

# Permeability of artificial barriers (fences) for wild boar (*Sus scrofa*) in Mediterranean mixed landscapes

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## Abstract

**BACKGROUND:** Fences are one of the most widespread manmade features in nature, constituting an artificial limitation to the movement of wildlife. To date, their effects on wildlife behavior have been understudied but this knowledge is required to design effective management procedures. Using 21 GPS-monitored wild boar, we evaluated the permeability of different types of fences and described temporal patterns and spatial hotspots for crossing events. A fence's permeability was inferred by the crossing success, i.e., the number of times that animals crossed a barrier vs the number of times they did not cross. The vulnerability of fences at watercourses was explored by assessing whether the frequency of crossings was higher around watercourse intersections than expected by chance.

**RESULTS:** Well-maintained big game proof fences were the most effective in reducing successful wild boar crossings; they were, on average, 30% more efficient than livestock type fences. Crossing success was higher for males than females and during the food shortage period than in the food abundance period. The frequency of crossings around watercourses was higher than expected by chance, especially in moderately and well-maintained big game proof type fences.

**CONCLUSION:** While no fence type was 100% wild boar proof, well-maintained big game proof fences substantially constrained the movement of boar. However, they are vulnerable around watercourses. Managing the conflicts in which this species is involved, such as shared infections and agricultural damage, would require fences that are even more effective than the ones analyzed here, ideally in conjunction with other preventive actions.

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Supporting information may be found in the online version of this article.

**Keywords:** animal movement; corridors; fence crossing; management; risk of disease transmission

## 1 INTRODUCTION

Animal movement is the result of the interplay between intrinsic and extrinsic factors.<sup>1,2</sup> Extrinsic factors include structural elements of the landscape and/or land use such as crop fields, hedges or ditches, natural corridors, refuge areas or natural barriers (e.g., rivers, mountains).<sup>3–6</sup> In this way, the movements of wildlife are affected by natural and anthropogenic barriers, sometimes related to human infrastructures (e.g., roads, railways) and those directly aimed at controlling the movement of (domestic and/or wild) animal populations (e.g., fences).<sup>7–9</sup> Fences, defined as a physical linear feature with vertical load-bearing components (e.g., poles) and non-continuous structures (e.g., boards, wires, rails, nettings) spanning these vertical components,<sup>10</sup> can impact on wildlife in ways that vary from the positive (e.g., protection from poaching) to the primarily negative (e.g., barriers to movement).

Nowadays, the rapid increase in fencing, due to a global trend towards land partitioning and privatization further highlights the importance of understanding their effects on wildlife ecology.<sup>11</sup> For example, the erection of fences has altered the grazing

behavior in some species, which, by increasing grazing intensity has degraded pastures and changed the vegetation community and ecological regime.<sup>12</sup> Further, terrestrial mammals, such as migratory ungulates, are particularly susceptible to the effects of these barriers because fences directly block movement paths.<sup>13</sup> However, animals' behavioral responses to fencing have scarcely been studied, even though this information is valuable for basic management and land-use planning.<sup>14</sup> Upon encountering a

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fence, an animal may patrol along such boundaries, seeking breaks for crossing opportunities or immediately deflect away.<sup>15,16</sup> Animals may also move more quickly in the immediate vicinity of fences or not exhibit visible changes in their movement pattern.<sup>17,18</sup> In this context, the effectiveness of fences in restricting the movements of wildlife remains unclear,<sup>19,20</sup> although some species challenge fences, jumping and/or climbing over, others crawl under them.<sup>21</sup>

Fences are one of the most effective tools to prevent human-wildlife conflicts, and are commonly used: (i) to reduce the roadway collisions caused by animals<sup>22</sup>; (ii) to protect crops and forestry<sup>23,24</sup>; and (iii) to reduce transmission of shared infections.<sup>21</sup> However, some drawbacks have been identified. In addition to the initial cost of installing the fences, their effectiveness is highly dependent of the maintenance status, especially when they are intended to retain wildlife populations, and this is costly.<sup>19,25</sup> Their effectiveness may be compromised by some vulnerable points (e.g., an intersection with a river/road)<sup>23,26</sup> in concomitance with the increased attraction of the resources they protect (e.g., harvest period on agricultural land).<sup>27</sup> Most fences do not work against a wide variety of species,<sup>10</sup> and normally involve animal conservation costs (e.g., cutting migration routes, promoting landscape fragmentation).<sup>28,29</sup>

