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Conservation strategies for endangered arable plant *Euphorbia gaditana*

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Abstract

Fragmentation and habitat loss are considered among the most important threats to biodiversity. More precisely, transformation of natural habitats into farmlands has been identified as one of the primary causes of plant species extinction. Therefore, understanding the effects of habitat fragmentation is crucial to the successful conservation of threatened species. Metapopulation modeling is one of the prospective tools used in conservation biology to evaluate long-term survival in fragmented landscapes. In this work, we applied a metapopulation approach to the conservation of the rare plant *Euphorbia gaditana* Coss., an endangered species growing on the margins of crops in southern Spain. The species is threatened due to herbicide application and intensification of cultivation, which results in a highly patchy distribution, with more than 50 patches of habitat across three separate networks of patches. We used IFM (Incidence Function Modeling) to compare the relative effectiveness of four conservation management scenarios and the effect of three threat scenarios on the risk of extinction of the species. The results of our simulations of population dynamics under plausible management scenarios will aid conservation decision-making, for example, allowing priority conservation areas to be identified or assessing the effect of future reintroductions.

KEYWORDS

arable plant, conservation, fragmentation, metapopulation, weed

1 | INTRODUCTION

Fragmentation and habitat loss are among the most widely reported biodiversity threats (Fahrig, 2003; Wilson et al., 2016). More precisely, the transformation of natural habitats into farmlands has been linked to the extinction of or threat to plant populations throughout Europe (Lang et al., 2021). However, some species have been able to adapt to arable ecosystems and substitute their natural habitats for artificial ones. These species are commonly thought of as weeds and traditionally have been considered a major problem for agriculture. However, recent studies have highlighted the benefits of these plants to both the environment and human well-being, and they are now valued as an essential element of agroecosystems (see, for example, Fagúndez, 2014).

However, scarce research has focused on the role of agroecosystems as habitats for rare weed species. Of particular interest is the case of rare endangered species for which arable fields have become an important secondary habitat due to the degradation of their natural habitats. Thus, a general trend in diversity loss in the weed community has been reported in recent decades, with many of the plant species typically inhabiting arable fields having severely declined (Storkey et al., 2012). Consequently, the number of studies addressing the conservation of threatened weeds has increased (Hulina, 2005; Lang et al., 2021; Pinke et al., 2011).

Global change in the form of agricultural intensification is affecting the stability of these agroecosystems. Once again, fragmentation and habitat loss are affecting the survival of species adapted to artificial habitats. Thus, habitat fragmentation in arable plants has been reported as a direct cause of rarefaction, low genetic diversity, and high extinction risk (Brütting et al., 2012; Le Corre et al., 2014; Petit et al., 2015).

In the face of this, there is an increasing need for knowledge with regard to management approaches for the conservation of threatened plant species, which depend on artificial habitats (but see, for example, Albrecht et al., 2016). The concept of metapopulation, defined as an assemblage of local populations existing in equilibrium between extinction and colonization, is central to determining the persistence of species in fragmented landscapes. Metapopulation modeling is one of the prospective tools used in conservation biology to evaluate long-term survival in fragmented landscapes (van Nouhuys, 2016). Among metapopulation models, the incidence function model (IFM) is one of the most commonly used to predict metapopulation dynamics because it only requires data on occupancy, patch size, and distance between patches instead of detailed demographic data, which unfortunately are not always available (Hanski, 1994). However, for many endangered plant species, the lack of long-term presence–absence data for model parameterization is the rule rather than the exception. Che-Castaldo and Neel (2016) developed a method to apply these models to such data-poor situations based on spatial data.

In this study, we applied this metapopulation approach to the conservation of the rare endangered plant *Euphorbia gaditana* Coss., an annual plant distributed throughout southern Spain (western Andalusia) and Northern Africa (Algeria and Tunisia). In Spain, the species is threatened due to herbicide application and intensification of cultivation, which results in a highly patchy distribution, with more than 50 patches of habitat across three separate networks of patches. By modeling the data based on extensive field surveys by the Environmental Agency of Andalusia, we compare the relative effectiveness of four conservation management scenarios and the effect of three threat scenarios on the risk of extinction of the species.

