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This is a postprint version of the following published document:

The final publication is available at Springer via:

http://dx.doi.org/10.1007/s11056-015-9490-8

(Article begins on next page)

1 **Predation and aridity slow down the spread of 21-year-old planted woodland islets**

2 **in restored Mediterranean farmland**

3

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9

10 **Abstract**

11 Planted woodland islets act as sources of seed that may accelerate woodland

12 development in extensive agricultural landscapes. We assessed a 1-ha plot that was

13 planted with 16 100-m^2 islets of holm oak *Quercus ilex* subsp. *ballota* seedlings near

14 Toledo (Spain) in 1993. In spring 2014 we measured (1) acorn predation and (2)

15 seedling emergence from seeded acorns at different distances from and orientations

16 around the islets with half of the acorns protected to prevent predation, (3) survival of

17 emerged seedlings, and (4) natural tree establishment outside of the planted islets. Most

18 (96.9%) unprotected acorns were removed or predated. Seedling emergence from

19 protected acorns ranged from 42.9% on the northern side of the islets to 13.2% on the

20 southern side, suggesting a less stressful microclimate on the northern side. Survival of

21 naturally established seedlings was 28.6% by the end of first summer; seedling

22 mortality was chiefly due to drought (45.0%) and herbivory (35.0%). Density of

23 emerged seedlings, surviving seedlings after first dry season, and established oaks > 1-

24 yr old was similar at different distances from the islets. Over the 21 year time period, 58

25 new oak individuals >1-yr old have established (an average of 3.3 established

26 individuals per ha per year) at an average distance of 6.3 ± 5.4 m away from the closest

27 islet. We conclude that initial oak regeneration triggered by small planted islets in

28 Mediterranean abandoned farmland is slowed down by high acorn predation, seedling

29 herbivory, and stressful microclimatic conditions. Regardless, these islets are a viable

30 tool for regeneration of Mediterranean oak woodland.

1. Introduction

Natural forest regeneration or passive restoration of Mediterranean abandoned agricultural land is usually slow due to a number of limiting factors (Maestre et al. 2003; Bonet and Pausas 2004; Vallejo et al. 2006; Rey Benayas et al. 2008a). Key constraints on the speed of regeneration include (1) dispersal limitation because seed sources are remote and dispersal vectors may be rare (Rey Benayas et al. 2008a; Pons and Pausas 2007a; Zamora et al. 2010; Ramos-Palacios et al. 2014); (2) seed predation (Gómez et al. 2003; Gómez et al. 2008; Pérez-Ramos and Marañón 2008; Gómez and Hódar 2008; Leiva and Fernández 2013); (3) biotic limitation such as competition from established woody vegetation and herbaceous vegetation (Rey Benayas et al. 2005; Cuesta et al. 2010a), and herbivory (Gómez et al. 2003; Puerta et al. 2012); and (4) abiotic limitation such as low water availability, extreme temperatures, poor soil structure and low nutrient availability (Rey Benayas 1998; Cuesta et al. 2010b). Intensification of land use has brought remnant areas of natural or semi-natural vegetation into mainstream agriculture and as a result many of such areas have been lost or severely degraded. As a consequence, many agricultural landscapes, particularly those that are highly productive, lack parental trees or shrubs which severely limits seed availability, the first step for natural regeneration in circumstances where the socio-ecological dynamics promote abandonment (Pulido and Díaz 2005; Rey Benayas and Bullock 2012).

In actively farmed fields, strategic revegetation actions can include planting woodland islets (clusters of trees), hedgerows and isolated trees that have the potential to enhance wildlife, agricultural production, and other services at the field and landscape scales since they compete minimally for farmland use (Rey Benayas and Bullock 2015). Rey Benayas et al. (2008a) suggested a new concept for designing restoration of forest ecosystems on agricultural land, which uses small-scale active restoration as a driver for passive recovery over much larger areas. Establishment of "woodland islets" is an approach to designing restoration of woodlands in extensive agricultural landscapes where no remnants of native natural or semi-natural vegetation

exist. It involves planting a number of small, dense, and sparse blocks of native shrubs and trees within agricultural land that together occupy a small fraction of the area to be restored. This approach, also called "tree islands", "applied nucleation" (Corbin and Holl 2012; Zahawi et al. 2013), "dispersion and attraction nuclei" (García and Ferrer 2013), and cluster plantings (Stanturf et al. 2014), facilitates secondary succession by establishing small colonisation *foci*, while using a fraction of the resources required for large-scale afforestation. If the surrounding land is abandoned, colonists from the islets could accelerate woodland development through enhanced seed dispersal. Design of islets at a landscape scale benefits wildlife and provides the potential for larger-scale afforestation if the surrounding land is abandoned (Navarro and Pereira 2012).