Wild boar (*Sus scrofa*) is the ungulate most involved in conflicts in Europe, where effective solutions to manage the species are in high demand.<sup>30</sup> Recently, Carpio et al.<sup>31</sup> reported that wild boars produce density-related conflicts mainly in arable farming, livestock farming and (peri-) urban areas across Europe. However, while a number of authors have studied the effects of fencing to reduce crop damage,<sup>32,33</sup> disease control,<sup>21</sup> wildlife-livestock segregation,<sup>34</sup> and vehicle collisions with wild boar,<sup>35</sup> the effect of fencing on wild boar's spatial behavior remains poorly studied.<sup>36–38</sup> Fences were found to temporarily reduce the damage caused by wild boars (or wild pigs) and restrict their movements, but with different levels of efficiency in relation to the fences' characteristics.<sup>32,33,38</sup> The effectiveness of a fence to exclude wild boars requires continuous fence monitoring and maintenance.<sup>39</sup> Currently, there is no evidence of affordable fence designs that are 100% wild boar proof on a large scale and for a prolonged period. However, nowadays, fences are deployed to prevent the spread of emerging wildlife pathogens.<sup>21</sup> For instance, new large-scale fences are being built in many countries

in Europe to combat the spread of African Swine Fever (ASF), although surprisingly little scientific literature is available on the efficacy of fencing to control wildlife disease.<sup>40–42</sup>

To date, the effect of the fences has not been clearly determined as most fences are still undocumented or unmapped,<sup>10</sup> and only a few studies have described animals' behavioral responses to fencing.<sup>14</sup> Scientists, conservationists, resource managers, and private landholders require this knowledge for wildlife management and land-use planning in order to understand how fences affect individual animals, populations, or processes within the ecosystem. This information is particularly essential in the complex context of mixed land uses, where conflict between wild boar-human, wild boar-livestock or wild boar-conservation occur (e.g., urban, farming, livestock or protected areas) and in the different management scenarios (e.g., fenced areas, feeding states) present in Mediterranean ecosystems.<sup>31</sup> We hypothesize that crossing success (i.e. as the number of times that animals crossed a barrier vs the number of times they did not) can be affected by the type of fence and its maintenance, after controlling for individual and temporal factors, and all fence types have vulnerable points where animals tend to cross. In this context, our aim was to evaluate the permeability (in terms of crossings and bounces) of the different types of fences typically used in mixed land use in Mediterranean areas, and to describe the presence of vulnerable points (hotspots) of fences in terms of wild boar crossings.

## 2 MATERIALS AND METHODS

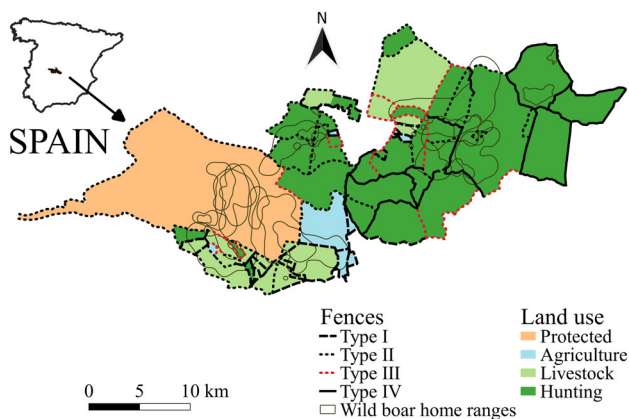
### 2.1 Study area

The study was performed in Montes de Toledo, a mountain chain located between Ciudad Real and Toledo provinces, on the central Spanish plateau, characterized by fragmented agroforestry systems with Mediterranean woodlands and scrublands (Fig. 1). In the western area, mixed land uses are present within the Cabañeros National Park (hereafter CNP), where livestock and agricultural farming predominate on the periphery of the park. In the eastern area, a continuous distribution of independently managed hunting estates is present, mainly devoted to the recreational hunting of wild ungulates, wild boar, and red deer (*Cervus elaphus*) are the main game species. Therefore, throughout the study area there is a mosaic of estates with different land uses: hunting, livestock, agricultural and protected areas (Fig. 1). Fences are abundant in the study area to delimit livestock pastures, protect crops and constitute the boundaries of hunting estates.

The hunting management unit in this area are the estates (public or private). Here the harvest is mostly conducted by drive hunts (locally called *montería*). The hunting tally from the study area is high with an average annual extraction quota of 2.26 wild boar-km<sup>-2</sup>.<sup>43</sup> The study area is also one of the areas with the highest prevalence and incidence of tuberculosis (TB) in cattle in Spain, with high rates of TB-like lesions in wildlife.<sup>44</sup> In this context, we have to highlight two problems: (i) the conflicts related to the protection of natural processes and conservation of species in protected areas<sup>45,46</sup>; and (ii) conflicts with livestock farmers related to the risk of pathogen spread from wild animals to livestock.<sup>47</sup> Areas like this with mixed land uses are common in southern Europe.<sup>31</sup>

### 2.2 Capture and monitoring

From July 2009 to August 2010, 21 adult wild boars (12 males and nine females) were captured using 3 × 1.2 m portable cage traps and corral traps, each consisting of seven panels over 5 m wide



**Figure 1.** Study area. The map shows the main land use for each plot, the location of the different type of fences and the home ranges (kernel 95%) of the 21-radio collared wild boars.

