World Rabbit Science

World Rabbit Sci. 2024, 32: 113-127
https://doi.org/10.4995/wrs.2024.20814
WRSA, UPV, 2003

SELECTION OF ARTIFICIAL WARRENS FOLLOWING THE RESTOCKING OF AN ENDANGERED KEYSTONE PREY

Cláudia Encarnação [*,†], Helena Sabino-Marques [†], Paula Pinheiro, Sara Santos [*,†], Paulo Célio Alves [‡,§,#,¶], António Mira [*,†]

* MED – Mediterranean Institute for Agriculture, Environment and Development and CHANGE – Global Change and Sustainability Institute, Institute for Advanced Studies and Research, Universidade de Évora, Polo da Mitra, Ap. 94, 7006-554 Évora, Portugal.
[†]Unidade de Biologia da Conservação, Departamento de Biologia, Escola de Ciências e Tecnologia, Universidade de Évora, Polo da Mitra, 7002–554 Évora, Portugal.
[‡]CIBIO, Centro de Investigação em Biodiversidade e Recursos Genéticos, InBIO Laboratório Associado, Universidade do Porto, Campus de Vairão, Rua Padre Armando Quinta 7, 4485-661 Vairão, Portugal.
[§]Departamento de Biologia, Faculdade de Ciências, Universidade do Porto, Rua do Campo Alegre S/N, Edifício FC4, 4169-007 Porto, Portugal.
[#]BIOPOLIS Program in Genomics, Biodiversity and Land Planning, CIBIO, Campus de Vairão, 4485-661 Vairão, Portugal.
[¶]Estação Biológica de Mértola (EBM), Praça Luís de Camões, 7750-329 Mértola, Portugal.

Abstract: The European rabbit (*Oryctolagus cuniculus*) is an endangered species native to the Iberian Peninsula, playing a vital ecological role in Mediterranean ecosystems as prey for several threatened predators. Conservation efforts have been implemented to halt its decline, with a particular focus on the Iberian rabbit subspecies (*Oryctolagus cuniculus algirus*). Many conservation programmes involve restocking and habitat management, including the construction of artificial warrens to provide essential refuge sites. In this study, we examined the use of four types of artificial warrens (logs, Mayoral®, pallets and tubes) by a restocked Iberian rabbit population within a fenced park in southern Portugal. We investigated the factors influencing warren use, basing our analysis on faecal pellet counts at the entrances of artificial warrens. We analysed spatial and temporal patterns in warren use using a generalised additive mixed model. Additionally, we determined the efficiency of each type of artificial warren by computing the ratio between the costs of building the warren and the level of warren use by the rabbits. Our results indicate that Mayoral, tube and log warrens are significantly less used compared to pallet warrens (Logs: $\beta=-0.171\pm0.041$; Mayoral: $\beta=-0.149\pm0.058$; Tube: $\beta=-0.240\pm0.071$). Moreover, pallet warrens were found to be more cost-effective compared to other types analysed. Furthermore, rabbits preferred artificial warrens surrounded by a higher proportion of shrubs ($\beta=0.132\pm0.037$). Artificial warren use exhibited seasonal variation, declining gradually during the winter and early spring, and recovering in late spring, coinciding with the expected breeding peak. Based on our findings, we recommend the implementation of pallet warrens in rabbit restocking programmes to provide immediate shelter and breeding sites for the released rabbits. Furthermore, artificial warrens should be strategically located near shrub patches to facilitate safe access to vital resources such as food and water.

Key Words: habitat management, Mediterranean, Iberian rabbit, restocking, warren use.

Correspondence: C. Encarnação, *claudiae@uevora.pt*. Received *December 2023* - Accepted *March 2024*.
https://doi.org/10.4995/wrs.2024.20814

Cite as: Encarnação C., Sabino-Marques H., Pinheiro P., Santos S., Alves P.C., Mira A. 2024. Selection of artificial warrens following the restocking of an endangered keystone prey. *World Rabbit Sci., 32: 113-127. https://doi.org/10.4995/wrs.2024.20814*

INTRODUCTION

The European rabbit (*Oryctolagus cuniculus*) is a native species of the Iberian Peninsula (Delibes-Mateos *et al.*, 2021). In addition, it has been introduced in numerous countries and can now be found in scattered areas across all continents, except Antarctica (Thompson and King, 1994). Although the species is considered a pest that can cause irreversible economic and ecological damage in many introduced regions (Courchamp *et al.*, 1999; Eldridge and Myers, 2001; Scanlan *et al.*, 2006; Ríos-Saldaña *et al.*, 2013; Delibes-Mateus *et al.*, 2018), it plays a significant ecological and economic role in Mediterranean ecosystems where is a native species.

In its natural range, as a keystone species within food webs, the European rabbit serves as a fundamental prey for many Iberian predators, some of which are globally threatened, such as the Iberian lynx (*Lynx pardinus*) and the Spanish imperial eagle (*Aquila adalberti*) (Delibes and Hiraldo, 1981; Delibes-Mateos *et al.*, 2008). Additionally, this lagomorph acts as an ecosystem engineer (Jones *et al.*, 1994; Gálvez *et al.*, 2008), promoting flora diversity and landscape heterogeneity through grazing and seed dispersal. Its faecal pellets contribute to improving soil fertility, and its warrens provide refuge for other animals (Willot *et al.*, 2000; Gálvez-Bravo *et al.*, 2009; Dellafiore *et al.*, 2010). The European rabbit is also one of the most managed small game species and is intensively harvested within its original distribution range in the Iberian Peninsula, where hunting holds high socio-economic importance (Paixão *et al.*, 2009; Villafuerte *et al.*, 1998).

The European rabbit population, particularly the southern Iberian subspecies, *O. c. algirus*, has experienced a decline in its native range since the 1950s, primarily due to human-induced habitat changes and two viral diseases, myxomatosis and rabbit haemorrhagic disease (Villafuerte *et al.*, 1995; Delibes-Mateos *et al.*, 2009). Between 2009 and 2019, the rabbit suffered an estimated population size reduction of ≥50%, mainly due to outbreaks of a new variant of rabbit haemorrhagic disease virus (RHDV2), resulting in negative consequences for several endangered predator species and ecosystems (Delibes-Mateos *et al.*, 2014; Monterroso *et al.*, 2016; Villafuerte and Delibes-Mateos, 2019). As a result, the International Union for Conservation of Nature (IUCN) recently classified *O. cuniculus* as an endangered species (Villafuerte and Delibes-Mateos, 2019).

Wildlife managers and hunters have continuously made efforts to reverse the rabbit population decline through restocking (e.g., Calvete *et al.*, 1997; Moreno *et al.*, 2004; Guil *et al.*, 2014) and/or increasing habitat carrying capacity by enhancing food and/or shelter availability (e.g., Moreno and Villafuerte, 1995; Ferreira and Alves, 2009; Encarnação *et al.*, 2019).

Rabbits are strongly territorial and form social groups, typically living in burrows they dig out of the ground (Macdonald and Norris, 2001). This behaviour earned the rabbit its scientific name, *Oryctolagus*, meaning “digging hare” (Thompson and King, 1994). Warrens play a fundamental role in maintaining viable rabbit populations, serving as breeding sites and providing refuge from predators (Parer and Libke, 1985; Kolb, 1991). They also optimise the physiological requirements during the most unfavourable climatic periods (Villafuerte *et al.*, 1993) and play a role as an element of cohesion of social relationships (Roberts, 1987).

The provision of artificial warrens has long been used. The initial efforts to provide artificial shelter for the species occurred in the last decades of the previous century within extensive rabbit production farms, aiming to enhance animal health and welfare (Roca, 2009; EFSA AHAW Panel, 2020), using materials such as straw, hay or wood shavings (EFSA AHAW Panel, 2020). Recently, artificial warrens have been frequently employed in rabbit conservation programmes and hunting management, especially in adverse habitat conditions, such as open habitats with no shrub protection or unfavourable soils for digging (Rouco *et al.*, 2011).

Several works have shown the great importance of artificial warrens for rabbit populations, sometimes combined with other habitat management practices (e.g., Cabezas and Moreno 2007; Catalán *et al.*, 2008; Godinho *et al.*, 2013).

Some authors have also studied the factors determining the use of artificial warrens by rabbit populations (e.g., Fernández-Olalla *et al.*, 2010; D’Amico *et al.*, 2014). However, little is known about the selection and use of different types of artificial warrens, particularly in controlled experiments, such as restocking in fenced areas, although artificial warrens may provide immediate refuge to released rabbits during the acclimation period, minimising predation.