We have been conducting an experiment on former cropland, where we introduced holm oak (*Quercus ilex* susbsp. *ballota* (Desf.) Samp.*,* hereafter *Q. ilex*) seedlings into 100-m^2 plots in 1993. *Q. ilex* is a late successional, slow-growing tree with high capacity of resprouting (Zavala et al. 2000). We found that, 21 years after the start of this restoration project, the planted woodland islets have grown in volume and produce large amounts of acorns (Rey Benayas et al. 2008b); however, the islets have not increased in area beyond the original planted surface of 100 m^2. Moreover, whereas a number of holm oaks of different size have established around the islets, there is a ca. 1.5-2 m wide border at the edge of the islands with minimal grass or herbs (**Fig. 1**).

In this study we assessed several demographic processes affecting early seedling recruitment around the woodland islets based on field experiments and long-term recruitment based on field observations. We hypothesized that biotic limitations (primarily acorn and seedling predation), and stressful microclimatic conditions (primarily water stress) would explain overall observed low initial natural regeneration in this system. It was difficult to predict the effect of distance to the islets on long-term oak establishment as a result of two opposing effects, namely more abundant acorn rain and facilitation but also more intense competition from established oaks for water and nutrients, as well as intense rabbit herbivory close to the islets (Bartholomew 1970). We expected high acorn predation for unprotected acorns (H1), highest seedling emergence and survival at the northern-oriented edges of the islets due to micro-climate amelioration by islet canopy (H2), and high predation of unprotected oak seedlings (H3). Results from this study will be particularly useful to practitioners and land use planners of woodland restoration projects in agricultural landscapes.

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2. Methods

2.1. Study site

The study site was located at "La Higueruela", a Consejo Superior de
Investigaciones Científicas research station in Toledo, central Spain (4º3'N, 4º24'W,
altitude 450 m). We ran our experiment on a 1 ha field on previous cropland which had
been cultivated for grain for many years until afforestation took place, and that was
surrounded by rain-fed cereal crops in a highly farmed landscape context. In 1993, 1-
year old *Q. ilex* seedlings were planted in 16 100-m^2 plots − the planted woodland
islets− at a density of 50 seedlings per plot and a spacing of 2 m between seedlings.
Mean distance separating islets is 11.8 m. Planted seedlings were subjected to
experimental management summer irrigation and artificial shading for three consecutive
years, after which time shading and irrigation were stopped and there was no further
management (Rey Benayas and Camacho 2004). Whereas the initial treatments affected
survival of oaks and hence the density of trees (Rey Benayas 1998), by the time of the
current data collection the overall cover of islets was similar across treatments (>90% in
all islets; see aerial photo in **Fig. 4**). At the time of the current data collection oaks in
the islets were at an average density of 41.9 oaks per islet and all oaks in the periphery
(i.e. at least 20 oaks in each islet) were producing abundant acorns. The climate is
continental Mediterranean, characterized by a long summer drought that imposes severe
water stress on the vegetation and cold winters. Total annual precipitation averaged
470.2 mm and mean temperature averaged 14.7 ºC during the 1993-2013 period. The
spring of 2014 was dry and total precipitation from the initiation of the experiment (24
February) through the last spring rainfall in 22 June was 64.1 mm), whereas average
precipitation for the same period since 2000 was 153.18 mm. The soil is a relatively
fertile, deep luvisol type, and derives from arkoses. The use of the land in the area is
mostly agricultural. Potential predators/dispersers of acorns and oak seedlings in the
study area are chiefly rodents (e.g. *Apodemus sylvaticus* L. and *Mus spretus* Lataste),
magpies (*Pica pica* L.), rabbits (*Oryctolagus cuniculus* L.), and hares (*Lepus europaeus*
Pallas) that shelter in the woodland islets. However, the European jay *Garrulus
glandarius* L., which is and effective acorn disperser in Mediterranean forests (Gomez
2003) is absent in this highly deforested area.