(Supporting information, Table S1). The capture of the animals was performed following a protocol approved by the Animal Experiment Committee of Castilla-La Mancha University and by the Spanish Ethic Committee (PR-2015-2103-08). The protocol was designed by specifically trained and certified scientists (B and C animal experimentation categories) according to the EC Directive 86/609/EEC. The animals captured were equipped with GPS-GSM collars (MICROSENSORY S.L.) that were programmed to acquire one location every hour 24/7. The data collected by the collars included date, time, geographic coordinates, and the individual's ID. The mean positioning error was estimated to be 26 m (standard deviation; SD = 23.5 m). For the analyses, locations from the first day were not considered, since the animals could have anomalous behaviors after the handling procedure.<sup>48</sup>

### 2.3 Characterization of the estates

Previous studies have attributed success in crossing fences to the type of fence, and the lack of maintenance with the presence of holes or breakage points.<sup>19,20,27</sup> The 28 estates present in the study area (64 390 ha) were characterized by means of a survey, conducted with the managers and farmers during the 2009 and 2010 summers (July–September), which is the season when water resources are most limited for wildlife, the availability of food is, therefore, severely reduced and thus the animals displayed longer daily movements in the study area (Supporting information, Table S2). The aim of the survey was to gather information on the fences, both internal and on the perimeter. We used a printed map to locate the limits of each internal plot and the main land use. In this study a plot is a small area without internal barriers with a specific land use; one estate can be then divided into several plots with the same or different land use (e.g., two plots used for agriculture and one for livestock breeding). The map was supported by tables to register the description of fence and the frequency of the fence maintenance (e.g., weekly, monthly, sporadic). The time required to conduct the questionnaire, including the annotations on the map, was typically 1 h per estate. In addition, a walking tour was carried out to count the number of holes and breakage points per kilometer (hereafter km) in each fence, to be used as a proxy for the permeability index (Supporting information, Table S2 and Figs S1 and S2):

- Type I. Simple or reinforced livestock type fence, height between 120 and 150 cm with horizontal and vertical wires (30 cm wide between vertical lines) and wooden or steel posts, which may have one or two lines of barbed wire on top. Average permeability index of  $10.94 \pm 3.63$  holes per km of fence.
- Type II. Poorly-maintained big game proof type fence, height of 200 cm, with old horizontal and vertical wires (minimum  $15 \times 15$  cm) and sporadic maintenance of breakage parts. Average permeability index of  $4.21 \pm 2.86$  holes per km of fence.
- Type III. Moderately-maintained big game proof type fence with a height of 200 cm and tightened horizontal and vertical wires (minimum  $15 \times 15$  cm) and monthly maintenance activities. Average permeability index of  $1.37 \pm 1.89$  holes per km of fence.
- Type IV. Well-maintained big game proof type fence, height of 200 cm, with tightened horizontal and vertical wires (minimum  $15 \times 15$  cm) and weekly maintenance. Average permeability index of  $0.15 \pm 0.54$  holes per km of fence.

None of these fence types is fixed into the ground. Permeability indices were designed to show intra-annual variations. The transects were, for this reason, created in the worst scenario (summer) and the values were just used as a confirmatory and objective parameter to support the classification of the fence that had been determined from the questionnaires.

We obtained information for 59 plots and identified four main land uses in the study area (protected area 18 040 ha, agriculture 2700 ha, livestock 9850 ha and hunting estates 33 800 ha) and 189 fences with an extension of 483 km (Type I 97 km, Type II 200 km, Type III 74 km and Type IV 112 km) (see Fig. 1). Type II covered 100% of the perimeter in the protected areas. On agricultural and livestock farms, Type I accounted for 91% and 45%, respectively. However, for those plots where hunting was the main land use, 92% of their perimeters was formed with big game proof fences, with different frequencies of maintenance activities (Supporting information, Table S3). Thus, fence classification is inherently associated with the land uses of the territory.