Moreover, the materials used and costs involved in artificial warren construction may vary, so it is important to evaluate their efficiency and point to more appropriate conservation strategies that optimise existing funds (Fernández-Olalla *et al.*, 2010; Ferreira *et al.*, 2013).

In this study, we analyse the use of four types of artificial warrens (logs, Mayoral – registered trademark, pallets, and tubes) by a recently restocked Iberian rabbit population in southern Portugal. To estimate warren use, we conducted pellet counts at the entrances of artificial warrens. To the best of our knowledge, this is the first time such an analysis has been performed, simultaneously comparing the use of four different types of artificial warrens by a restocked population inside a fenced restocking park. The behaviour of the released population may differ from that of natural populations, influenced by the rabbit's adaptation period to the new habitat and the carrying capacity of the restocking park. Additionally, we quantify the costs associated with warren installation and discuss the best options in terms of cost-benefit.

Specifically, we aimed to answer the following four questions and associated hypotheses:

1. Which warren types are the most used by restocked rabbits? We hypothesised that rabbits would prefer artificial warrens built with natural features, such as log warrens or with structures resembling their natural warrens, such as tube warrens (Fernández-Olalla *et al.*, 2010; San Miguel, 2014).

2. What habitat characteristics around artificial warrens promote warren use by the restocked population inside the restocking park? We hypothesised that the presence of crops, shrubs, drinking troughs, and/or ecotone around the warren would enhance its use (Rogers and Myers, 1979; Carvalho and Gomes, 2004; Encarnação *et al.*, 2019).

3. Does rabbit artificial warren use vary through the annual life cycle? We anticipated warren use would be higher after the peak of the breeding period, which generally occurs in late spring (Gonçalves *et al.*, 2002).

4. What is the efficiency of different artificial warrens, considering the financial investment and the level of warren use? We expect that warrens built with natural materials will be cheaper and more utilised by rabbits.

Overall, our results will provide practical guidelines to improve the success of rabbit restocking programmes in the Mediterranean region, particularly those requiring artificial warrens.

MATERIALS AND METHODS

Study area

We conducted this study in the Algarve region, southern Portugal (37º 16' 33'' N, 8º 29' 27'' W; Figure 1), specifically within a hunting estate located in the Monchique Natura 2000 Special Conservation Area (SAC) (PTCON0037) (Regulatory Decree n. º 1/2020 of 16th March). The climate of the area is characterised by mild and moist winters and hot and dry summers. The mean annual total rainfall is 937.9 mm, and the mean annual daily temperature is 14.3 ºC, as recorded in Monchique from 1980 to 2021 (SNIRH, 2022).

The landscape surrounding the restocking park is dominated by dense Mediterranean shrubs, with scattered eucalyptus (*Eucalyptus globulus*) plantations and agricultural fields, primarily consisting of cereal crops and orchards. The terrain is undulating, with elevations reaching approximately 165 m above sea level (CNA, 1982). The soils in the area are poor and mainly dominated by incipient soils, particularly schist or greywacke lithosols of xeric-regime climates (IHERA, 1999).

Restocking park

A restocking park, covering an area of approximately 1.7 ha, was designed to acclimate and breed reintroduced rabbits that would subsequently restock the surrounding area (Figure 1). The park was enclosed by a 1.8 m high fence, with an additional 0.5 m buried underground in an "L-shape" configuration, intended to prevent terrestrial carnivores from entering and enhance rabbit survival (Rouco *et al.*, 2008). However, we did not take any measures to exclude aerial predators, as the restocking was conducted as part of the "Compensatory measures and specific

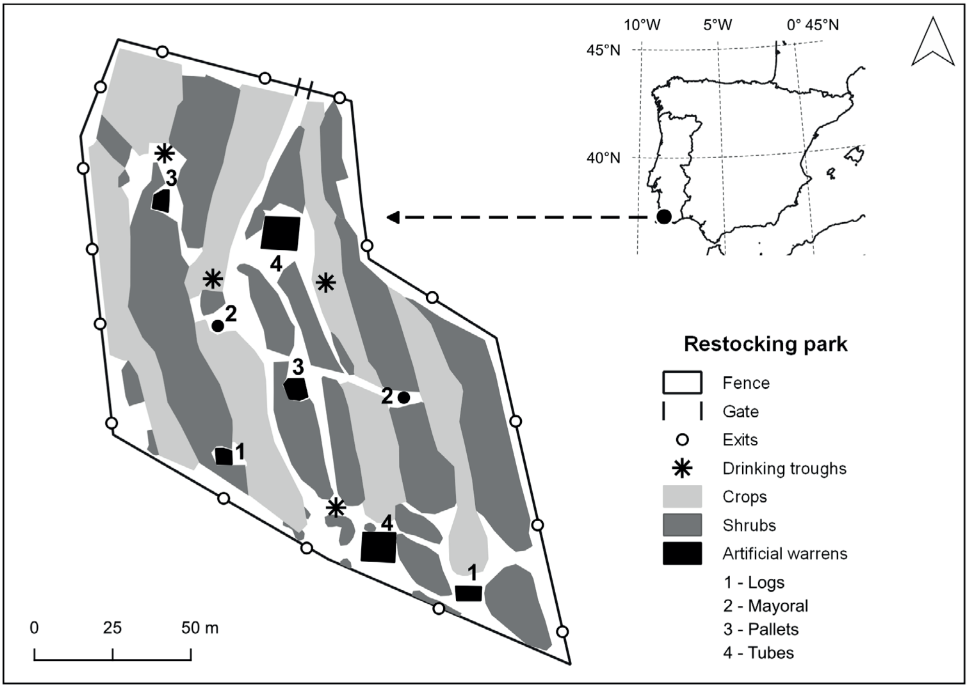

Figure 1: Schematic representation of the restocking park in southern Portugal.

monitoring of the Odelouca's Bonelli eagle couple, arising from the environmental impact assessment process of the Sines-Portimão high-voltage power line" project (REN *et al*., 2009). To facilitate rabbit dispersion, 16 passages made of plastic tubes, each with a diameter of 12.5 cm, were installed under the fence.

Inside the fenced area, we ensured the availability of essential requirements for rabbit survival, including food, water and shelter (Figure 1). Initially, the restocking park surface was covered with dense scrubland. To create a suitable habitat for the rabbits, we cleared elongated parcels of shrubs and sowed them with herbaceous crops, a mixture of Leguminosae and Graminae, creating alternating patches of food (crops) and shelter (shrubs). Additionally, we installed four drinking troughs, assuring water availability.

To further enhance the availability of shelter and breeding sites, we built eight artificial warrens, spaced as uniformly as possible throughout the area. The artificial warrens included two of each type (See Supplementary Information A for photos):

- Log warren – A warren with a diameter of approximately 4-5 m, constructed using natural materials such as logs, branches and rocks and covered with surrounding soil. The materials were piled to create galleries to facilitate rabbit movement.
- Mayoral® warren – A prefabricated plastic warren specifically designed for rabbits, consisting of several independent modules that together form a circular structure measuring 3 m in diameter. The bottom of the structure is open to allow rabbits to construct their galleries. It contains several internal galleries and has six entrances (González and San Miguel, 2004). Each warren was installed on the ground surface, with its perimeter protected by rocks and its top covered with cork boards and bushes to mimic the surrounding area and help regulate internal temperature.

- Pallet warren – A warren constructed by overlapping several wooden pallets on the ground, with nine pallets on the lower level and six on the upper level. We placed rocks inside the pallets to compartmentalise and reinforce the structure, which was then covered with branches and soil.
- Tube warren – A warren developed by the CBD-Habitat Foundation to mimic the labyrinth structure and dimensions of natural warrens, following Kolb's (1985) description. This type of warren consisted of several bottomless PVC chambers, for passage or breeding, interconnected by plastic tubes (1 m long and 12.5 cm in diameter), which were perforated to allow drainage. We placed the structure underground, at approximately 0.60 m in depth, following the layout described by González and San Miguel (2004), and subsequently covered it with soil, with the four entrances at ground level.

The shrubs were initially cleared, and the ground was levelled. Since the artificial warrens were located within the restocking park, they shared similar characteristics in terms of elevation, slope and soil type.

As of 2023, the updated prices for installing each type of artificial warren in this study area are approximately as follows: 260 € for a log warren, 320 € for a pallet warren, 630 € for a tube warren, and 750 € for a Mayoral warren. These estimated prices include costs for backhoe work, materials, transport and technician's labour. However, the final cost of establishing a warren in a specific area could vary significantly based on factors such as location, materials used and fuel costs.

