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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 in southern 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, diagnosing and monitoring of wildlife diseases are integral to 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-Vizcaíno 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 (endemization) 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*. Psoroptic mange can lead to severe morbidity and mortality in bighorn sheep, but examples of relatively benign mite infestations have also 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), 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) in southern Spain, we obtained information about the monthly prevalence of mange from January 2003 to March 2021.

STUDY AREA

We conducted our study from 2003–2021 on the Iberian ibex population in SNNS (36°00′–37°10′N, 2°34′–3°40′W) in southern 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

FIGURE 1 Adult male ibex from Prado Llano Sky Station in Sierra Nevada Natural Space in southern Spain, March 2021, showing clear symptoms of sarcoptic mange (alopecia) in the ventral area. In the background of the image, another male ibex is visible with the same symptoms, on the back of the hind legs. Photograph by J. E. Granados.

protected as a national park, with a surrounding buffer zone designated as a natural park. Owing to its latitudinal position (36°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 south of the Iberian Peninsula. The ibex population 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. Espinosa et al. (2017*c*) reported that mange-induced lesions of skin and inner organs are reversible. 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. Because of the ease of access to animals for sampling, this reservoir has been used for many research activities and since 1996, 129 animals from this enclosure have been donated to diverse research centers and authorities for scientific and reintroduction purposes.

Red deer (*Cervus elaphus*) have recently colonized the SNNS (Palomares and Amaya 2014), and wild boar (*Sus scrofa*) are abundant. Red foxes (*Vulpes vulpes*), European badgers (*Meles meles*), martens (*Martes* spp.), European wild cats (*Felis sylvestris*), 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 harbors a diversity of insects (e.g., 20 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 focused on agriculture, animal husbandry, and tourism.

METHODS

Field sampling and prevalence estimation

We monitored the monthly prevalence of sarcoptic mange from January 2003 to March 2021. We obtained data on the abundance and demographic structure of the ibex population in SNNS using distance sampling methodology (Buckland et al. 2004) from 1993 to 2018 (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% potassium hydroxide and mite counts under stereomicroscope (Castro et al. 2016). Such skin samples consisted on small skin biopsies, in the case of live animals (Castro et al. 2018) or 6.25-cm^2 pieces obtained from the whole skin of dead animals as described by 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).

Statistical analyses

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

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

where Y_t is the percentage time-series data values for prevalence, t the integer index, $(1 - B^d)$ is the d order of the difference of the non-seasonal part of the model, $(1 - B^S)^D$ is the D order of the difference of the seasonal part of the model, e_t is the error term with zero mean and unit standard deviation, B the backshift operator (operating on Y_t has the effect of shifting the data back 1 period, that is: $BY_t = Y_{t-1}$), and S the seasonal length (Modarres and Ouarda 2013, Rahman and Lateh 2015). Each SARIMA competing model is named as SARIMA $(p,d,q)(P,D,Q)[m]$, where p, d, and q are non-negative integers parameters, p is the order (number of time lags) of the autoregressive term, d is the degree of differencing (the number of times the data have had past values subtracted), q is the order of the moving-average term, the uppercase P,D,Q refer to the autoregressive, differencing, and moving average terms for the seasonal part of the model, and m refers to the number of periods in each season. The randomness of the model residuals is used to ensure the adequacy of the fitted 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 modeling 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 term e_t^2, l is the order of the ARCH term 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:

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

We simultaneously estimated all the parameters of this model 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).

In the first 4 steps of the hybrid SARIMA-GARCH methodology, we fitted the SARIMA part of the hybrid model (Figure 2). Once the model satisfied these steps, we tested whether or not there was conditional heteroscedasticity in the series. If we did not find conditional heterocedasticity, the process ended here and we made the predictions using only a SARIMA model. If we confirmed conditional heteroscedasticity, 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 analysis are provided in the Supporting Information.

We also analyzed the evolution of the year-by-year prevalence of the disease (i.e., monthly throughout the study). We plotted the monthly values together with their standard deviations, and then compared the monthly means 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 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. We used this nonparametric test 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 Core Team 2017) to conduct all the statistical analyses.