### 2.4 Data analysis

#### 2.4.1 Availability of fences

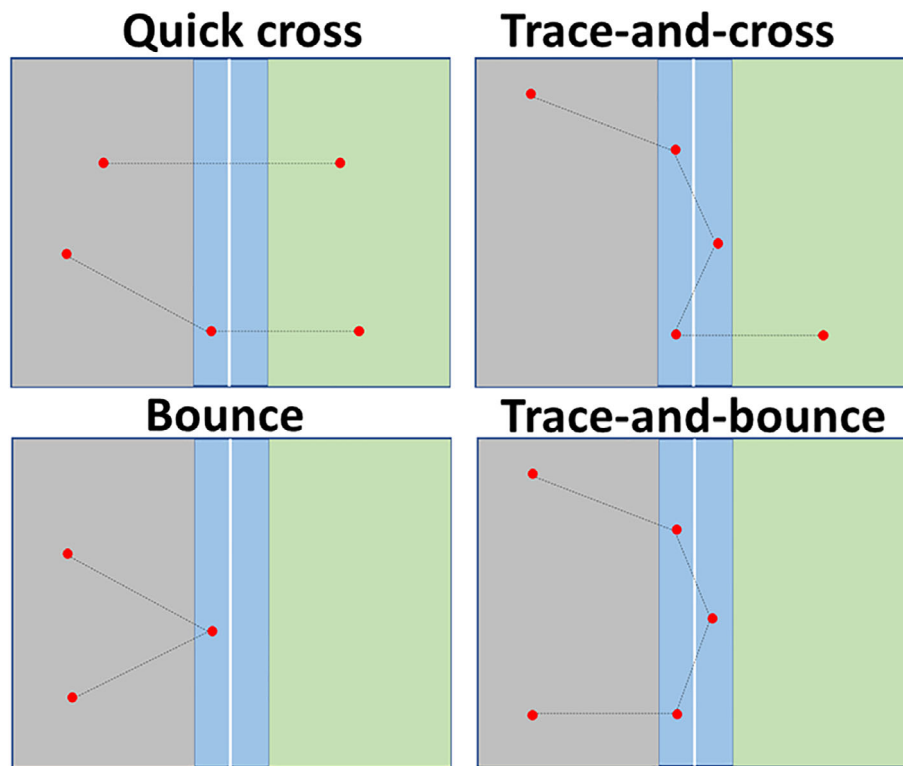
Animal movement can be estimated from telemetry data summing the raw straight-line distances between consecutive locations; however, this approach underestimate total displacement due to animal paths are mostly tortuous.<sup>49</sup> Recently, Palencia *et al.*,<sup>49</sup> using GPS technology, reported an average movement speed of  $500 \text{ m} \cdot \text{h}^{-1}$  for wild boars in southern Spain after the rescaling of the raw value with a tortuosity-related correction factor derived from camera-trap data. Therefore, given our fixation rate ( $1 \text{ loc} \cdot \text{h}^{-1}$ ), a fence was considered available for the monitored individuals when at least one location was recorded within a 500 m distance. It should be noted that this value is consistent with that obtained for our study area using telemetry data from our collared individuals and camera trap data from an unpublished experiment (data not shown).

#### 2.4.2 Events at fences

We established a buffer area with a radius of 50 m (GPS error + SD) around fences to represent an area where we are not sure of the plot at which the animal is located. Following the rationale of Xu *et al.*,<sup>14</sup> we defined four types of events, i.e., interactions between animals and fences (Fig. 2; for further details see Supporting information, Appendix S1):

- (1) Quick cross: consecutive locations in different plots, outside the buffered area, whose trajectory intersects a fence. The maximum number of locations involved in the trajectory is three for this behavior (with or without an intermediate location in the buffered area).
- (2) Trace-and-cross: like a quick cross but involving more than one location in the fence's buffered area.
- (3) Bounce: a location in the buffered area, with the previous and posterior locations in the same plot and outside the buffered area.
- (4) Trace-and-bounce: like a bounce but involving more than one consecutive location in the buffered area.

Data registered for each event included the ID of the fence involved, its type (I–IV), the individual's ID, sex, date, time and the geographic coordinates where each crossing potentially occurred (intersection between the fence and the lineal trajectory determined by consecutive GPS fixations). Also, the number and



**Figure 2.** Theoretical scenarios used to define the four behaviors in relation to fences: quick cross, trace-and-cross, bounce and trace-and-bounce. Blue rectangles show the buffer area around the fence (white line), red points show the GPS locations, and the dotted lines show the trajectories. Grey and green rectangles represent two different plots.

frequency of the different events were quantified per each individual/ID fence. We searched the database of animal locations for the presence of these events using programmed functions in R,<sup>50</sup> with 'sf', 'sp' and 'dplyr' R packages (see also Supporting information, Appendix S1 for further descriptions of the events).<sup>51–53</sup>

To avoid the inclusion of false bounces caused by resting places near the fences, we excluded data within the period of inactivity. An average hourly movement speed was calculated using the information from the 21 wild boars monitored by GPS-collars. The interpretation of this pattern allowed us to define the period of inactivity in our study area as being between 8.00 a.m. and 4.00 p.m. (Supporting information, see Fig. S3); sensitivity analyses showed no effects of period definition on the results obtained (data not shown). Finally, a temporal pattern for the movement of wild boars was observed.<sup>54,55</sup> To control the temporality, three periods were defined according to the availability of natural resources and hunting disturbances: (i) the food shortage period (hereafter, FSP) (from June 16th to October 15th), which includes the summer when resources become limited for wild boars in the Mediterranean ecosystem; (ii) the hunting season (from October 16th to February 15th), which comprises the regular hunting period in our study regions; and (iii) the food abundance period (hereafter, FAP) (from February 16th to June 15th), which includes the spring and the peak of births. Each event was associated to one of these periods.

We designed a generalized linear mixed model (GzLMM), binomial distribution and logit link function, to explore the differences due to: the type of fence (I–IV), sex (males, females), period (FSP, Hunting, FAP) and their interactions (sex\*period, sex\*type and type\*period) in relation to the crossing success, which is defined as the ratio between crossings (quick cross + trace-and-cross

and bounces (bounce + trace-and-bounce). Individual IDs were included as a random effect factor. The selection of the 'best model' was made using the corrected Akaike's information criterion (AICc).<sup>56</sup> Analyses were carried out using the 'lme4' R package.<sup>57</sup> A protocol for data exploration was applied and the assumptions were checked on the residuals of the model.<sup>58</sup> The statistical significance of the *P*-value was set at 0.05. Fisher's least significant difference test (LSD test) was used to check the differences among the levels of categorical variables retained in the model.