Rabbit release protocol

On 28th October 2007, at sunrise, a total of 75 adult Iberian rabbits (19 males and 56 females) were released into the restocking park. To ensure genetic similarity to native populations (Branco *et al.*, 2000; Carneiro *et al.*, 2010), we carefully selected a certified breeder from the natural distribution area of *O. c. algirus*.

Before release, each rabbit underwent a series of preparatory measures. We weighed and sexed each individual and administered both internal and external deworming treatments. Additionally, all rabbits were vaccinated against rabbit haemorrhagic disease and myxomatosis, with the entire process being supervised by a team of veterinarians. All applicable international, national and/or institutional guidelines for the care and use of animals were followed.

Following these preparations, the rabbits were released in groups of 5-8 individuals per release location, with the sex ratio (2-3 females for each male) being maintained, approximately, across all ten release sites inside the restocking park. Specifically, the release locations comprised each of the eight artificial warrens and two randomly selected spots within the shrub patches. To allow for rabbit dispersion outside the restocking park, the fence passages were opened on 8th January 2008, after an acclimation period of 72 d.

Artificial warren use

Over six months, we conducted weekly estimations of rabbit use for each artificial warren by counting the number of faecal pellets within a 0.5 m^2 radius area outside the entrance of each warren. The sampling started in early January 2008, immediately after the acclimation period following the restocking, to minimise disturbance to the rabbits. Data collection was concluded at the end of June. The number of pellets was used as a proxy for the number of rabbits utilising each warren (Palomares, 2001; Guerrero-Casado *et al.*, 2020). In every visit, we ensured the removal of pellets, thus guaranteeing that we exclusively counted fresh pellets less than one week old (Iborra and Lumaret, 1997). Subsequently, we estimated warren use for each artificial warren by dividing the number of pellets per square metre by the number of days elapsed since the last cleaning (Guerrero-Casado *et al.*, 2020). This methodology allowed for the comparison of abundance values between warrens with a different number of entrances.

Predictors of warren use

We modelled warren use as a function of the predictors listed in Table 1. We assessed the proportion of food patches, shelter patches and ecotone length within a 10 m radius buffer around each warren. The ecotone corresponded to the edges between food and shelter patches. To account for the potential impact of rainfall on pellet persistence

Table 1: Predictors used in the analysis of rabbit artificial warren use.

Predictors description (Units)	Mean (±SE)	Range
Sample week	-	1-24
Type of artificial warren: Logs, Mayoral, Pallets[1], Tubes	-	-
Ecotone length (m)	73.680±1.036	42.284–89.703
Proportion of food patches	0.175±0.008	0.027–0.320
Proportion of shelter patches	0.319±0.008	0.193–0.536
Distance to the nearest food patch (m)	4.187±0.143	0.976–8.073
Distance to the nearest shelter patch (m)	0.996±0.057	0.300–2.900
Distance to the nearest drinking trough (m)	25.035±1.037	9.711–44.997
Mean weekly rainfall (mm)	2.845±0.272	0.000–13.613
Accumulated weekly rainfall (mm)	24.575±2.464	0.000–111.200

SE: standard error; [1]Pallets is the reference category for the type of artificial warren predictor.

(Iborra and Lumaret, 1997; Fernández-de-Simon *et al.*, 2011), we included two predictors: mean weekly rainfall and accumulated weekly rainfall (SNIRH, 2022). We extracted distance and proportion predictors, along with ecotone length, from original vegetation cover maps created by the team using QGIS (QGIS Development Team, 2021).

Data analysis

We analysed spatial and temporal patterns in warren use using a generalised additive mixed model (GAMM), with a Gaussian error distribution and an identity link function (Hastie and Tibshirani, 1990; Wood, 2017). We decided to use GAMM because the exploratory analysis of the data indicated the presence of a non-linear pattern between the response variable and several continuous predictors. To account for multiple surveys of the same warrens, we used the warren identity code of every artificial warren as a random variable.

We subjected the response variable to a logarithmic transformation (log(x+1)) to approach normality, stabilise the variance and reduce the influence of outliers (Zuur *et al.*, 2010). Three predictors, namely the distance to the nearest shelter patch (log x), mean weekly rainfall (log(x+1)) and accumulated weekly rainfall (log(x+1)), were also logarithmically transformed to meet these assumptions. All continuous predictors were standardised to facilitate direct comparisons of regression coefficients (Schielzeth, 2010).

To identify potential collinearity problems, we calculated Spearman correlations (rs) among all predictors (Zuur *et al.*, 2010). For each pair of highly correlated predictors ($|rs|>0.7$) (Dormann *et al.*, 2013), only the predictor with the stronger correlation with the response variable was retained for further analysis (Tabachnick and Fidell, 1996). As a result, we removed the ecotone length, the proportion of food patches and the mean weekly rainfall predictors from the analysis.

To evaluate the linearity of non-collinear predictors, we individually tested each predictor against the response variable as a smoothing term. Only predictors showing non-linearity (edf>2; edf - effective degrees of freedom of non-linear (smooth) terms) and statistical significance ($P<0.05$) were included in the subsequent analysis. We found that the sample week and accumulated weekly rainfall were significant non-linear terms, with the optimal amount of smoothness estimated via generalised cross-validation (Zuur *et al.*, 2009).

Then, for each predictor, we compared the respective univariate model Akaike's Information Criterion corrected for small sample sizes (AICc) with the null model AICc. Only predictors that produced univariate models with an AICc at least four units lower than the null model were considered to have strong support and were retained as candidates for the multivariate model. The selected predictors (sample week, type of artificial warren, proportion of shelter patches and distance to the nearest food patch) were then used to build multivariate mixed models with all possible combinations, including the null (intercept-only) and full models (with all candidate predictors). A multi-model inference procedure was applied to rank the models based on their Akaike weights (wi) (Burnham and Anderson, 2002).

To account for heterogeneity in model residuals, we allowed variances to differ per warren by adding a variance structure (varIdent) to the model (Zuur *et al.*, 2009). This resulted in lower AICc values and improved the model fit.

As no single model was convincingly the most plausible (wi≥0.95), we performed a model averaging approach, basing inferences of the averaged parameters, unconditional standard errors (SE) and 95% confidence interval (CI) on the set of models showing an AICc within four units (ΔAICc<4) of the best model (Burnham and Anderson, 2002). We determined the relative importance of each predictor (w+) by the sum of Akaike weights (wi) of all models where the predictor was included (Burnham and Anderson, 2002). Predictors with 95% CIs including zero were considered to have low support (Burnham and Anderson, 2002). The best model incorporated all predictors of the group of models with ΔAICc<4.

We checked for potential spatial autocorrelation in the best model residuals by computing Moran's I and inspected temporal autocorrelation by plotting the autocorrelation function (ACF) (Zuur *et al.*, 2009). We validated the best model using diagnostic plots (Zuur *et al.*, 2009) and assessed the best model performance through the adjusted R-squared (Wood, 2017).

Additionally, we performed a simple efficiency assessment of each warren type by computing the ratio between the costs of building the warren and the level of warren use by the rabbits for each type. The efficiency of artificial warrens was hierarchised based on these ratios, with lower values indicating higher artificial warren efficiency, implying fewer costs invested to achieve greater warren use.

All the statistical analyses were conducted in R version 4.1.3 (R Core Team, 2022) using the packages: "car" (Fox and Weisberg, 2019) to assess collinearity, "mgcv" (Wood, 2017) for GAMM, "MuMIn" (Barton, 2020) for model averaging and "ape" (Paradis and Schliep, 2019) to check spatial autocorrelation. Plots were generated using "ggplot2" (Wickham, 2016).

RESULTS

Warren use, as measured by mean pellet abundance, varied significantly among the different types of artificial warrens. Warren use was higher in pallet warrens (0.922 pellets/d/m^2), followed by log warrens (0.411 pellets/d/m^2) and Mayoral warrens (0.403 pellets/d/m^2). Tube warrens were the least used (0.313 pellets/day/m^2).

Pallet warrens had the lowest ratio cost/warren use value (347.1 €/pellets/d/m^2) and tube warrens had the highest (2012.8 €/pellets/d/m^2). Log warrens and Mayoral warrens fell in between, with efficiency ratios of 632.6 €/pellets/d/m^2 and 1861.0 €/pellets/d/m^2, respectively.

The best-fitted model explaining artificial warren use had an adjusted R-squared of 0.545. Model residuals did not exhibit any temporal or spatial autocorrelation (Moran's I= –0.0002, P<0.237).