The results of our simulations of population dynamics under plausible management scenarios will aid conservation decision-making, allowing the identification of priority conservation areas or the effect of future reintroductions.

This approach may be exported to other similar data-poor endangered plant species living in non-natural habitats to inform all stakeholders involved in their conservation management.

2 | MATERIALS AND METHODS

2.1 | Species description, study site, and data

Euphorbia gaditana Coss is an annual plant species present in southern Spain and Northern Africa (Algeria and Tunisia). Flowering period is April and May and fruition from May to July. It is an allogamous species with generalist entomophilous pollination and authocorous and myrmecochorous dispersion (Gallego, 1999). The species is linked to clay soils (vertisols), living as a weed species on the margins of non-irrigated cultivated fields. Information about the species in Northern Africa is scarce. Nevertheless, in all revised herbarium labels, the species was collected in farmlands. We found only one specimen collected in maquis vegetation in Tunisia in 1933 (MNHN & Chagnoux, 2021).

E. gaditana is threatened by farming practices, such as the type of crops planted and the widespread use of herbicides. Dense crops where many plants grow close together (as in the case of cereals or sunflower) prevent the growth of any other plant species, including *E. gaditana*. This species is benefited by well-spaced and not very tall crops, as is often the case in garlic, beet crops, or cotton, which, in addition, are not treated with herbicides during the *E. gaditana* seedling development period (Junta de Andalucía, 2013). The species is listed as critically endangered (CR) in the Spanish National Red List of threatened species (Moreno, 2008).

The study area is located in the provinces of Seville, Córdoba, and Cádiz in Andalusia, southern Spain. The species has a patchy distribution with three independent networks of patches, each separated from the others by more than 40 km, and a recently discovered small isolated population in Cádiz (Figure 1). This last population is located at a distance of more than 39 km from the nearest network, hence it was not included in the analyses. The three networks are designated as *Cabezas*,