128

2.2. Predation and germination of seeded acorns

We seeded holm oak acorns in our experimental field around the 16 planted woodland islets on 24 February 2014. All acorns were from the Leonesa provenance region (NW Spain) and acquired at the Centro Nacional de Mejora Forestal "El Serranillo" (MAGRAMA). Prior to seeding, acorns were submerged in water for 12 hours and floating acorns were eliminated, as they were assumed to be dead or unfilled. A *posteriori* test resulted in 71.4% of acorn emergence. A total of 386 points were seeded, with five acorns buried at a depth of 3 cm at each seeding point. Seeding points were located along two 10-m long transects extending out from each of the four corners of every woodland islet (**Fig. 1S** in Supplemental material). Most seeding points were located at 0, 1, 5 and 10 m from the woodland islet edge. However, in some cases the distance between adjacent islets and between islets and nearby active crop fields impeded seeding at the 5 and 10 m distances; consequently, for these cases seeding points were located either equidistant between adjacent islets or at the edge of the experimental field. In total, 36 points were located between 1 and 5 m, 23 between 5 and 10 m, and 9 points were at 10 m.

One of the two seeding points located at the same distance of each woodland islet side was protected (**Fig. 1S** in Supplemental material) with a 25 cm plastic tree shelter buried 10 cm and topped with a 15-mm wire mesh to prevent access by acorn predators. This resulted in 193 protected seeding points and 193 unprotected ones. The protection of seeding points at the same distance from each woodland islet side was randomly assigned. Three protected and three unprotected seeding points were accidentally ploughed and lost from the experiment. We buried a 7-cm iron nail together with the unprotected seeding points to facilitate later detection with a metal detector. We monitored seeding points five times on 14 May, 4-6 June, and on 1, 6 and 19 July for acorn predation and seedling emergence. One third of emerged seedlings occurred after a late spring rain event (18 mm). As seeded acorns were not marked for radio-tracking, we were not able to assess where moved acorns were placed by dispersers.

157

2.3. Seedling survival

159   On 22 June, after seedling emergence ended, we carefully removed the plastic

160   protectors at half of the seeding points that contained at least one emerged seedling to

161   leave them unprotected from herbivores. For the other half of seeding points with

162   emerged seedlings, the tree shelter was replaced by a wire cage to prevent the micro-

163   climate effects by tree shelters on seedling performance (Puértolas et al. 2010; Oliet et

164   al. 2012). We monitored seedling survival six times, once every ca. 10 days starting at

165   the beginning of July and ending at the end of August, and a final time on 19 October

166   2014.

167

2.4. Natural early establishment of holm-oak

169   To assess natural establishment of holm oak seedlings during the 2014 growing

170   season, *i.e.* not from our experimental acorn seeding, we sampled 192 rectangular plots

171   and nine squared plots between the islets or between the islets and nearby active crops

172   to count seedling emergence in the spring of 2014 and monitor their survival through

173   the end of summer (mid-October). The rectangular plots were placed at the edge of the

174   woodland islets in all four orientations, two at each corner and one between them (**Fig.**

175   **1S** in Supplemental material). These plots were 1×5 m between adjacent islets or $1 \times$

176   10 m between islets and active crop fields. The squared plots between islets were 5×5

177   m. The 201 plots, which covered a total area of 1474.9 m^2 (i.e. 17.6% of the

178   experimental field area that was not occupied by woodland islets), were initially

179   surveyed once between May 17 and June 22 and later on July 6 and October 19 due to

180   rain events after the start of the first seedling counting and to account for final survival

181   after summer, respectively. The emerged seedlings in all plots were tagged for easy later

182   localization. The density of both dead and surviving seedlings in bands at different

183   distance to the islets (0-2, 2.01-4, 4.01-6, 6.01-8, 8.01-10 and > 10 m) was measured.

184   Recruitment within the islets was not measured as this study focuses on regeneration

185   outside the islets; additionally, the islets were very dense and shaded and visual

186   inspection hinted new established oaks in them were sprouts.

187

2.5. Mapping and size measurement of naturally established holm oak since islet

189   *planting*

190   All naturally established holm oaks, *i.e*. those at least 1-yr old, were located,

191   positioned with a GPS (Garmin DAKOTA 20) and mapped using high resolution

192   imagery taken by a drone-borne visible camera of 2×2 cm spatial resolution pixel that

193   produced an ortho-photo of the 1-ha experimental field. We measured their density in

194   the bands explained above and, for illustrative purposes, their height, basal diameter and

195   crown projected area (Rey Benayas 1998; Rey Benayas and Camacho 2004).

196

197   *2.6. Data analysis*

198   Acorn removal at unprotected seeding points was so high (H1, see below) that

199   we could not statistically test the effects of orientation and distance to the woodland

200   islets on this rate. All subsequent statistical analyses of seedling emergence and survival

201   in relation to orientation and distance (H2) to the islets are thus only based on the

202   protected seeding points.