The level of artificial warren use was significantly associated with the type of artificial warren, the proportion of shrub cover, the distance to food patches and the sample week. The sample week and the proportion of shelter patches had the highest relative importance (w+), with a relative importance value of 1.00 for both, indicating that they were included in all the candidate models with ΔAICc<4. The type of artificial warren also had a considerable influence on warren use, with a relative importance value of 0.49. On the other hand, the distance to the nearest food patch had the lowest relative importance (w+=0.33) (Table SB1, Supplementary Information B).

Sample week exhibited a non-linear relationship with warren use (edf=6.840; F=13.350, P=0.000) (Figure 2a). Warren use gradually decreased from January onwards, reaching its lowest values in May, specifically between the 16th and 20th sampling weeks. The decrease in warren use was particularly sharp in the first four sampling weeks, followed by a more stable period until the end of March. In June, the last sampling month, there was an inversion of the trend and an increase in warren use was observed.

The proportion of shrubs around the warren positively influenced warren use (β =0.132±0.037) (Figure 2b). This means that the higher the proportion of shrubs around warrens, the greater their use by rabbits.

The type of artificial warren also had a significant effect on warren use. Warren use was significantly lower in Mayoral, tube and log warrens than in pallet warrens (Logs: β= –0.171±0.041; Mayoral: β= –0.149±0.058; Tube: β= –0.240±0.071) (Figure 2c).

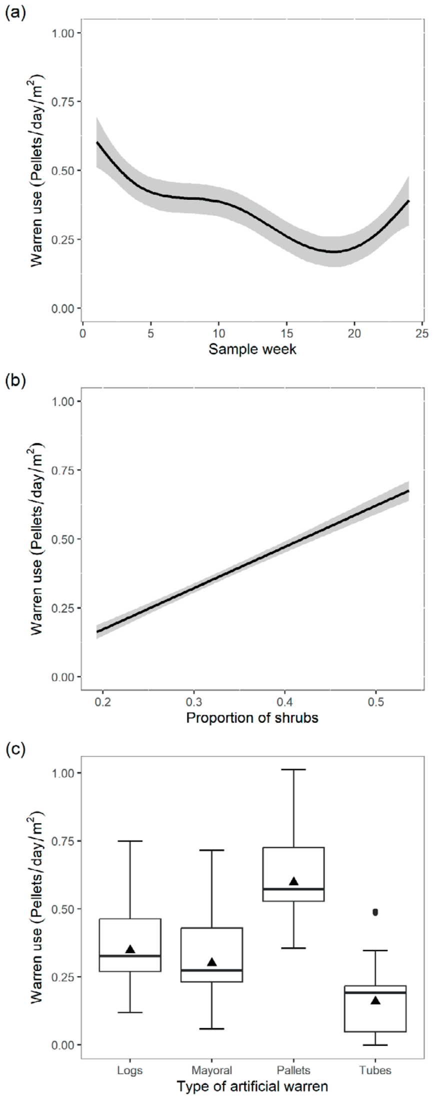

Figure 2: Relationship between warren use, expressed as logarithmic mean pellet abundance [log(x+1) (pellets/d/m^2)], and (a) sample week, (b) proportion of shrubs and (c) type of artificial warren. Predicted values of warren use were calculated using the averaged GAMM model. In graphs (a) and (b) the grey zone represents the 95% confidence interval of the predicted values. In each boxplot of graph (c), the triangle is the mean and the darker horizontal line is the median. The length of the box represents the interquartile range (i.e., the difference between the 75th and 25th percentiles). The dots outside the whiskers are outliers.

The distance to the nearest food patch did not show a significant effect on warren use, as the unconditional CI for its coefficient included zero (Table SB1, Supplementary Information B).

All candidate models and the average model describing the estimated effects of predictors on warren use are presented in Table SB2, Supplementary Information A.

DISCUSSION

In this study, we compared the use of four distinct types of artificial warrens, commonly employed in Iberian rabbit recovery programmes (García, 2003; Fernández-Olalla *et al.*, 2010; San Miguel, 2014). To the best of our knowledge, limited research has been undertaken to compare the use of different artificial warren types (e.g., Fernández-Olalla *et al.*, 2010) and identify the factors influencing the use of artificial (e.g., D'Amico *et al.*, 2014) and natural warrens (e.g., Barrio *et al.*, 2009). Our study provides a novel contribution by examining these aspects in a confined and controlled population, immediately after restocking, evaluating the temporal variation in use and discussing the cost-benefit implications associated with each artificial warren type.

However, it is essential to acknowledge that our findings should be approached with caution, considering the limitations inherent in this study. The research was confined to a singular restocking park, encompassing a relatively small area, and our sampling was limited to two artificial warrens per warren type. Conducting similar studies with a higher number of replicates, including more artificial warrens of each type, and across multiple restocking plots simultaneously, would be ideal to corroborate and reinforce these findings. However, we acknowledge the challenges related to budget constraints, particularly when it comes to fence installation and the construction of certain types of artificial warrens, such as tube and Mayoral warrens. Despite the constraints, we were able to gather statistically meaningful results, which are a promising step to support better choices in rabbit restocking programmes.

Our findings reveal significant variations in the use of the four types of artificial warrens, which is consistent with our initial hypothesis, despite the similar number of animals released in each warren. Iberian rabbits demonstrated a preference for pallet warrens over the other options, contrary to our prediction that they would favour warrens constructed solely with natural materials (logs) or those closely resembling natural warrens (tubes). It is interesting to note that a previous study by

Fernández-Olalla and colleagues (2010), which examined three types of artificial warrens in the context of rabbit natural populations occupancy, found that subterranean warrens made of tubes exhibited higher rates of rabbit occupancy. In our case, we speculate that the restocked rabbits showed a higher preference for pallet warrens in our study area due to the robust structure and resistance to collapse offered by the arrangement of pallets (García, 2003). Moreover, the design of pallet warrens seemed to facilitate tunnel excavation, which might have contributed to their increased use. Another noteworthy advantage of pallet warrens is that they cost less than most artificial warren types usually installed for habitat improvement in rabbit recovery programmes. Thus, in this study, they presented the best efficiency ratio.

The use of all other warren types by rabbits was comparatively lower. For instance, tube warrens presented challenges as their structure needed to be buried, requiring the clearance of a larger area of shrubs. This increased the warrens' exposure and potentially reduced the level of protection for rabbits when they came out of the warrens. Additionally, the risk of flooding might have been higher for tube warrens, as they were installed below ground level. However, we were unable to confirm this hypothesis, as the interior of tube warrens was inaccessible for observation. Contrary to our initial prediction, log warrens did not emerge as one of the most utilised artificial warren types, despite the use of natural materials. The logs used to construct the warrens may have been too large, resulting in limited space between logs filled with dirt, hindering rabbits from effectively building their tunnels (Figure SA1, Supplementary Information A). As for Mayoral warrens, rabbits likely use them less due to their significant structural differences from natural warrens. Being made of plastic and placed on the surface of the soil, the interior of Mayoral warrens could experience higher humidity and temperature levels. Although we attempted to provide protection against extreme climate conditions by covering them with branches and cork (Villafuerte *et al.*, 1993), this may not have fully buffered weather conditions, leading to decreased use by rabbits.

Our results revealed a positive association between the proportion of shrub patches surrounding the artificial warrens and the level of warren use by Iberian rabbits. The presence of shrubs near the warrens ensures the availability of suitable conditions for the rabbits to safely access essential resources, such as food and water. This result aligns with previous studies that also reported similar findings concerning natural warrens (Palomares, 2003; Gea-Izquierdo *et al.*, 2005; Dellafiore *et al.*, 2008), as well as artificial warrens (Fernández-Olalla *et al.*, 2010).

We observed a decline in the use of warrens by Iberian rabbits over time, following the acclimation period, which is likely related to the digging and use of natural burrows. Although we did not conduct a specific search for natural warrens, we occasionally found natural warrens, a fact that may be related to rabbit reproductive activity (Kolb, 1991), which occurs between October and June (Alves and Moreno, 1996). Another possible explanation for the decline in warren use could be the dispersal of some restocked and/or young Iberian rabbits to the surrounding areas of the restocking park. While this might explain the reduced warren use observed after the beginning of March (when we noticed signs of activity near the passages installed under the fence), it does not explain the initial decrease observed earlier in the study. The mortality rate of the restocked rabbits could also explain the decline in warren use, particularly since we did not take any measures to exclude aerial predators from the restocking park. However, there is no concrete evidence to support this hypothesis, as most recorded deaths occurred during the acclimation period. During our study, we radio-tagged some of the restocked rabbits and closely monitored them for approximately six months or until their death. We only detected signs of predation, both from radio-tagged animals and during field surveys conducted inside the restocking park and its surroundings, up until January 11th, 2008, which coincided with the beginning of artificial warren pellet counts. We observed a slight recovery in warrens' use in June, as predicted, which coincided with the period immediately after the breeding peak (Gonçalves *et al.*, 2002). The confirmation of successful reproduction just a few months after the restocking process indicates that the rabbits successfully adapted to the new habitat, and the restocking park provided suitable conditions for their thriving.