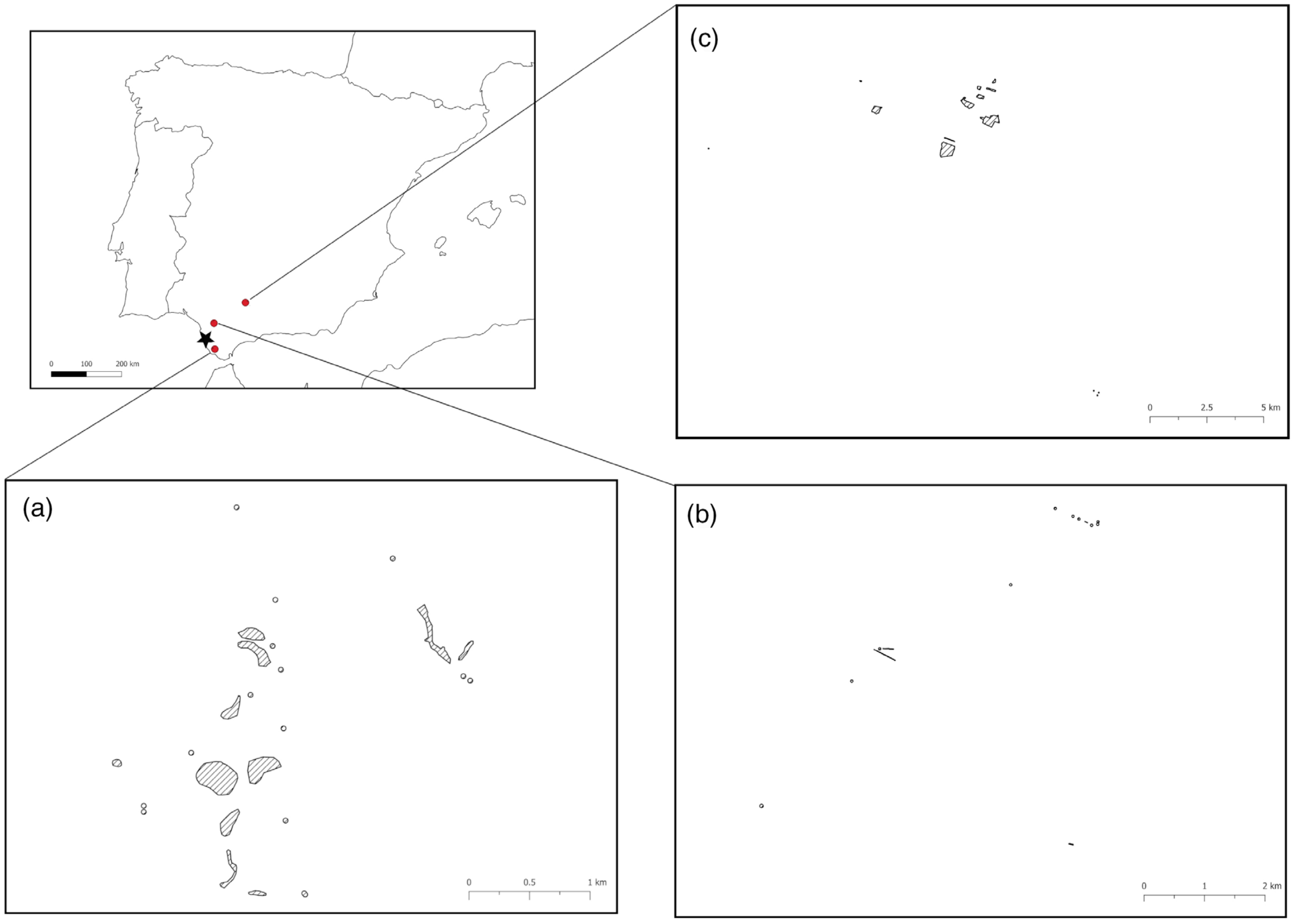

FIGURE 1 Location and distribution of patches of *E. gaditana* in Spain. a) Naveros, b) Cabezas, c) Écija. The location of the recently discovered small isolated population of *E. gaditana* is marked *

Écija (in Seville and-Córdoba), and *Naveros* (in Cádiz). The landscape consists of agricultural land dominated by crops of sugar beet cereals, sunflower, legumes, and garlic. The climate is typically Mediterranean, with a mean rainfall between 500 and 700 mm and mean annual temperatures ranging from 17 to 18°C (Gallego, 1999).

Data on *E. gaditana* distribution were provided by the Environmental Agency of Andalusia and the FAME project (Database of Threatened Flora of Andalusia; Mateos et al., 2010). The data, based on extensive field surveys, include patch sizes of all known habitat patches and distances between them, as well as conservation and risk assessments of every patch in the network.

2.2 | Model simulation and scenarios

We use the incidence function model (IFM) as a tool for conservation planning of threatened plants. The IFM is a stochastic patch occupancy model that allows the long-term persistence of a metapopulation to be evaluated by using presence/absence data (Hanski, 1994). The approach describes how the fraction of occupied habitat patches depends on patch areas and isolations at a dynamic equilibrium between extinctions (E_i) and colonizations (C_i). The incidence J_i in patch i is defined with the following equation:

$$J_i = \frac{C_i}{C_i + E_i - C_i E_i} \quad (1)$$

where E_i is the extinction probability of each patch i, which decreases patch area A_i:

$$E_i = min\left(1, \frac{e}{A_i^x}\right) \quad (2)$$

C_i is the colonization probability of each patch i:

$$C_i = \frac{S_i^2}{S_i^2 + y^2} \quad (3)$$

S_i is a connectivity measure, which is a function of the distance from patch i to patch j (d_{ij}), the occupancy (p_j) and the area of patch j (A_j):

$$S_i = \sum_{j=1}^{n} p_j exp(\alpha d_{ij}) A_j^b, \qquad j \neq i \, (4)$$

Parameter α is a constant, setting the species mean dispersal ability (1/α is the average migration distance, Moilanen & Nieminen, 2002), and e, x, y, and b are parameters estimated by the model.