#### 2.4.3 Watercourses as crossing hotspots

Previous studies have reported that fences near watercourses constitute points of vulnerability for wildlife crossings.<sup>17,25,26</sup> We assessed whether the frequency of crossings was higher at watercourse intersections than expected by chance and whether its potential effect varied among the types of fence. The locations of the watercourses were obtained from the Guadiana basin cartography institute (Instituto Geográfico Nacional, IGR Hidrografía, www.ign.es). Firstly, crossings were plotted over the lines of fences to identify potential hotspots using the software QGIS version 3.6.<sup>59</sup> Then, we quantified the number of crossings around the intersection points between the watercourses and fences (see Section 2.4.1). We then randomly located the same number of intersections along the fences and quantified the number of crossings to compare whether the frequency of crossings at watercourses was higher than expected by chance (estimated from random intersections). The abundance of crossings around watercourses and random points was quantified as the number of crossings reported in a radius of 100 m around the point. Finally, a generalized linear model, Poisson distribution and log

link function, were parameterized to analyze any interaction between the presence of a watercourse (1 = watercourse intersection, 0 = random intersection) and type of fence (I–IV) relating to the frequency of crossings.

### 3 RESULTS

#### 3.1 Descriptive results

Of the fences characterized in the questionnaire, 117 fences (306 km) were available to our monitored individuals. We identified 1405 events around fences (922 quick-cross, 104 trace-cross,

247 bounce, 132 trace-bounce) during 1870 wild boar monitoring days, where wild boar crossings were detected for 73% of them. On average, a wild boar visited  $2.57 \pm 2.13$  estates and  $1.69 \pm 0.92$  land uses. Nine wild boars remained on the estate they were captured on throughout the overall study period (see Table 1). Regarding the temporal and seasonal patterns, of the interactions between our 21 monitored wild boar and fences (events), an average of  $32 \pm 29$  bounces and  $86 \pm 43$  crossings per month, and an average  $126 \pm 97$  bounces and  $343 \pm 158$  crossings per period, were reported (Supporting information, see Fig. S4). The highest values per month were observed in August and September for crossings

**Table 1.** Description of the types of events for each collared wild boar (ID)

ID	Visit estates	Land use <sup>a</sup>	Days	Number of events				Number of days			
				Cross	Trace-cross	Bounce	Trace-Bounce	Cross	Trace-cross	Bounce	Trace-Bounce
1	5	4	177	3	4	92	41	2	2	72	36
2	3	4	10	7	0	4	3	3	0	4	3
3	3	3,4	37	33	14	8	20	19	10	6	18
4	2	4	33	0	0	9	5	0	0	7	5
5	1	1	18	0	0	0	0	0	0	0	0
6	1	1	76	0	0	0	0	0	0	0	0
7	1	4	6	0	0	0	0	0	0	0	0
8	2	4	29	26	12	10	7	16	6	10	6
9	1	1	234	0	0	0	0	0	0	0	0
10	10	3,4	143	175	11	69	30	80	10	54	24
11	4	1,2,3	343	394	16	17	12	135	8	17	12
12	4	4	7	5	2	0	0	3	1	0	0
13	3	1,3,4	107	29	8	9	4	18	6	8	4
14	1	1	3	0	0	0	0	0	0	0	0
15	4	1,2,3	37	70	0	3	1	26	0	3	1
16	1	3,4	3	3	1	2	2	2	1	2	2
17	3	1,2,3,4	251	177	36	4	3	42	10	4	3
18	1	4	149	0	0	0	0	0	0	0	0
19	1	4	45	0	0	20	4	0	0	14	4
20	2	1,3	15	0	0	0	0	0	0	0	0
21	1	1	147	0	0	0	0	0	0	0	0
<b>Sum</b>			<b>1870</b>	<b>922</b>	<b>104</b>	<b>247</b>	<b>132</b>	<b>346</b>	<b>54</b>	<b>201</b>	<b>118</b>

The number of monitoring days, estates visited, and land uses exploited, the number of each type of event and the number of days experiencing each type of event are shown.