While it is well-documented that rainfall can have an impact on pellet persistence (Fernández-de-Simon *et al.*, 2011), in this study, the influence of precipitation on warren use was negligible. One possible explanation for this finding is that the short intervals between our pellet counts ensured pellet persistence (Moreno and Villafuerte, 1995).

Since 2011, there has been a drastic reduction in Iberian rabbit populations, mainly due to the outbreak of RHDV2. Numerous studies have reported declining trends in wild rabbit populations in both Portugal and Spain after the rapid spread of RHDV2 throughout the Iberian Peninsula (Guerrero-Casado *et al.*, 2016; Monterroso *et al.*, 2016). The ongoing decrease in populations is a cause for concern regarding their survival and its impact on Mediterranean ecosystems (Delibes-Mateos *et al.*, 2014; Monterroso *et al.*, 2016), given their roles as keystone prey species, ecosystem engineers and small game species (Delibes-Mateos *et al.*, 2008; Gálvez *et al.*, 2008; Paixão *et al.*, 2009). Therefore, enhancing rabbit populations also benefits the ecosystem and predator species specialised in preying on rabbits, many of which are of conservation concern (Delibes-Mateos *et al.*, 2008).

In southern Europe, conservationists and hunters often invest in restocking operations to boost rabbit populations. However, such efforts come with significant economic costs (Ferreira and Delibes-Mateos, 2010) and varying success rates (Calvete *et al.*, 1997; Letty *et al.*, 2002). To optimise the effectiveness of restocking interventions, it is crucial to carefully evaluate every aspect of the process, including the design, characteristics and costs of artificial warrens.

In this context, we believe our study provides valuable insights into the selection and use of artificial warrens by restocked Iberian rabbit populations and contributes with practical recommendations to enhance the success and effectiveness of rabbit restocking efforts, thereby aiding the conservation of Iberian rabbit populations in the Mediterranean region.

CONCLUSIONS

Based on our research findings, we emphasise the importance of installing artificial warrens, even within fenced restocking parks, as they create favourable conditions for the Iberian rabbits' shelter, breeding success and recruitment. These artificial warrens play a crucial role in supporting the initial adaptation of the rabbits to their new environment. We highly recommend the implementation of pallet warrens as a cost-effective and practical option for conservationists and game managers tasked with constructing artificial warrens to support restocking operations. Pallet warrens offer a budget-friendly alternative compared to more intricate and expensive designs. Furthermore, we strongly advise the strategic placement of artificial warrens near shrub patches. This placement ensures that restocked rabbits can safely access vital resources such as food and water, optimising their chances of survival and successful adaptation to the new habitat. Additionally, to enhance the dispersal and survival of rabbits, we advocate the strategic installation of additional pallet warrens around the restocking parks, providing essential shelter for dispersing rabbits.

Acknowledgements: This research was supported by "Redes Energéticas Nacionais" (REN) and coordinated by "EGSP - Energia e Sistemas de Potência, Lda./Ecossistema". CE was financed by a PhD fellowship from "Fundação para a Ciência e a Tecnologia" (FCT) SFRH/BD/80908/2011. We thank MED – Mediterranean Institute for Agriculture, Environment and Development (https://doi.org/10.54499/UIDB/05183/2020; https://doi.org/10.54499/UIDP/05183/2020), and CHANGE – Global Change and Sustainability Institute (https://doi.org/10.54499/LA/P/0121/2020). We thank Hermano Pina and João Colaço for supervising the veterinarian procedures. We also thank Giovanni Manghi for the help with GIS tasks and Carmo Silva for collaborating in fieldwork. We are grateful to the game estate "Zona de Caça Associativa de Alferce", for their support. Finally, we thank the reviewers who provided valuable suggestions to improve the manuscript.

Authors contribution: Encarnação C.: conceptualization, methodology, investigation, formal analysis and writing – original draft. Sabino-Marques H.: investigation and writing – review & editing. Pinheiro P.: conceptualization, methodology and investigation. Santos S.: formal analysis and writing – review & editing. Alves P.C.: conceptualization and writing – review & editing. Mira A.: conceptualization, methodology and writing – review & editing.

Conflict of interest: The authors declare no conflict of interest that might have influenced the content of this publication.

REFERENCES

Alves P.C., Moreno S. 1996. Estudo da reprodução do coelho-bravo em Portugal. *Revista Florestal, 9: 149-166 (in Portuguese).*

Barrio I.C., Bueno C.G., Tortosa F.S. 2009. Improving predictions of the location and use of warrens in sensitive rabbit populations. *Anim. Conserv., 12: 426-433. https://doi.org/10.1111/j.1469-1795.2009.00268.x*

Barton K. 2020. MuMIn: Multi-Model Inference. R package version 1.43.17. *https://CRAN.R-project.org/package=MuMIn*

Branco M., Ferrand N., Monnerot N. 2000. Phylogeography of the European rabbit (*Oryctolagus cuniculus*) on the Iberian Peninsula inferred from RFLP analysis of the cytochrome b gene. *Heredity, 85: 307-317. https://doi.org/10.1046/j.1365-2540.2000.00756.x*

Burnham K.P., Anderson D.R. 2002. Model selection and multi-model inference: a practical information—theoretic approach, 2nd edition. *Springer-Verlag, New York, 488.*

Cabezas S., Moreno S. 2007. An experimental study of translocation success and habitat improvement in wild rabbits. *Anim. Conserv., 10: 340-348. https://doi.org/10.1111/j.1469-1795.2007.00119.x*

Calvete C., Villafuerte R., Lucientes J., Osacar J.J. 1997. Effectiveness of traditional wild rabbit restocking in Spain. *J. Zool., 241: 271-277. https://doi.org/10.1111/j.1469-7998.1997.tb01957.x*

Carneiro M., Blanco J.A., Villafuerte R., Ferrand N., Nachman M.W. 2010. Speciation in the European rabbit (*Oryctolagus cuniculus*): islands of differentiation on the X-chromosome and autosomes. *Evolution, 64: 3443-3460. https://doi.org/10.1111/j.1558-5646.2010.01092.x*

Carvalho J.C., Gomes P. 2004. Influence of herbaceous cover, shelter and land cover structure on wild rabbit abundance in the NW Portugal. *Acta Theriol., 49: 63-74. https://doi.org/10.1007/BF03192509*

Catalán I., Rodríguez-Hidalgo P., Tortosa F.S. 2008. Is habitat management an effective tool for wild rabbit (*Oryctolagus cuniculus*) population reinforcement? *Eur. J. Wildl. Res., 54: 449-453. https://doi.org/10.1007/s10344-007-0169-0*

CNA - Comissão nacional do ambiente. 1982. Carta I.15 –Carta hipsométrica, 1:1 000 000. *Atlas do Ambiente Digital– Instituto do Ambiente*. http://www.apambiente.pt

Courchamp F., Langlais M., Sugihara G. 1999. Control of rabbits to protect island birds from cat predation. *Biol. Conserv., 89: 219-225. https://doi.org/10.1016/S0006-3207(98)00131-1*

D'Amico M., Tablado Z., Revilla E., Palomares F. 2014. Free housing for declining populations: Optimizing the provision of artificial breeding structures. *J. Nat. Conserv., 22: 369-376. https://doi.org/10.1016/j.jnc.2014.03.006*

Delibes M., Hiraldo F. 1981. The rabbit as prey in the Iberian Mediterranean ecosystem. In: *Myers K., MacInnes C.D. (eds) In Proc.: World Lagomorph Conference. University of Güelph and Wildlife Research, Ministry of Natural Resources, Ontario, 614-622.*

Delibes-Mateos M., Delibes M., Ferreras P., Villafuerte R. 2008. Key role of European rabbits in the conservation of the western Mediterranean Basin Hotspot. *Conserv. Biol., 22: 1106-1117. https://doi.org/10.1111/j.1523-1739.2008.00993.x*

Delibes-Mateos M., Ferreras P., Villafuerte R. 2009. European rabbit population trends and associated factors: A review of the situation in the Iberian Peninsula. *Mamm. Rev., 39: 124-140. https://doi.org/10.1111/j.1365-2907.2009.00140.x*