Because we lacked presence–absence data over time to empirically estimate the parameters of the IFM, we followed the approach described in Che-Castaldo and Neel (2016). We set e to the smallest patch size observed for *E. gaditana* ($e = 0.03$ ha), assuming that patches smaller than these are not viable. By choosing parameter $\alpha = 0.0015$, we assume a negative exponential dispersal kernel with 95% probability of seeds dispersing within 2 km. We fixed the remaining parameters (x, b, y) based on published studies as in Che-Castaldo and Neel (2016).

2.3 | Scenarios description

IFM provides an effective tool to make predictions of the impact on metapopulation dynamics from varying area-related measures of patch structure. We apply it in a conservation planning context, to evaluate the effect of changes to distribution resulting from conservation strategies and habitat loss. For each patch network we considered eight contrasting scenarios. We first simulated the model under current conditions (Current, C). Then, we simulated four recovery scenarios according to possible recovery and/or reintroduction strategies within conservation plans: R1 = 20% increase in area for each patch; R2 = 20% increase in area only for the largest patches (patch area > 1 ha); R3 = 40% increase in area for all patches; and R4 = 40% increase in area for the largest patches (See Table 1 for details).

Similarly, to evaluate the effect of declining area, we designed another two threat or habitat loss scenarios: HL1, which involved a reduction of 20% in the area of each patch and HL2 with a 40% habitat loss. In addition, we simulated a severely fragmented scenario (SV). We removed all patches that were considered critically endangered by the Andalusia Plant Conservation technicians.

For each site (network) and scenario, we estimated two persistence measures of species that indicate metapopulation viability: mean occupancy and metapopulation capacity. Mean occupancy was calculated as the absolute number of occupied patches and also as the proportion of occupied patches after the simulation. Metapopulation capacity describes the ability of a patch network to sustain a metapopulation (Hanski & Ovaskainen, 2000).

We simulated patch dynamics for 100 time steps, 100 years, and calculated mean values across 1000 replicates for each conservation scenario. As a starting point for all the simulations, we assumed that all patches were occupied.

To determine the sensitivity of our results to parameter values, we performed models with a range of values for the different parameters of each model. Although the absolute mean occupancy and proportion of mean occupancy values changed, relative rankings of scenarios were unaffected.

All simulations and analyses were performed in R v4.0.3 (R Core Team, 2020).

3 | RESULTS

3.1 | Patch structure

A total of 53 patches were identified (Table 2; Figure 1). We found large differences in spatial distribution of patches between sites. *Écija* was the largest network with a

TABLE 1 Description of the 8 scenarios proposed for simulations

	Name	Abbreviation	Description
Conservation	Current	C	Current conditions
	Recovery 1	R1	Increase of 20% of each patch area
	Recovery 2	R2	Increase of 20% of patch area only in larger patches
	Recovery 3	R3	Increase of 40% of each patch area
	Recovery 4	R4	Increase of 40% of patch area only in larger patches
Threatened	Habitat loss 20%	HL1	Reduction of 20% of each patch area
	Habitat loss 40%	HL 2	Reduction of 40% of each patch area
	Severely fragmented	SV	Removal of critically endangered patches

TABLE 2 Summary of number of patches, mean patch area, total area and mean distance between patches of *E. gaditana* in the three locations (patch networks). We also included the number of patches per site resulting from a severely fragmented scenario (reduced number of patches)