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 after the end (Mar 2021) of the original time series.

RESULTS

The adapted series for the prevalence of mange in the Iberian ibex showed non-stationary behavior, 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 the best of several competing models. All the parameters of the SARIMA-GARCH model were significant ($P < 0.05$; Tables 1–2).

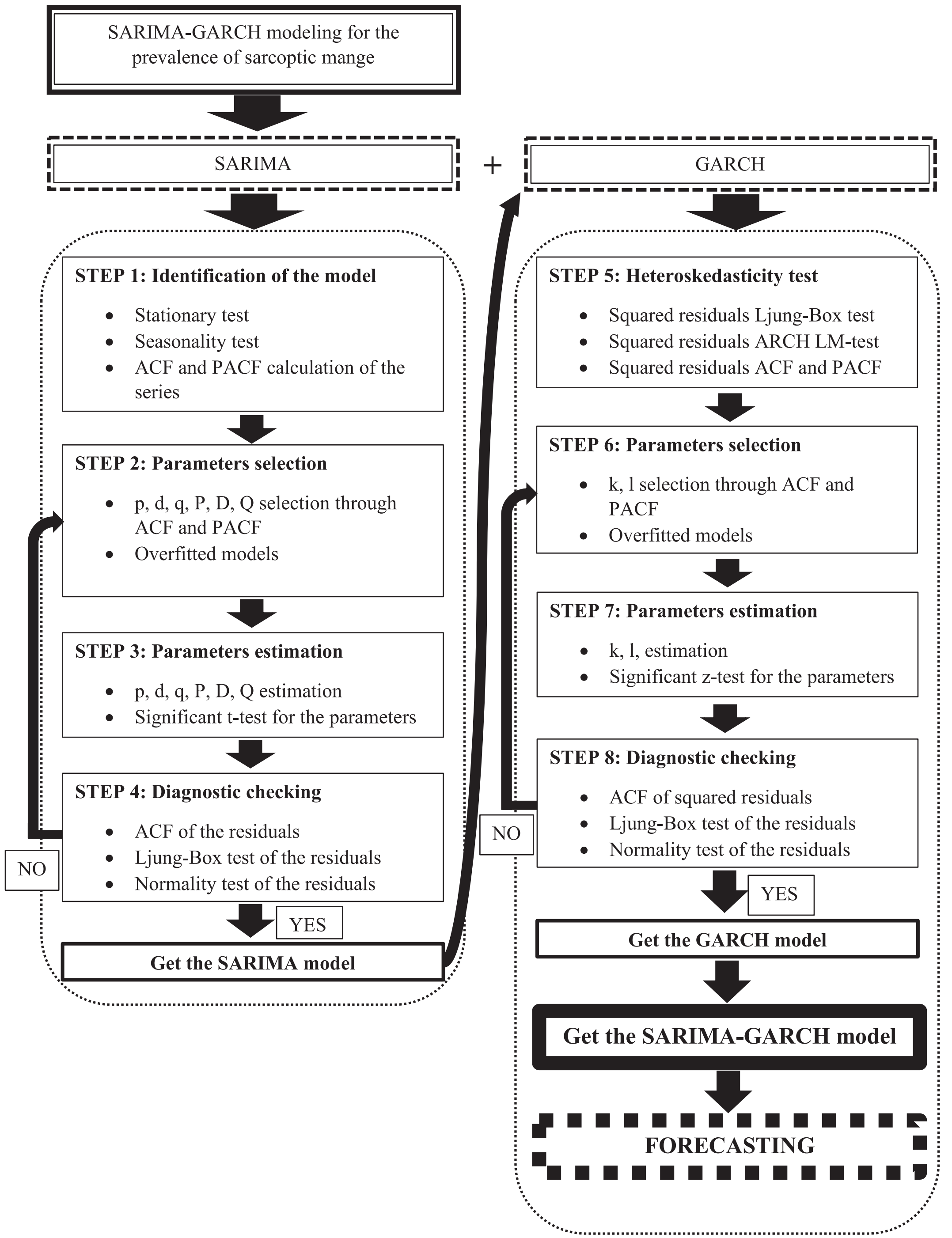

FIGURE 2 The steps for the selection of the seasonal autoregressive integrated moving average (SARIMA)-generalized autoregressive conditional heteroscedasticity (GARCH) model for the monthly prevalence of sarcoptic mange affecting Iberian ibex from Sierra Nevada Natural Space in southern Spain, January 2003–March 2021: selection, estimation of parameters, and forecasting. Model fitting includes use of the autocorrelation function (ACF) and the partial autocorrelation function (PACF).