203   We analyzed differences in seedling emergence using generalized linear mixed-

204   effects model (GLMM) with a binomial error distribution and a logit link function to

205   test the effects of the woodland islets (random effect), orientation and distance to the

206   islets and their interaction (fixed effects). Akaike's (1987) information criterion (AIC)

207   was calculated for each model; a smaller AIC indicates a better-fitting model as

208   determined from the parsimony in the number of parameters. We used the cutoff of

209   ΔAIC < 2 units to differentiate models with better explanatory power (*sensu* Burnham

210   and Anderson 2002). Likewise, we performed a binomial generalized linear model

211   including orientation, distance and their interaction based on previous results from the

212   GLMM to test specific hypotheses in relation to these factors (H2).

213   Seedling survival from seeded acorns (H3) or naturally established in the Spring

214   of 2014 was assessed by survival analysis based on a Cox's Proportional Hazards semi-

215   parametric model using the maximum partial likelihood as the estimation method (Fox

216   1993; Allison 1995). We correlated the volume (i.e., height $\times$crown projected area) and

217   distance to the closest planted woodland islet of the naturally established oaks > 1 yr old

218   since 1993. Finally, we tested the density distribution of naturally emerged and

219   surviving seedlings after the first dry season and of established oaks > 1 yr old at the

220   bands of different distance to the islets using contingency analysis. GLMM analysis was

221   performed with packages stats (R core team 2014) lme4 (Bates et al. 2014) and MuMIn

222   (Barton 2014) with R software v. 3.1.2. GLMs and survival analysis were carried out

223   with Statistica 7.0 (Statsoft. Tulsa, Oklahoma, USA).

224

225   **3. Results**

226   *3.1. Predation of seeded acorns*

227   Acorns were not found in 83.7% of the unprotected seeding points; these acorns

228   could have been moved or predated. Of the rest of the acorns, 13.2% were predated *in*

229   *situ* and only six (3.1%) out of the 190 unprotected seeding points remained with acorns

230   at the end of the spring.

231

232   *3.2. Seedling emergence*

233   At least one seedling emerged at 51 seeding points (13.5%), 49 of which were

234   protected and two were unprotected. However, only 6.7% of all seeded acorns with

235   protection produced a seedling. The two GLMMs that best explained seedling

236   emergence included the interaction between orientation and distance from the woodland

237   islet (AIC = 212.6; χ^2_3 = 14.12, p = 0.0028) and the orientation relative to woodland islet

238   (AIC = 213.9; χ^2_6 = 21.26, p = 0.0016), respectively, but distance by itself did not have

239   any effect χ^2_3 = 3.07, p = 0.38). Seedling emergence was highest (42.9%) on the

240   northern side and lowest on the southern side (13.2%) of islets.

241   We found 28 naturally established oak seedlings that emerged in 2014 (189.8

242   seedlings ha^{-1}). Mean distance of these seedlings to islets was 4.1 ± 2.7 m. Density

243   distribution of these seedlings did not show any significant pattern at different distance

244   to the islets (χ^2_5= 10.16, p = 0.07) (**Fig. 2**).

245

246   *3.3. Early seedling survival*

247   All emerged unprotected seedlings were predated (i.e. they were found with no

248   aerial organs) while survival of protected seedlings at the end of the first growing

249 season was 33.3% (protection effect $\chi_1^2 = 13.33$, p = 0.0003; **Fig. 3**). There was a peak of

250 mortality at days 41 to 51 that was much higher for protected than for unprotected

251 seedlings. Neither orientation ($\chi_3^2 = 3.03$, p = 0.39) nor distance ($\chi_3^2 = 2.1$, p = 0.83)

252 affected seedling survival, but sample size was low (n = 49) and the design was highly

253 unbalanced.

254   Survival of the 28 naturally established oak seedlings that emerged in 2014 was

255 28.6% by the end of summer (54.2 seedlings ha^{-1}), and it was independent of orientation

256 ($\chi_3^2 = 1.81$, p = 0.77) or distance ($\chi_4^2 = 2.97$, p = 0.56) according to the survival analysis.

257 Mean distance of surviving and dead seedlings to islets was 3.0 ± 3.0 m and 4.6 ± 2.5

258 m, respectively (differences in these distances were not significant, t-test p = 0.15).

259 Density distribution of emerged seedlings that survived after first dry season did not

260 differ among distance bands ($\chi_5^2 = 7.92$, p = 0.16). Thirty per cent of dead seedlings

261 dried out, 35% were predated when they were alive and 15% once dry, and for the

262 remaining 20% dead seedlings we could not conclude the cause of death.