Location	*Number of patches*	*Reduced number of patches*	*Mean area (ha) (min-max)*	*Total area (ha)*	*Mean distance (km) (min-max)*
Cabezas (Sevilla)	14	1	0.13 (0.03–0.246)	1.84	3 (0.041–7)
Écija (Sevilla)	14	10	6.15 (0.125–30.2)	86.16	7.9 (0.14–20.3)
Naveros (Cádiz)	25	21	0.9 (0.123–6.7)	22.09	1.5 (0.05–3)

total area of 83.16 ha in 14 patches, while *Cabezas* comprised only 1.84 ha distributed across 14 patches. *Naveros* was the most numerous and clustered network with 25 patches. The mean patch areas were 0.16, 6.15, and 0.9 ha in *Cabezas*, *Écija*, and *Naveros*, respectively, and median patch area 0.12, 1.49, and 0.13 ha. The mean nearest neighbor distance between patches was equal to 3, 7.9, and 1.5 km in *Cabezas*, *Écija*, and *Naveros*, respectively, with a maximum distance between any two patches of 7, 20.3, and 3 km.

3.2 | Incidence function model and simulations

All three systems *E. gaditana* had highest persistence under recovery conservation scenarios (R1, R2, R3, and R4), and lowest persistence under threat scenarios (HL1, HL2, and SV) both for mean occupancy and metapopulation capacity (Table 3).

When we compare these two persistence measures, proportion of mean occupancy and metapopulation capacity, under different scenarios from the three sites, we observed that, although *Écija* showed higher metapopulation capacities, simulations showed a higher proportion of occupied patches in *Naveros* in all cases. This is due to the fact that metapopulation capacity, which describes the ability of a species to persist in a given network of habitat patches, is especially sensitive to patch area, and the *Écija* network contained fewer but larger patches. There were no clear differences between scenarios when the area of all patches was increased or only that of larger patches. Measures of persistence (proportion of mean patch occupancy and metapopulation capacity) of *E. gaditana* in *Cabezas* indicated the species is close to extinction in this network, with a proportion of mean occupancy of 0.05 and a metapopulation capacity of 0.05 under current conditions. Moreover, persistence did not increase as a result of recovery scenarios.

An unexpected result was that simulations of severely fragmented scenarios (SV) showed very similar proportions of mean patch occupancy to those of current conditions, both in *Naveros* and *Écija*, which could reflect the removal of smaller and more isolated patches with low contribution to metapopulation viability.

4 | DISCUSSION

4.1 | Metapopulation scenarios of Euphorbia gaditana

As might be expected in the case of fragmented landscapes, our results indicate that habitat area is a key factor in assessing viability, with larger patches contributing more to overall stability than smaller ones (Fahrig, 2001; Fahrig, 2003). Thus, one important result of our analysis is the fact that future predictions do not differ regardless of whether patch size increases for larger patches only or for all patches in the system. Why is this so? It seems to us that regional persistence of this plant may be driven by a limited number of larger patches. In addition, present land use in these areas may be detrimental to the smallest patches of the system, which are less suited to coping with rapid changes in the size of fields and type of crop in the area. Consequently, results are the same when increasing the area of the biggest patches only as when increasing the area of all patches.

This finding is in line with the predictions made for the threat scenarios. Surprisingly, the worst results were obtained when proportionally reducing the patch area of all patches rather than when removing vulnerable patches from the system. Thus, the disappearance of the vulnerable patches does not contribute much to the fate of the metapopulations. In most cases, those small patches are represented by a handful of individuals living on road verges or at the corner of a crop field already disconnected from the system (See Appendix A, Figure 1).

We consider that recovery scenarios related to area increase are realistic and easy to assess. Nevertheless, increasing the area of occupancy for this species feasibly is difficult but possible. Future area acquisition to fulfill proposed recovery scenarios could be made through both conservation and agricultural policies, the latter being

TABLE 3 Simulated occupancy level—mean occupancy, as absolute number and proportion of mean occupancy, and metapopulation capacity of *E. gaditana* for the three-patch networks (*Naveros*, *Écija*, and *Cabezas*), in eight scenarios