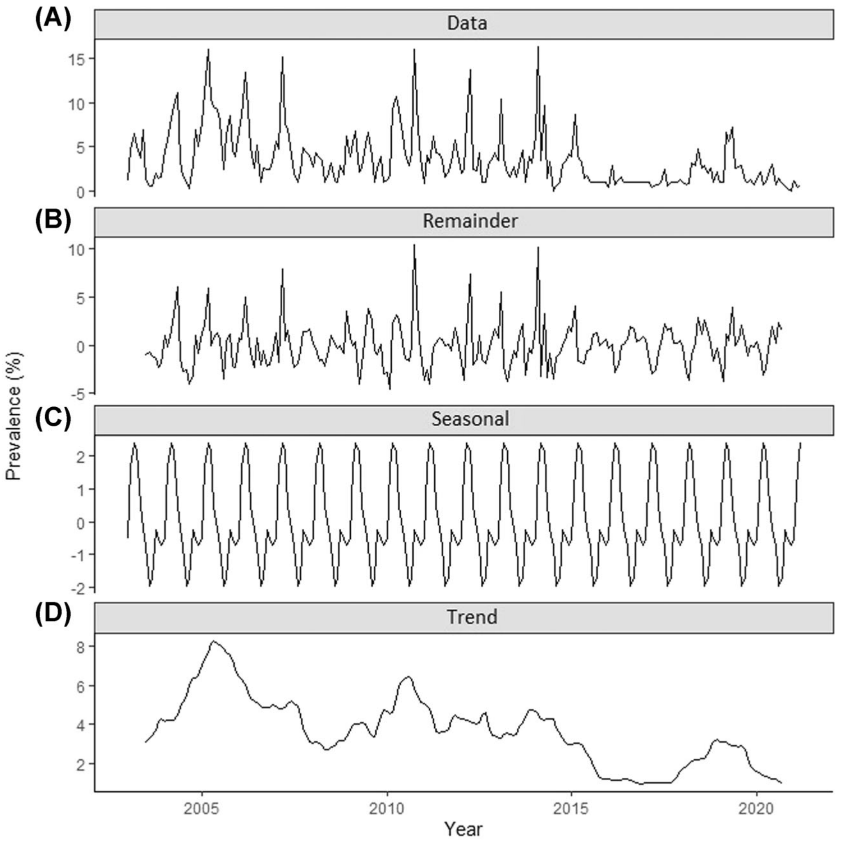

FIGURE 3 Decomposition of the time series model for the monthly prevalence of sarcoptic mange affecting Iberian ibex from the Sierra Nevada Natural Space in southern Spain, January 2003–March 2021. Prevalence is modeled based on the observed time series (A), random variation in the series (B), repeating short-term cycles in the series (seasonality; C), and increasing or decreasing value in the series (D).

TABLE 1 Results of the estimated coefficients of the selected seasonal autoregressive integrated moving average (SARIMA) model for the monthly prevalence of sarcoptic mange affecting Iberian ibex from Sierra Nevada Natural Space, southern Spain during the period January 2003–March 2021.

Coefficient[a]	Estimate	SE	Z	*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

[a]AR1 is the first order of the autoregressive regular part of the SARIMA model, MA1 is the first order of the moving average regular part of the SARIMA model, SMA1 is the first order of the moving average seasonal part of the SARIMA model, and SMA2 is the second order of the moving average seasonal part of the SARIMA model.

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

TABLE 2 Estimated coefficients of 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 in southern Spain, January 2003–March 2021.

