mange prevalence to zero or, in other words, the local extinction of scabies, is to be expected in practice; however, this affirmation contradicts the known persistence of scabies infection in wildlife (Moroni et al. 2021). We must thus take into

account possible future changes in environmental conditions (mean temp, humidity), host abundance, parasite virulence, sympatric livestock, which can act as disease reservoirs, and human-driven wildlife movements, among other factors, all of which could invalidate, at least partially, any such predictions.

Given the similarity between sarcoptic and psoroptic mange, regarding phylogenetic relationships between *Sarcoptes* and *Psoroptes* mites, the type of lesions they caused, and their epidemiology as well, we consider that sharing diagnostic methods, monitoring protocols and experience would benefit the management of both kinds of mange.

MANAGEMENT IMPLICATIONS

Obtaining reliable data on wildlife disease epidemiology is challenging but essential for appropriate management. Differences between host species or between the demographic and genetic structures in a single host species (even in populations that are physically close), and between environmental conditions (e.g., climate) and particular host and parasite assemblages, ensure that the dynamics of sarcoptic mange are unique to a particular place and moment in time. Therefore, each affected population will need an *ad hoc* or a specific management plan. Moreover, long-term monitoring of these epidemiological variables will improve knowledge of the disease and its spatio-temporal dynamics, and help adapt management strategies and measures to each time and place and, even, to test their effectiveness. In terms of wild caprinae, unless the host population is under threat, a mildly invasive control plan for managing sarcoptic mange (e.g., only a few individuals handled, treated and removed) is probably the best option and preferable to strategies based on massive treatment with macrocyclic lactones, which can promote the development of resistance in mites and produce undesirable effects in non-target invertebrate fauna.

CONFLICT OF INTEREST

The authors declare that they have no competing interests.

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554 Figure captions

555 Figure 1. Adult male ibex from Sierra Nevada Natural Space (S Spain) showing clear
556 symptoms of sarcoptic mange (alopecia) in the ventral area. In the background of the
557 image, another male specimen is visible with the same symptoms but, in this case, on
558 the back of the hind legs. Photograph by J. E. Granados, Prado Llano Sky Station (~
559 2,750 m), March 2021.

560 Figure 2. Diagram showing the steps for the selection of the seasonal autoregressive
561 integrated moving average (SARIMA)-generalized autoregressive conditional
562 heteroscedasticity (GARCH) model for the monthly prevalence of sarcoptic mange
563 affecting Iberian ibex from Sierra Nevada Natural Space (S Spain), January 2003 -
564 March 2021: selection, estimation of parameters and forecasting. ACF means
565 autocorrelation function, PACF means partial autocorrelation function, SARIMA means
566 seasonal autoregressive integrated moving average and GARCH means generalized
567 autoregressive conditional heteroskedasticity.

568 Figure 3. Decomposition of the time series model for the monthly prevalence of
569 sarcoptic mange affecting Iberian ibex from the Sierra Nevada Natura Space (S Spain),
570 January 2003 - March 2021. A) observed time series, B) random variation in the series,
571 C) repeating short-term cycle in the series (seasonality), and D) increasing or decreasing
572 value in the series.

573 Figure 4. Box-plot diagrams of all observations relating to the monthly prevalence of
574 sarcoptic mange affecting Iberian ibex in the Sierra Nevada Natural Space (S Spain),
575 January 2003–March 2021.

576 Figure 5. Monthly dynamics of prevalence (%) of sarcoptic mange in the Iberian ibex
577 population in the Sierra Nevada Natural Space (S Spain), 2003–2021. Points refer to the

monthly average value for prevalence; bars represent the standard deviation; the blue line represents the smoothed average values; the grey area is the associated 95% CI.

Figure 6. Forecasting the seasonal autoregressive integrated moving average (SARIMA)-generalized autoregressive conditional heteroscedasticity (GARCH) model for the monthly prevalence of sarcoptic mange affecting Iberian ibex in the Sierra Nevada Natural Space (S Spain) in January 2003–March 2021. The expected prevalence trend values (forecasted, lower and upper band) for the subsequent 24-month period are shown in black, green and yellow, respectively.

Figure 7. Observed (black) and forecasted (green) values of the prevalence of sarcoptic mange in the Iberian ibex used for assessing the reliability of the forecasting carried out with the selected seasonal autoregressive integrated moving average (SARIMA)-generalized autoregressive conditional heteroscedasticity (GARCH) model for the monthly prevalence of sarcoptic mange affecting Iberian ibex in the Sierra Nevada Natural Space (S Spain) in January 2003–March 2021.

Table 1. Estimated coefficients of the selected SARIMA(1,1,1)(0,0,2)[12] model for the monthly prevalence of sarcoptic mange affecting Iberian ibex in the Sierra Nevada Natural Space (S Spain) in January 2003–March 2021.

Coefficient	Estimate	SE	z value	*P*
AR1	0.459	0.070	6.536	< 0.001 ***
MA1	-0.973	0.023	-42.286	< 0.001***
SMA1	0.226	0.070	3.220	0.001 **
SMA2	0.256	0.073	3.503	< 0.001 ***

$^{***}P < 0.001$; $^{**}P < 0.01$; $^{*}P < 0.05$

Table 2. Estimated coefficients of the selected SARIMA(1,1,1)(0,0,2)[12] - GARCH(1,1) model for the monthly prevalence of sarcoptic mange affecting Iberian ibex in the Sierra Nevada Natural Space (S Spain) in January 2003–March 2021.

Coefficient	Estimate	SE	t value	*P*
ω	0.154	0.065	2.344	0.019 *
α_1	0.210	0.095	2.195	0.028 *
β_1	0.575	0.134	4.275	< 0.001 ***

$^{***}P<0.001$; $^{**}P<0.01$; $^{*}P<0.05$

601 Table 3. Significant pairwise comparisons using Dunn's test between monthly
602 prevalence values (p) of sarcoptic mange affecting Iberian ibex in the Sierra Nevada
603 Natural Space (S Spain) in January 2003–March 2021.

Comparison	Z	p-unadjusted	p-adjusted
Apr - Aug	4.156	< 0.001	0.002
Aug - Feb	-3.560	< 0.001	0.006
Aug - Mar	-3.908	< 0.001	0.003
Aug - May	-2.771	< 0.001	0.046
Apr - Sep	3.781	< 0.001	0.003
Feb - Sep	3.181	< 0.001	0.016
Mar - Sep	3.530	< 0.001	0.005

604

605 **Summary for online Table of Contents**:

606 In 2003–2021 an anlysis of the prevalence of sarcoptic mange in an Ibex population
607 showed a significant decreasing and seasonal trend, which suggests that a degree of
608 resistance to this parasitosis has developed in this host. We also predict a decrease in
609 prevalence values over the following 2 years based on our models. Obtaining reliable
610 data on wildlife disease prevalence and other epidemiological variables is pivotal for the
611 appropriate management of such diseases. Moreover, long-term monitoring of these
612 variables can help improve knowledge of how host-parasite relationships influence the
613 dynamics of diseases.

SUPPORTING INFORMATION

Additional supporting information can be found in the online version of this article at the publisher's website.