	Mean occupancy			*Proportion of mean occupancy*			*Metapopulation capacity*		
Scenario	*Naveros*	*Écija*	*Cabezas*	*Naveros*	*Écija*	*Cabezas*	*Naveros*	*Écija*	*Cabezas*
Current	23.33	9.62	0.64	0.93	0.69	0.05	18.76	65.09	0.05
Recovery 1	24.17	9.90	0.77	0.97	0.71	0.05	27.01	93.73	0.07
Recovery 2	23.77	9.92	-	0.95	0.71	-	26.85	93.46	-
Recovery 3	24.22	10.07	0.95	0.97	0.72	0.07	36.77	127.58	0.09
Recovery 4	23.94	9.89	-	0.96	0.71	-	36.41	126.99	-
H Loss 1	22.22	9.54	0.49	0.89	0.68	0.03	12.01	41.66	0.03
H Loss 2	20.19	9.21	0.37	0.81	0.66	0.02	6.75	23.43	0.02
SV	19.46	6.95	-	0.93	0.69	-	18.48	56.34	-

more realistic. Two conservation tools are micro-reserves and recovery plans implementation. Micro-reserves are well established in other Spanish regions but not in Andalusia, so it is more reliable to set aside land for *Euphorbia* recovery and area increase using recovery plans enforcements. Spanish legislation allows to increase area protection for endangered plants provided that those plants have an official recovery plan approved by Parliaments. Nevertheless, we think that European Union's common agricultural policy (CAP) constitutes the optimal resource to increase conservation area for this plant. There are several budgets instruments related to farmland biodiversity conservation (Pe'er et al., 2020) that may provide conservation measures in agricultural land.

4.2 | Management options for fragmentation: Increasing size of patches or increasing number of patches

E. gaditana is a small annual plant growing in warm or semiarid exposures, with an above-ground ephemeral presence. These biological traits fit with a climatically fragmented arid environment, where patchy rain favors explosive population growth, undirected colonization propagules, and dormant stages waiting for new windows of opportunity for emergence (Salguero-Gómez et al., 2012). This situation may match to some extent the present anthropogenic fragmented landscapes in the Guadalquivir basin where the three networks of patches exist. Colonization events, land clearing, and vegetation gaps resulting from the agricultural use of the land may help to create new habitat patches or increase the size of preexisting patches. The existence and persistence of a seed bank also play an important role in plant metapopulation dynamics, contributing to the recolonization of extinct patches (Ouborg & Eriksson, 2004).

Generally speaking, the most widely accepted strategy to reduce fragmentation is to increase the size of existing patches or create new patches in the network. However, based on the results from the models, we propose that the fragments of suitable habitat in which the plant is currently absent, close to the larger patches of the species, should also be protected. This is particularly applicable to the *Ecija* network. Landscape heterogeneity is significant in this area. There are small forested ravines free of agricultural plowing scattered across the area and rolling hills. In addition, tree crops (olive groves) exist in the area (see Appendix S1, Figure 1). These plots of land provide greater patch heterogeneity, together with slightly less disturbance, and may contribute through colonization to increasing the size of existing patches in the future.

Small patches in the network may be signs of possible early colonization events or they may be remnants of larger habitats, which are now close to extinction. The former would appear to be applicable to the *Cabezas* network. This area was covered by marshland 60 years ago (Cruz-Villalón, 1988). Today it is a highly productive rice and sugar beet cropland. We think that, in this case, management should focus not on its role as a metapopulation but on its value for the general distribution of the species in the Guadalquivir valley. Further analyses, including genetic diversity, should be of help to ascertain the utility of this population. Nevertheless, we consider *Cabezas* to be a single manifestation of the high colonization and persistence capabilities of this plant. In this regard, remnant fragmented populations have been shown to play a significant role in maintaining the genetic diversity of a species (Young et al., 1996). For example, small fragmented populations of the rare endangered segetal plant *Anagalis foemina* have been reported to increase genetic variation among populations, highlighting the importance of the conservation of each population to preserve biodiversity (Kwiecińska-Poppe et al., 2020). In any case, as smaller patches are more sensitive to extinction, habitat loss in the future should be avoided at all costs in the *Cabezas* system.