Coefficient[a]	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

[a] ω, α_1 and β_1 are the estimated parameters of the GARCH part of model.

TABLE 3 Significant pairwise comparisons using Dunn's test between monthly prevalence values of sarcoptic mange affecting Iberian ibex in the Sierra Nevada Natural Space in southern Spain, January 2003–March 2021. *P*-unadjusted and *P*-adjusted are the *P*-values for the multiple comparisons in Dunn's test. *P*-unadjusted are the raw *P*-values and *P*-adjusted are the *P*-values that represent the smallest family error rate at which a particular null hypothesis will be rejected. If you use a *P*-unadjusted for multiple comparisons, then the family error rate grows with each additional comparison.

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

According to the estimated coefficients, 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 6). The predicted and observed values do not deviate from each other (Figure 7), 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

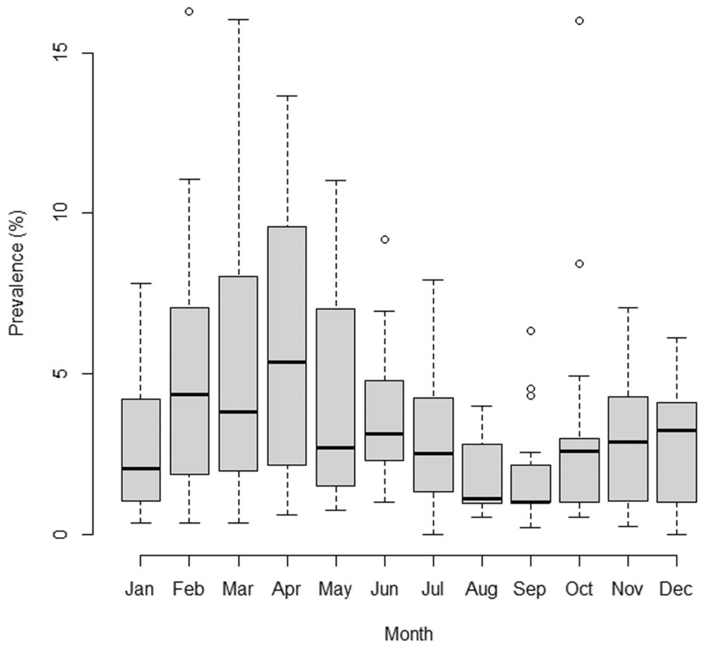

FIGURE 4 Box-plot diagrams of all observations relating to the monthly prevalence of sarcoptic mange affecting Iberian ibex in the Sierra Nevada Natural Space in southern Spain, January 2003–March 2021. Lower and upper box boundaries represent 25th and 75th percentiles, respectively; whiskers are the minimun and maximum values calculated as 1.5 times the difference between 75th and 25th percentiles from either the 25th or 75th percentile, respectively; line inside the box is the median; points above the whiskers indicate outliers.

at 10–15-year intervals but generally with less severity as the host population gradually acquires resistance to the disease (Miller 1985, Rossi et al. 1995). In the studied host population, we observed a similar trend, although epizootic waves or peaks tended to occur more frequently (~5 yr; Figure 3C). Iacopelli et al. (2020) report high cluster rates for the number of sarcoptic mange cases in Iberian ibex from the neighboring Sierras de Cazorla, Segura y Las Villas Natural Park in southern Spain, with peaks every 5 years, similar to those described in our study, that differed from the periodicity of mange peaks in the red deer present in this park. These differences are possibly due to the climatic, behavioral, or demographic differences (e.g., host density) between the 2 study areas or between the susceptibility to disease in host species (Iacopelli et al. 2020). Differences in the exposure or contact with infested livestock could also explain, at least in part, the observed trends. According to Pence et al. (1983), several potential sources play an important role in epizootic processes: the introduction of a pathogenic strain of *Sarcoptes scabiei* of external origin, the mutation of an established but previously less virulent mite strain, or an increase in the susceptibility of the host population.