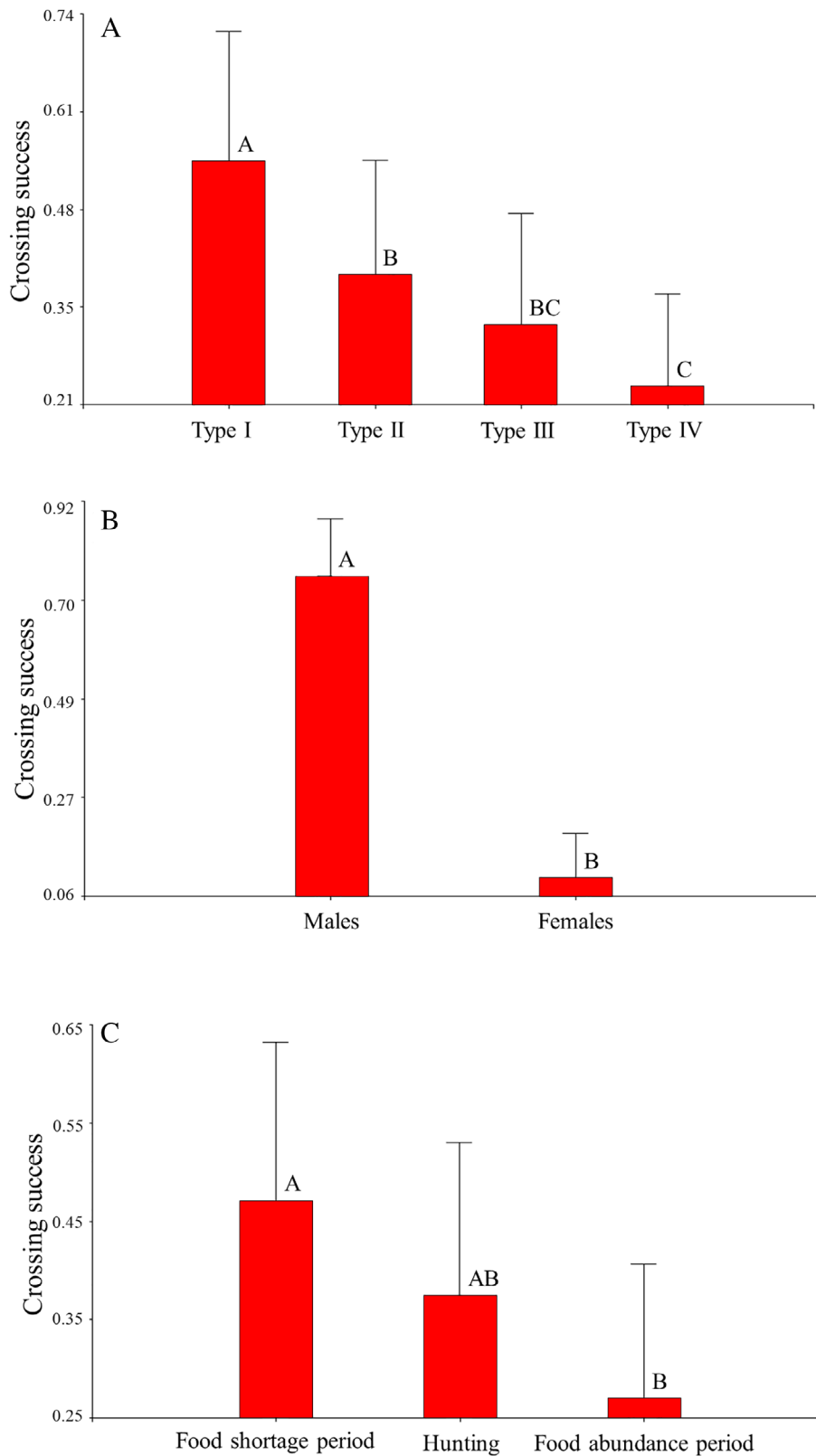
<sup>a</sup> Land use (1-protected, 2-agriculture, 3-livestock and 4-hunting).

**Table 2.** Final model to explain variations in crossing success regarding the: type of fence (Types I–IV), sex (males and females) and period (the food shortage period [FSP], the hunting season and the food abundance period [FAP]). Individual was considered as a random effect factor

Crossing success				
Model terms	Estimate	Std. Error	z value	P-value
Intercept	2.268	0.717	3.164	0.0016
Type II	−0.624	0.287	−2.169	0.0301
Type III	−0.915	0.385	−2.378	0.0174
Type IV	−1.326	0.451	−2.939	0.0033
Females	−3.357	1.311	−2.560	0.0105
Hunting	−0.404	0.247	−1.637	0.1016
FAP	−0.879	0.320	−2.747	0.0060

Parameter estimates for the level of fixed factors were computed by considering a reference value of for: level ‘Type I’ for type of fence; level ‘males’ for sex; and level ‘FSP’ for period.





**Figure 3.** Differences in crossing success (crossings/bounces) by: (A) type of fence (Types I–IV), (B) sex (males and females), and (C) period (the food shortage period, the hunting season, and the food abundance period). The letters represent the significant differences in crossing success between the different levels of each factor.

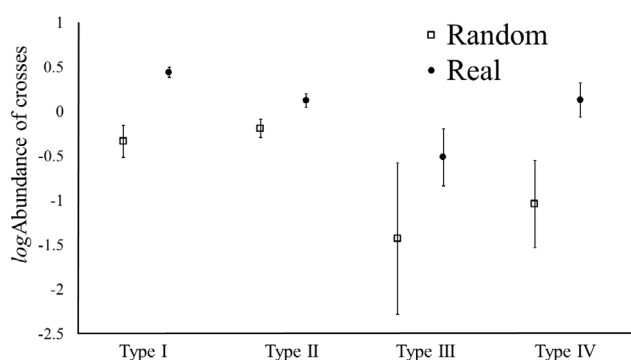
and in August and October for bounces, these months were grouped within the FSP. Therefore, the highest values per period

for both crossings and bounces were observed in the FSP, in comparison with the other periods.