Delibes-Mateos M., Farfán M.Á., Rouco C., Olivero J., Márquez A.L., Fa J.E., Vargas J.M., Villafuerte R. 2018. A large-scale assessment of European rabbit damage to agriculture in Spain. *Pest Manag. Sci., 74: 111-119. https://doi.org/10.1002/ps.4658*

Delibes-Mateos M., Ferreira C., Carro F., Escudero M.A., Gortázar C. 2014. Ecosystem Effects of Variant Rabbit Hemorrhagic Disease Virus, Iberian Peninsula. *Emerg. Infect. Dis., 20: 2166-2168. https://doi.org/10.3201/eid2012.140517*

Delibes-Mateos M., Rödel H.G., Rouco C., Alves P.C., Carneiro M., Villafuerte R. 2021. European Rabbit *Oryctolagus cuniculus* (Linnaeus, 1758). In: *Hackländer K., Zachos F.E. (eds) Handbook of the Mammals of Europe. Handbook of the Mammals of Europe. Springer, Cham, Switzerland. https://doi.org/10.1007/978-3-319-65038-8_13-1*

Dellafiore C.M., Gallego Fernández J.B., Vallés S.M. 2008. Habitat use for warren building by European rabbits (*Oryctolagus cuniculus*) in relation to landscape structure in a sand dune system. *Acta Oecol., 33: 372-379. https://doi.org/10.1016/j.actao.2008.02.002*

Dellafiore C.M., Gallego Fernández J.B., Vallés S.M. 2010. The rabbit (*Oryctolagus cuniculus*) as a seed disperser in a coastal dune system. *Plant Ecol., 206: 251-261. https://doi.org/10.1007/s11258-009-9639-7*

Dormann C.F., Elith J., Bacher S., Buchmann C., Carl G., Carré G., Marquéz J.R.G., Gruber B., Lafourcade B., Leitão P.J., Munkemuller T., McClean C., Osborne P.E., Reineking B., Schroder B., Skidmore A.K., Zurell D., Lautenbach S. 2013. Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. *Ecography, 36: 27-46. https://doi.org/10.1111/j.1600-0587.2012.07348.x*

EFSA AHAW Panel (EFSA Panel on Animal Health and Welfare), Saxmose Nielsen S., Alvarez J., Bicout D.J., Calistri P., Depner K., Drewe J.A., Garin-Bastuji B., Gonzales Rojas J.L., Gortazar Schmidt C., Michel V., Miranda Chueca M.A., Roberts H.C., Sihvonen L.H., Spoolder H., Stahl K., Velarde Calvo A., Viltrop A., Buijs S., Edwards S., Candiani D., Mosbach-Schulz O., Van der Stede Y., Winckler C. 2020. Scientific Opinion on the health and welfare of rabbits farmed in different production systems. *EFSA Journal 2020; 18: 5944. https://doi.org/10.2903/j.efsa.2020.5944*

Eldridge D.J., Myers C.A. 2001. The impact of warrens of the European rabbit (*Oryctolagus cuniculus* L.) on soil and ecological processes in a semi-arid Australian woodland. *J. Arid Environ., 47: 325-337. https://doi.org/10.1006/jare.2000.0685*

Encarnação C., Medinas D., Alves P.C., Mira A. 2019. Does short-term habitat management for the European rabbit (*Oryctolagus cuniculus*) have lasting effects? *Ecol. Res., 34: 296-308. https://doi.org/10.1111/1440-1703.1064*

Fernandez-de-Simon J., Díaz-Ruiz F., Villafuerte R., Delibes-Mateos M., Ferreras P. 2011. Assessing predictors of pellet persistence in European rabbits *Oryctolagus cuniculus*: towards reliable population estimates from pellet counts. *Wildl. Res., 17: 317-325. https://doi.org/10.2981/10-001*

Fernández-Olalla M., Martínez-Jauregui M., Guil F., San A. 2010. Provision of artificial warrens as a means to enhance native wild rabbit populations: what type of warren and where should they be sited? *Eur. J. Wildl. Res., 56: 829-837. https://doi.org/10.1007/s10344-010-0377-x*

Ferreira C., Alves P.C. 2009. Influence of habitat management on the abundance and diet of wild rabbit (*Oryctolagus cuniculus algirus*) populations in Mediterranean ecosystems. *Eur. J. Wildl. Res., 55: 487-496. https://doi.org/10.1007/s10344-009-0257-4*

Ferreira C., Delibes-Mateos M. 2010. Wild Rabbit Management in the Iberian Peninsula: State of the Art and Future Perspectives for Iberian Lynx Conservation. *Wildl. Biol. Pract., 6: 48-66. https://doi.org/10.2461/wbp.lynx.4*

Ferreira C., Touza J., Rouco C., Díaz-Ruiz F., Fernandez-de-Simon J., Ríos-Saldaña C.A., Ferreras P., Villafuerte R., Delibes-Mateos M. 2013. Habitat management as a generalized tool to boost European rabbit *Oryctolagus cuniculus* populations in the Iberian Peninsula: a cost-effectiveness analysis. *Mamm. Rev., 44: 30-43. https://doi.org/10.1111/mam.12006*

Finzi A., Mariani G. 2011. L'allevamento ecologico del coniglio (Organic rabbit farming). *Edagricole. Milano, Italy. 130 (in Italian).*

Fox J., Weisberg S. 2019. An {R} Companion to Applied Regression, 3rd edition. *Sage, Thousand Oaks CA. https://socialsciences.mcmaster.ca/jfox/Books/Companion/*

Gálvez L., López-Pintor A., De Miguel J.M., Alonso G., Rueda M., Rebollo S., Gómez-Sal A. 2008. Ecosystem engineering effects of European rabbits in a Mediterranean habitat. In: *Lagomorph Biology: Evolution, Ecology and Conservation: 125-140. Alves PC, Ferrand N, Hackländer K (Eds.), Springer-Verlag, Berlin, Heidelberg.*

Gálvez-Bravo L., Belliure J., Rebollo S. 2009. European rabbits as ecosystem engineers: warrens increase lizard density and diversity. *Biodivers. Conserv., 18: 869-885. https://doi.org/10.1007/s10531-008-9438-9*

García F. 2003. Revisión de las actuaciones para el fomento de las poblaciones de conejo de monte. 1[er] Informe anual. *Madrid: Dirección General para la Conservación de la Naturaleza - Ministerio de Medio Ambiente, 171 (in Spanish).*

Gea-Izquierdo G., Muñoz-Igualada J., San Miguel-Ayanz A. 2005. Rabbit warren distribution in relation to pasture communities in Mediterranean habitats: consequences for management of rabbit populations. *Wildl. Res., 32: 723-731. https://doi.org/10.1071/WR04129*

Godinho S., Mestre F., Ferreira J.P., Machado R., Santos P. 2013. Effectiveness of habitat management in the recovery of low-density populations of wild rabbit. *Eur. J. Wildl. Res., 59: 847-858. https://doi.org/10.1007/s10344-013-0738-3*

Gonçalves H., Alves P.C., Rocha A. 2002. Seasonal variation in the reproductive activity of the wild rabbit (*Oryctolagus cuniculus algirus*) in a Mediterranean ecosystem. *Wildl. Res., 29: 165-173. https://doi.org/10.1071/wr00048*

González L.M., San Miguel A. 2004. Manual de gestión de fincas de monte mediterráneo de la Red Natura 2000. *Ministerio de Medio Ambiente. Madrid, 327 (in Spanish).*

Guerrero-Casado J., Letty J., Tortosa F.S. 2013. European rabbit restocking: a critical review in accordance with IUCN (1998) guidelines for re-introduction. *Anim. Biodivers. Conserv., 2: 177-185. https://doi.org/10.32800/abc.2013.36.0177*

Guerrero-Casado J., Carpio A.J., Tortosa F.S. 2016. Recent negative trends of wild rabbit populations in southern Spain after the arrival of the new variant of the rabbit haemorrhagic disease virus RHDV2. *Mamm. Biol., 81: 361-364. https://doi.org/10.1016/j.mambio.2016.03.006*

Guerrero-Casado J., Ström H., Hilström L., Prada L.M., Carpio A.J., Tortosa F.S. 2020. Assessment of the suitability of latrine counts as an indirect method by which to estimate the abundance of European rabbit populations at high and low abundance. *Eur. J. Wildl. Res., 66: 10. https://doi.org/10.1007/s10344-019-1349-4*

Guil F., Higuero R., Moreno-Opo R. 2014. European wild rabbit (*Oryctolagus cuniculus*) restocking: effects on abundance and spatial distribution. *Wildl. Soc. Bull., 38: 524-529. https://doi.org/10.1002/wsb.440*

Hastie T.J., Tibshirani R.J. 1990. Generalized additive models. *Chapman and Hall/CRC, Boca Raton, London, New York, Washington D.C., 352.*

Iborra O.L., Lumaret J.P. 1997. Validity limits of the pellet group counts in wild rabbit (*Oryctolagus cuniculus*). *Mammalia, 61: 205-218. https://doi.org/10.1515/mamm.1997.61.2.205*

IHERA - Instituto de hidráulica engenharia rural e ambiente, DSRNAH, Divisão de solos. 1999. Carta dos solos de Portugal, 1:25000 (in Portuguese).