Present land use distribution around populations should be considered in the conservation strategy for this plant. Thus, the *Naveros* network is the closest to surrounding natural landscapes of the three networks considered in this work. *E. gaditana* has not been found in Iberia growing outside its current agricultural habitat. Future studies are needed to determine the precise role of, on the one hand, past extinctions of natural populations and the lack of remnant natural habitats and, on the other hand, the man-mediated dispersion process that may be involved in the colonization of non-natural habitats such as those currently occupied. The fact that this critically endangered plant is growing in a weed community in a highly artificial and anthropogenic habitat may pose a conservation dilemma when managing non-natural fragmented landscapes and biodiversity. Should we aim to maintain the fragmentation as it is or should we try to reverse the system toward more natural settings? In our particular case, we must stress the need to increase prospecting and exploration of North African locations in order to discover any possible existence of natural populations. Recording of these findings will offer invaluable insights for future restoration initiatives for Iberian plants.

Finally, crop rotation and herbicide suppression are factors shaping the dynamic of the three-patch network in our study. The lack of herbicide treatments in *Naveros* may be related to the better metapopulation results in that area. Thus, we propose halting herbicide use in the areas adjacent to all known patches of *Euphorbia*. In addition, future management action for the species should take into consideration how crop rotation shapes patch size in our systems. Crop type and size could easily be included in *Euphorbia* monitoring schemes.

4.3 | Final remarks

We are aware that our study lacks certain parameters related to metapopulations, such as dispersal abilities, seed bank dynamic, or demographic parameters (Freckleton & Watkinson, 2002, 2003; Le Coz et al., 2019; Manna et al., 2017). Nevertheless, as we have shown, the models that we present here are useful to compare real spatial configurations as well as to gauge the predictions for different management scenarios. In this sense, metapopulation analysis has already proved to be a useful planning tool when limited demographic data are available (Che-Castaldo & Neel, 2016) and for habitat restoration projects when both time and economics resources are scarce (Halsey et al., 2017; Machinski & Quintana-Ascencio, 2016; Menges, 2008).

We stress the need for regional or national monitoring of endangered plant species to include measures that allow extinction and colonization rates, as well as dispersal ability, to be estimated. Basic data for red list plant species, such as improved knowledge and annual monitoring of the presence/absence of the species in each patch, are highly recommended for future fine-tuning of models, which in turn will allow better predictions to be made.

5 | CONCLUSION

This research work points to the utility of metapopulation approaches in the conservation of endangered arable plants. These species live in fragmented, non-natural landscapes and their population dynamics, very often, rely on anthropic management rather than natural processes. In our case, this approach helped us to identify what made populations vulnerable, and also to link spatial patterns to present human land use. In this regard, although this plant has shown the ability to grow in the most intensive, homogeneous crop lands (*Cabezas*), it seems that the least vulnerable populations, with better future prospects, are those associated with less intensive and heterogeneous landscapes (*Ecija* and *Naveros*). Conservation and management of threatened arable species is intrinsically linked to farmland management. In our case, less intensive land use, such as management associated with tree crops or farmland intermingled with wind farms seems to increase patch occupancy and metapopulation capacity for the conservation of this plant.

As conservation practices are always a priority, this analysis provides a tool for prioritizing our fragmentation management options, promoting protection of patch size or dispersal abilities or both, depending on the case and the results obtained.

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AUTHOR CONTRIBUTIONS

All the authors have made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data. They have been involved in drafting the manuscript or revising it critically for important intellectual content. They have also given final approval of the version to be published. Each author has participated sufficiently in the work to take public responsibility for appropriate portions of the content. All of them agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

DATA AVAILABILITY STATEMENT

The R script used to generate the analyses is available in the supplementary material of this article. Data are available at FAME database http://www.juntadeandalucia.es/medioambiente/servtc2/fame/login.jsp with the permission of the Andalusian Environmental Agency.

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