**Table 3.** Final model to explain variations in the abundance of crossings regarding the interaction between the presence of a watercourse (Factor 1 = watercourse intersection, Factor 0 = random intersections) and type of fence (Types I-IV)

Abundance of crossings				
Model terms	Estimate	Std. Error	z value	P-value
Intercept	-0.780	0.213	-3.659	0.0002
Factor 1	1.786	0.224	7.980	<0.0001
Type II	0.336	0.245	1.371	0.1704
Type III	-2.516	1.023	-2.460	0.0139
Type IV	-1.618	0.616	-2.629	0.009
Factor 1* Type II	-1.065	0.269	-3.952	<0.0001
Factor 1* Type III	0.320	1.092	0.293	0.769
Factor 1* Type IV	0.899	0.658	1.366	0.172

Parameter estimates for the level of fixed factors were computed by considering a reference value of for: level '0' for factor and level "Type I" for fence.



**Figure 4.** Number of crossings at watercourses (real watercourse intersection and random intersections) as a function of the type of fence (Types I-IV).

### 3.2 Events at fences

According to the model selected, the crossing success was significantly related to the type of fence ( $F_{3,1400} = 3.19$ ,  $P = 0.023$ ), sex ( $F_{1,1400} = 6.54$ ,  $P = 0.011$ ) and period ( $F_{2,1400} = 5.00$ ,  $P = 0.007$ ) (see Table 2 and Fig. 3); not competing models were obtained with a  $\Delta AICc$  lower than 2 units (Supporting information, Table S4). Type I fences presented higher crossing success ( $0.54 \pm 0.17$ ) than the others. In addition, Type IV presented lower crossing success than Type II ( $0.24 \pm 0.12$  and  $0.39 \pm 0.16$ , respectively) (see Fig. 3(A)). The crossing success was higher for males than females ( $0.75 \pm 0.13$  and  $0.10 \pm 0.10$ , respectively) (see Fig. 3(B)), and in the FSP than in the FAP ( $0.47 \pm 0.16$  and  $0.27 \pm 0.14$ , respectively) (see Fig. 3(C)).

### 3.3 Watercourses as crossing hotspots

The number of crossings was higher around watercourses than at random intersections, although this effect was dependent on the type of fence ( $F_{18,2940} = 30.192$ ,  $P < 0.0001$ ) (see Table 3 and Fig. 4). Type III and IV presented the greatest differences in abundance of crossings between watercourses and random intersections. As expected, the number of crossings at random intersection points was higher for Type I and II than Type III and IV, although numbers were higher around watercourses at these fences, especially for Type I. Types III and IV presented a lower number of crossings at random intersections than Type I and II, and a higher abundance of crossings

near watercourses than at random points, especially for Type IV.

## 4 DISCUSSION

This study describes the permeability of the types of fences used in a mixed land use Mediterranean area. No fence design was 100% effective for wild boar; however, the well-maintained weekly revised big game proof type fence (Type IV) was the most effective at reducing the crossing success. Also, the crossing success varied significantly between sexes and periods, with higher values for males during the FSP. The effectiveness of the main fences in Mediterranean environments could be improved with better maintenance around the watercourses and, especially, during the FSP.

### 4.1 Events at fences

Previous studies have reported that livestock fences were effective in containing livestock, although they were permeable to wild ungulates.<sup>19,39,60</sup> Burkholder *et al.*,<sup>61</sup> reported a crossing success of 64.4% for deer relative to livestock fences, slightly higher than that observed here for wild boar ( $54 \pm 17\%$ ). Livestock fences were the most used type in agricultural areas for crop protection and on livestock farms to delimit pastures (Supporting information, see Table S3) in our study area. For this reason, the greater crossing success reported for this type of fence, and during the FSP, may well be relevant to farmers because of the damage to crops caused by this species.<sup>27</sup> For example, Apollonio *et al.*,<sup>62</sup> have estimated annual wild boar damage to agriculture in Europe as being valued at €80 000 000. In addition, the movement of wild boars across livestock farms is very relevant from an epidemiological point of view because wild boars represent a reservoir of shared infections.<sup>63</sup>