Jones C.G., Lawton J.H., Shachak M. 1994. Organisms as ecosystem engineers. *Oikos, 69: 373-386. https://doi.org/10.2307/3545850*

Kolb H.H. 1985. The burrow structure of the European rabbit (*Oryctolagus cuniculus* L). *J. Zool., 206: 253-262. http://dx.doi.org/10.1111/j.1469-7998.1985.tb05649.x*

Kolb H.H. 1991. Use of burrows and movements of wild rabbits (*Oryctolagus cuniculus*) in an area of hill grazing and forestry. *J. Appl. Ecol., 28: 892-905. https://doi.org/10.2307/2404215*

Letty J., Marchandeau S., Reitz F., Clobert J., Sarrazin F. 2002. Survival and movements of translocated wild rabbits (*Oryctolagus cuniculus*). *Game wildl. sci., 19: 1-23.*

Macdonald D.W., Norris S. 2001. The new encyclopedia of mammals. *Oxford University Press, Oxford, 930.*

Monterroso P., Garrote G., Serronha A., Santos E., Delibes-Mateos M., Abrantes J., Ayala R.P., Silvestre F., Carvalho J., Vasco I., Lopes A.M., Maio E., Magalhães M.J., Mills L.S., Esteves P.J., Simón M.A., Alves P.C. 2016. Disease-mediated bottom-up regulation: An emergent virus affects a keystone prey, and alters the dynamics of trophic webs. *Sci. Rep., 6: 6072. https://doi.org/10.1038/srep36072*

Moreno S., Villafuerte R. 1995. Traditional Management of scrubland for the Conservation of Rabbits *Oryctolagus cuniculus* and their Predators in Doñana National Park, Spain. *Biol. Conserv., 73: 81-85. https://doi.org/10.1016/0006-3207(95)90069-1*

Moreno S., Villafuerte R., Cabezas S., Lombardi L. 2004. Wild rabbit restocking for predator conservation in Spain. *Biol. Conserv., 118: 183-193. https://doi.org/10.1016/j.biocon.2003.07.020*

Paixão R., Godinho S., Santos P. 2009. Is the Nature 2000 Network associated with small-game bag results? *Eur. J. Wildl. Res., 55: 553-559. https://doi.org/10.1007/s10344-009-0274-3*

Palomares F. 2001. Comparison of three methods to estimate rabbit abundance in a Mediterranean environment. *Wildl. Soc. Bull., 29: 578-585. https://doi.org/10.1007/s10980-004-3976-7*

Palomares F. 2003. Warren building by European rabbits (*Oryctolagus cuniculus*) in relation to cover availability in a sandy area. *J. Zool., 259: 63-67. https://doi.org/10.1017/S0952836902002960*

Paradis E., Schliep K. 2019. ape 5.0: an environment for modern phylogenetics and evolutionary analyses. *R. Bioinformatics, 35: 526-528. https://doi.org/10.1093/bioinformatics/bty633*

Parer L., Libke J.A. 1985. Distribution of rabbit, *Oryctolagus cuniculus*, warrens in relation to soil type. *Aust. Wildl. Res., 12: 387-405.*

QGIS Development Team. 2021. QGIS geographic information system. *Open source geospatial foundation project. https://www.qgis.org*

R Core Team. 2022. R: A language and environment for statistical computing. *R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/*

REN, EGSP, Ecossistema. 2009. Linha Sines – Portimão 3 a 400 kV. Medidas compensatórias e monitorização específica para o casal de águia de Bonelli de Odelouca, decorrentes do processo de Avaliação de Impacte Ambiental. *Final report. Lisbon, Portugal (in Portuguese).*

Ríos-Saldaña C.A., Delibes-Mateos M., Castro F., Martínez E., Vargas J.M., Cooke B.D., Villafuerte R. 2013. Control of the European rabbit in central Spain. *Eur. J. Wildl. Res., 59: 573–580. https://doi.org/10.1007/s10344-013-0707-x*

Roberts S.C. 1987. Group-living and consortship in two populations of the European rabbit (*Oryctolagus cuniculus*). *J. Mammal., 68: 28-38. https://doi.org/10.2307/1381042*

Roca T. 2009. Historia de la cunicultura industrial en España. *Cunicultura, 35: 9-15 (in Spanish).*

Rogers P.M., Myers K. 1979. Ecology of the European wild rabbit, *Oryctolagus cuniculus* (L.), in Mediterranean habitats. I. Distribution in the landscape of the Coto Doñana, S. Spain. *Appl. Ecol., 16: 691-703*. https://doi.org/10.2307/2402846

Rouco C., Ferreras P., Castro F., Villafuerte R. 2008. The effect of exclusion of terrestrial predators on short-term survival of translocated European wild rabbits. *Wildl. Res., 35: 625-632. https://doi.org/10.1071/WR07151*

Rouco C., Villafuerte R., Castro F., Ferreras P. 2011. Effect of artificial warren size on a restocked European wild rabbit population. *Anim. Conserv., 14: 117-123 https://doi.org/10.1111/j.1469-1795.2010.00401.x*

San Miguel (Coord.). 2014. Manual para la gestión del hábitat el lince ibérico (*Lynx pardinus*) y de su presa principal, el conejo de monte (*Oryctolagus cuniculus*). 2ª Edición. *Fundación CBD-Habitat, Madrid, España, 325 (in Spanish).*

Scanlan J.C., Berman D.M., Grant W.E. 2006. Population dynamics of the European rabbit (*Oryctolagus cuniculus*) in northeastern Australia: simulated responses to control. *Ecol. Modell., 196: 221–236. https://doi.org/10.1016/j.ecolmodel.2006.02.008*

Schielzeth H. 2010. Simple means to improve the interpretability of regression coefficients. *Methods Ecol. Evol., 1: 103-113. https://doi.org/rg/10.1111/j.2041-210X.2010.00012.x*

SNIRH - Sistema nacional de informação de recursos hídricos. 2022. Portal do Sistema nacional de informação de recursos hídricos. *https://snirh.apambiente.pt/*

Tabachnick B., Fidell L. 1996. Using Multivariate Statistics. 3rd edition. *HarperCollins College Publishers, New York, 880*.

Thompson H.V., King C.M. 1994. The European Rabbit: the history and biology of a successful colonizer. *Oxford University Press, Great Britain, 245*.

Villafuerte R., Delibes-Mateos M. 2019. *Oryctolagus cuniculus* (errata version published in 2020). *The IUCN Red List of Threatened Species 2019: e.T41291A170619657. https://dx.doi.org/10.2305/IUCN.UK.2019-3.RLTS.T41291A170619657.en*

Villafuerte R., Kufner M.B., Delibes M., Moreno S. 1993. Environmental factors influencing the seasonal daily activity of the European rabbit (*Oryctolagus cuniculus*) in a Mediterranean area. *Mammalia, 57: 341-347. https://doi.org/10.1515/mamm.1993.57.3.341*

Villafuerte R., Calvete C., Blanco J.C., Lucientes J. 1995. Incidence of viral hemorrhagic disease in wild rabbit populations in Spain. *Mammalia, 59: 651-659. https://doi.org/10.1515/mamm.1995.59.4.651*

Villafuerte R., Viñuela J., Blanco J.C. 1998. Extensive predator persecution caused by population crash in a game species: The case of red kites and rabbits in Spain. *Biol. Conserv., 84: 181-188. https://doi.org/10.1016/S0006-3207(97)00094-3*

Wickham H. 2016. ggplot2: Elegant Graphics for Data Analysis. *Springer-Verlag, New York*.

Willot S.J., Miller A.J., Incoll L.D., Compton S.G. 2000. The contribution of rabbits (*Oryctolagus cuniculus* L.) to soil fertility in semi-arid Spain. *Biol. Fertil. Soils, 31: 379-384. https://doi.org/10.1007/s003749900183*

Wood S. 2017. Generalized Additive Models: An Introduction with R, 2nd edition. *Chapman and Hall/CRC, Boca Raton, London, New York, 476*.