In small domestic ruminants, immunoglobulin E (IgE) responses seem to be related to the development of acquired resistance to scabies mites (Tarigan and Huntley 2005, Rodríguez-Cadenas et al. 2010). In accordance with findings reported from naturally (Alasaad et al. 2013) and experimentally infested ibex (Castro et al. 2018), the ibex population in the SNNS seems to have acquired resistance to mange through long-term exposure to the disease because high mortality rates have not been reported and the number of spontaneously recovering animals (i.e., without treatment) is continuously increasing (J. E. Granados, Sierra Nevada Natural Space, unpublished data). In the absence of other factors (e.g., less severe winters as a consequence of climate warming or interference due to competition with other parasitic species) that could result in reduced prevalence or mite survival, a progressive decrease in prevalence, coupled with low

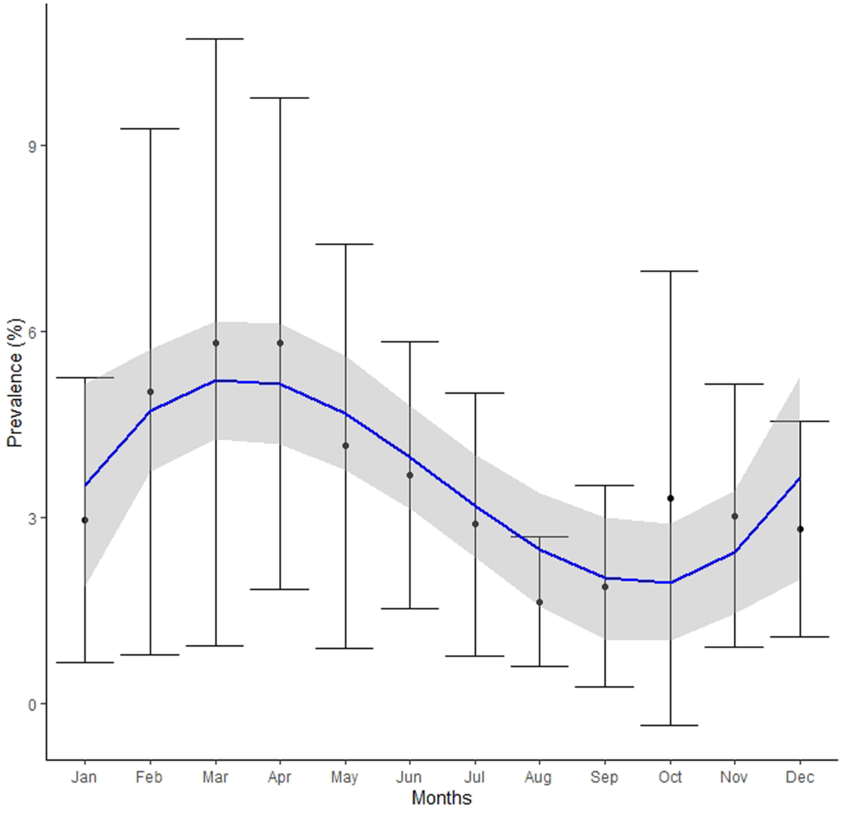

FIGURE 5 Monthly dynamics of prevalence (%) of sarcoptic mange in the Iberian ibex population in the Sierra Nevada Natural Space in southern Spain, 2003–2021. Points refer to the monthly mean value for prevalence, bars represent the standard deviation, the blue line represents the smoothed average values, and the grey area is the associated 95% confidence intervals.

mange-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, which favors 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, because of their immunosuppresive effects (Wyle and Kent 1977, Schust et al. 1996), could help explain the dynamics of monthly prevalence.

This disease affects animals for 1–4 months (León-Vizcaíno 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.