With regard to big game fences, previous studies have observed that a barrier's characteristics and its level of maintenance are the main factors in determining its permeability.<sup>17,19,20</sup> Accordingly, Negus *et al.*,<sup>39</sup> have stated that wild boar exclusion fences were more effective in reducing damage than livestock fences but only when the exclusion fences were well maintained, since wild animals make holes in fences to pass through them. This evidence reinforces our results where weekly revised big game proof type fence (Type IV) presented lower levels of crossing success than the poorly-maintained big game proof type fence (Type II). In our study area, big game fences, with different levels of crossing

success and maintenance, were the most used by hunting estates to contain big game species and in protected areas as perimeter fencing (Supporting information, see Table S3). The displacements between estates represent a high epidemiological risk for the transmission of shared multi-host infections,<sup>44,64</sup> affecting their main source of income, i.e. the exploitation of wild ungulates. However, the protected areas in our study area were delimited by Type II fences, whereas 43% of the perimeter around the hunting estates was a Type IV fence. The lower crossing success rate in the latter case indicates that hunting estates using a well-maintained big game proof type fence were safer in terms of spreading shared infections than protected areas. Nowadays, this information is essential in Europe where little scientific literature is available on the efficacy of fencing to control the spread of wildlife diseases.<sup>40,41</sup>

On the one hand, a higher level of crossing success was observed for males than females perhaps due to the longer displacements of males, especially during the hunting season and the FSP, recently reported in the same area.<sup>55</sup> However, we have not found any study that explicitly analyses the effect of sex on crossing success, although Lavelle *et al.*,<sup>38</sup> observed that of the seven wild pigs that escaped hog-panel fences, five were males. Previously, Hone and Atkinson,<sup>65</sup> did not observe any apparent effect of sex or age on the time taken by pigs to cross fences. Also, a higher rate of crossing success was observed in the FSP than in the FAP which coincided with the patterns observed in the number of crossings and bounces per month and period (Supporting information, see Fig. S4). The same pattern was observed by White *et al.*,<sup>27</sup> where wild pigs crossed and broke fences more intensively during the harvest period (September–October) when crops were ripe. Lombardini *et al.*,<sup>66</sup> have also reported that crop damage (e.g., vineyards, oat fields...) by wild boars were characterized by a peak incidence in the summer and early autumn (FSP), and a minimum in spring (FAP). In our study area, the harvest period is concentrated in June for rainfed crops and in September–October for irrigated crops (E. Laguna and J.A. Barasona, unpublished data). Our results suggest that increasing the monitoring and maintenance of fences during the FSP period may reduce the rate of successful crossing at these barriers.

Finally, well-maintained big game proof type fences presented less efficiency in containing wild boars than other electrified fence designs.<sup>38,65,67</sup> However, a significant effort and continuous surveillance is required in the latter case to prevent their deterioration and their cost is higher,<sup>65,67</sup> especially on a large scale and for a prolonged period. Nonetheless, a wild-boar proof fence must be buried to a depth of 20 cm or firmly anchored to the ground to prevent wild boars from lifting it up and passing underneath.<sup>68</sup> For instance, experts in ASF from EFSA concluded that the use of wild-boar proof fences is the biosecurity measure considered most likely to effectively reduce the risk of ASF introduction into outdoor pig farms where the single solid or double fences that are at least 1.5 m high must be fixed to the ground.<sup>42</sup> However, the installation of fences is regulated, and this type of fence is not allowed everywhere due to its potential effects on non-target species.<sup>69</sup>

#### 4.2 Watercourses as crossing hotspots

Previous studies have reported that watercourses constitute vulnerable points of fences, thus reducing their effectiveness.<sup>17,25,26</sup> For this reason, watercourses act as natural corridors for wild boars and are, therefore, frequently used by animals wishing to

cross them.<sup>4</sup> In addition, watercourses represent difficulties for fencing due to the seasonal oscillations in the water level and the pressure exerted by the water on the fence.<sup>70</sup> Therefore, farm managers should focus their efforts on reviewing these points, especially after heavy rains or prolonged periods of drought, to enhance the fence's effectiveness, as the vulnerability of a fence can be high at such locations. Despite fences fixed to the ground having been shown to be effective in containing wild boars,<sup>68</sup> and even if the regulations allow their use, special attention should be paid at their intersection with watercourses.

#### 4.3 Drawbacks of fences

Though fences can be a reliable solution to wildlife conflicts, there are some negative consequences of using fencing. For example, when ungulates are excluded from feeding in an agricultural field, they may simply shift to nearby unprotected areas thereby increasing damage.<sup>71</sup> Additionally, the habitat lost due to the exclusion of areas that were previously accessible may concentrate ungulates in smaller areas, potentially magnifying existing damage or exacerbating disease transmission.<sup>19</sup>

The rapid increase in fencing further highlights the importance of understanding its effects on nature.<sup>72</sup> Fences carry animal conservation costs (e.g., genetic drift, population isolation, an insufficient home range for large carnivores, cut migration routes, lower the carrying capacity of the landscape), since contiguous habitats are converted into islands.<sup>29,73</sup> Also, fences are built for specific species and purposes, and often achieve those purposes, although their effects on non-target species can create losers.<sup>10</sup> Nowadays, a relatively novel conservation tool aimed at mitigating these impacts is the use of wildlife-friendly fencing.<sup>74</sup> However, there is still an incomplete understanding as to how this tool affects, the movement of animals, and whether it increases habitat connectivity across barriers and future studies must fill these gaps.

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#### CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

#### DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

#### SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.



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