Zuur A.F., Ieno E.N., Walker N.J., Saveliev A.A., Smith G.M. 2009. Mixed-effects model and extensions in ecology with R. *Springer, New York, USA, 574.*

Zuur A.F., Ieno E.N., Elphick C.S. 2010. A protocol for data exploration to avoid common statistical problems. *Methods in Ecol. Evol., 1: 3-14. https://doi.org/10.1111/j.2041-210X.2009.00001.x*

SUPPLEMENTARY INFORMATION A – PHOTOGRAPHS OF THE FOUR TYPES OF ARTIFICIAL WARRENS

Photographs of the four types of artificial warrens installed inside the restocking park.

Figure SA1: Log warren.

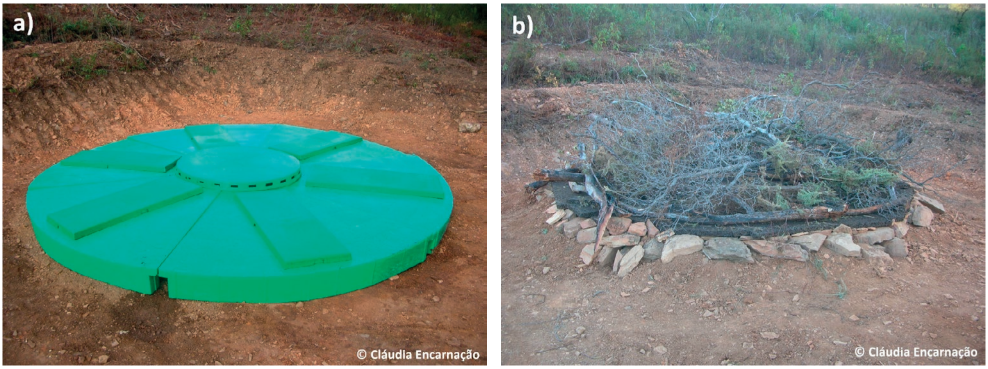

Figure SA2: Structure (a) and final appearance (b) of a Mayoral® warren.

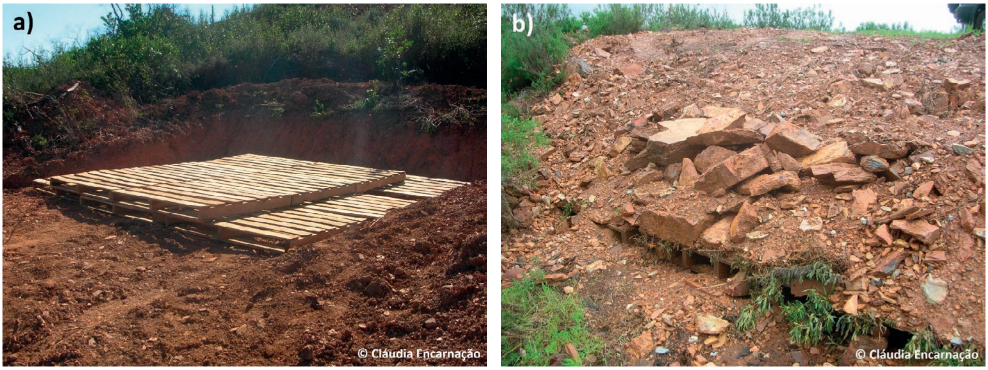

Figure SA3: Structure (a) and final appearance (b) of a pallet warren.

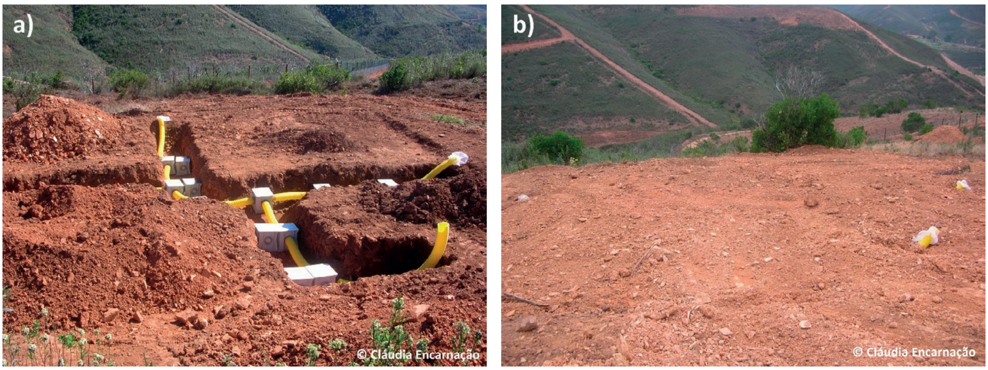

Figure SA4: Structure (a) and final appearance (b) of a tube warren.

SUPPLEMENTARY INFORMATION B – DETAILS OF MODEL SELECTION

Table SB1: Averaged model (GAMM) of the effects of predictors on rabbit use of artificial warrens. Model averaging accounted for "warren" as random effect and allowed for different variances per warren. Model averaging is based on the confidence set of models at ΔAICc<4 from the best model. The table shows standard errors (SE), 95% confidence intervals (CI) and relative importance (w+) of each predictor involved. Estimates whose 95% CI excluded zero are in bold. Predictors: WEEK - sample week, TYPE - type of artificial warren, D_FOOD - distance to the nearest food patch and P_SHRUB - proportion of shrub patches in a 10 meters buffer around the warren. The reference category for TYPE is Pallets.

	Estimate	SE	CI	w+
(Intercept)	0.418	0.071	(0.279, 0.556)	
TYPE				
Logs	**–0.165**	**0.047**	**(–0.258, –0.072)**	**0.49**
Majano	**–0.144**	**0.061**	**(–0.265, –0.023)**	
Tubes	**–0.239**	**0.071**	**(–0.379, –0.099)**	
P_SHRUB	**0.128**	**0.038**	**(0.054, 0.202)**	**1.00**
D_FOOD	0.035	0.037	(–0.039, 0.108)	0.33
s(WEEK).1	0.181	0.094	(–0.006, 0.368)	**1.00**
s(WEEK).2	**–1.272**	**0.277**	**(–1.819, –0.725)**	
s(WEEK).3	0.109	0.080	(–0.049, 0.266)	
s(WEEK).4	**0.748**	**0.204**	**(0.346, 1.151)**	
s(WEEK).5	**–0.167**	**0.082**	**(–0.329, –0.006)**	
s(WEEK).6	**–0.693**	**0.189**	**(–1.066, –0.320)**	
s(WEEK).7	–0.118	0.076	(–0.267, 0.032)	
s(WEEK).8	**–1.906**	**0.427**	**(–2.747, –1.064)**	
s(WEEK).9	–0.217	0.180	(–0.572, 0.138)	

Table SB2: Candidate models tested to access predictors potentially affecting rabbit use of artificial warrens, accounting for "warren" as random effect and allowing for different variances per warren. Models are ranked by AICc. Predictors: WEEK - sample week, TYPE - type of artificial warren, D_FOOD - distance to the nearest food patch and P_SHRUB - proportion of shrub patches in a 10 meters buffer around the warren. Delta are AICc differences to the best model and wi are Akaike weights based on the entire set of models. The table also shows values for each model's intercept (Int) and degrees of freedom (df). Models are ranked by ΔAICc. Models included in model averaging (confidence set of models at ΔAICc<4 from the best model) are highlighted in bold.

Model	(Int)	s(WEEK)	TYPE	D_FOOD	P_SHRUB	df	AICc	Delta	Wi
12	**0.4824**	+	+		+	**16**	**-40.1**	**0.00**	**0.336**
11	**0.3574**	+			+	**13**	**-40.1**	**0.30**	**0.289**
15	**0.3602**	+		+	+	**14**	**-39.0**	**1.13**	**0.190**
16	**0.4745**	+	+	+	+	**17**	**-38.0**	**2.13**	**0.116**
7	0.3682	+		+		13	-35.2	4.96	0.028
8	0.5134	+	+	+		16	-34.7	5.46	0.022
4	0.6175	+	+			15	-34.2	5.93	0.017
3	0.3663	+				12	-29.6	10.48	0.002
9	0.3557				+	11	3.4	43.51	0.000
10	0.4851		+		+	14	3.9	43.99	0.000
13	0.3578			+	+	12	4.3	44.43	0.000
14	0.4757		+	+	+	15	6.1	46.18	0.000
5	0.3661			+		11	8.2	48.30	0.000
6	0.5158		+	+		14	8.7	48.82	0.000
2	0.6164		+			13	8.9	48.99	0.000
1	0.3651					10	13.6	53.69	0.000