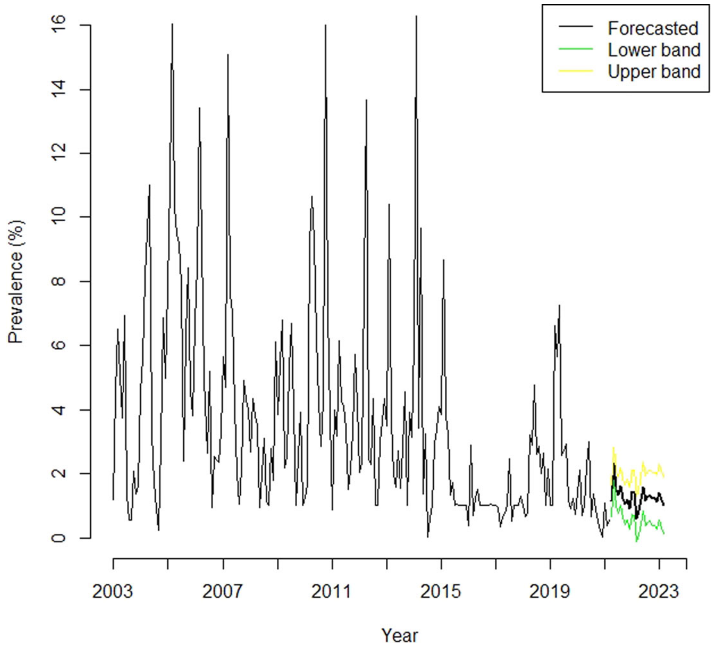

FIGURE 6 Forecasting the seasonal autoregressive integrated moving average (SARIMA)-generalized autoregressive conditional heteroscedasticity (GARCH) model for the monthly prevalence of sarcoptic mange affecting Iberian ibex in the Sierra Nevada Natural Space in southern Spain, January 2003–March 2021.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

Estimating the incidence of wildlife diseases is usually difficult 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 neighboring 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-Vizcaíno 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 because 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). In any case, a mildly invasive control plan for managing sarcoptic mange would be 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 (Rowe et al. 2019).

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 (e.g., 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-Vizcaíno 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

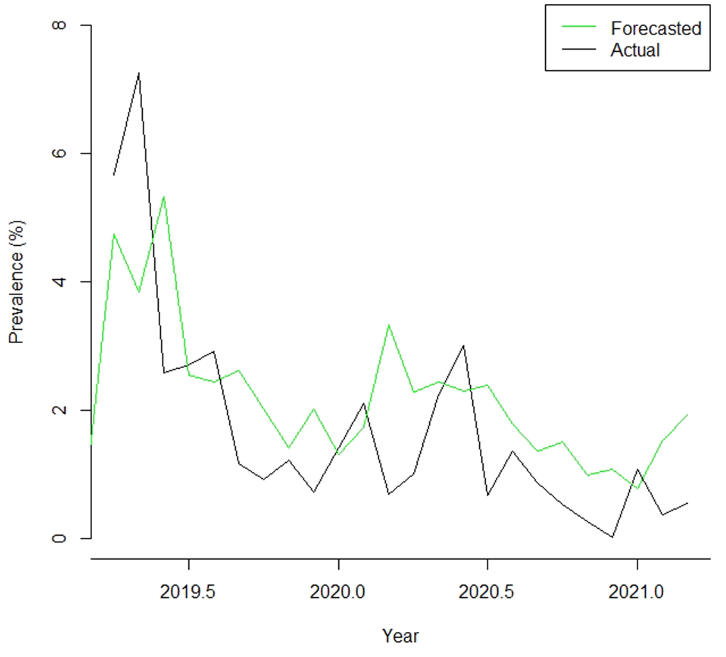

FIGURE 7 Observed (black) and forecasted (green) values of the prevalence of sarcoptic mange in the Iberian ibex used for assessing the reliability of the forecasting carried out with the selected seasonal autoregressive integrated moving average (SARIMA)-generalized autoregressive conditional heteroscedasticity (GARCH) model for the monthly prevalence of sarcoptic mange affecting Iberian ibex in the Sierra Nevada Natural Space in southern Spain, January 2003–March 2021. The time period chosen for comparisons is between April 2019 and March 2021.

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 (e.g., 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, the type of lesions they cause, and their epidemiology, 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 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 likely the best option when prevalence is decreasing.

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CONFLICT OF INTEREST

The authors declare that they have no competing interests.

DATA AVAILABILITY STATEMENT

Data used in this work can be sent upon reasonable request.

ETHICS 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).

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