263

264 *3.4. Oak establishment after 21 years*

265 Fifty-eight holm oak individuals >1-yr old that were developed from dispersed acorns

266 outside the planted islets have established in the experimental field after 21 years (**Fig.**

267 **4**), resulting in a density of 65.1 oaks per ha excluding the area occupied by the islets

268 with an average establishment rate of 3.3 oaks ha^{-1} yr^{-1}. Average distance of these to the

269 closest islet was 6.3 ± 5.4 m (5.8 ± 3.7 m excluding an outlier oak located at 35.7 m

270 from the closest islet), which is similar to half the average distance among islets (5.9

271 m). The density distribution of these established oaks did not differ among distance

272 bands ($\chi_5^2 = 5.75$, p = 0.33; **Fig. 2**). Height, basal diameter and crown projected area of

273 the established oaks averaged 49.2 ± 64.3 cm, 20.1 ± 31.3 mm, and 0.44 ± 1.09 m^2,

274 respectively.

275

276 **4. Discussion**

277

4.1. High acorn predation and low seedling survival

Our results clearly show that acorn predation is a major bottleneck for holm oak recruitment, consistent with our first hypothesis. Similar to our findings, Leiva and Fernández (2003) reported that only 0-2.4% of acorns escaped from predation in an oak savanna located in southern Spain, and Pons and Pausas (2007b) found that 98.7% of acorns were removed and/or predated by rodents in eastern Spain. Rodents and magpies are both predators and dispersers of acorns (Waite 1985), but rabbits and hares, which are abundant in our field site, are only predators (Zamora et al. 1985; Díaz et al. 1996; Leiva and Fernández 2003; Guzmán et al. 2008). We have clear evidence of acorn predation *in situ* for a small fraction of the unprotected acorns but suspect that most of the unfound acorns were either entirely consumed immediately after removal or re-cached and consumed later in other sites (Perea et al. 2011), as the farmland environment where our woodland islets are embedded may exacerbate predation. For instance, Gómez et al. (2008) found in the Sierra Nevada Mountains (SE Spain) that most caches were recovered and consumed, and only 1.3% of the original experimental acorns were found alive in caches the following spring. Likewise, in another experiment that we conducted for three years in old fields in central Spain with tagged acorns, we found that 100% of remobilized acorns were finally predated (Villar-Salvador and Pérez-Camacho, *unpublished data*). Other studies, however, have documented the spatial patterns and effects of long-distance oak dispersal at the landscape scale and hence the importance of isolated oaks as seed sources (Gómez, 2003; Purves et al. 2007). Acorn physical protection against predators is needed in Mediterranean environments to ensure oak establishment after seeding (Adams et al. 1992; Castro et al. 2015), as other methods such as chemical repellents have been shown to be unsuccessful (Leverkus et al. 2013).

We found low rates of seedling survival, consistent with previous studies on *Quercus* establishment in Mediterranean environments (Rey Benayas et al. 2005; Castro et al. 2006; Valdecantos et al. 2006; Del Campo et al. 2010, Cuesta et al. 2010a; Cuesta et al. 2010b). As we anticipated (H3), most of this mortality was a consequence of seedling predation; all of unprotected seedlings in the seeding experiment and at least 50% of the naturally established seedlings (which were not protected) were predated by the end of the first growing season. On the other hand, two-thirds of our caged seedlings and at least one third of the new naturally established seedlings dried out probably

311 reflecting mortality due to summer drought, which occurred quickly (**Fig. 3**). The

312 natural establishment rate we recorded in 2014 (54.2 seedlings ha^{-1}) is lower than those

313 we estimated from data reported by Pulido and Díaz (2005) in oak woodland (132

314 seedlings ha^{-1} yr^{-1}) and by García-Barreda and Reyna (2013) in gaps of a planted pine

315 forest (120 seedlings ha^{-1} yr$^{-1)}$, but higher than that found by Pulido and Díaz (2005) in

316 an oak savanna (2.8 seedlings ha^{-1} yr^{-1}). Gómez et al. (2003) also found that 98% of the

317 1000 experimental seedlings were killed by herbivores, notably wood mice, wild boar,

318 and domestic and wild ungulates.

319

320 *4.2. Low seedling emergence*

321 Seedling emergence was low when compared with results in previous studies of holm

322 oak. For instance, Smit et al. (2009) observed emergence values >90% while Pulido and

323 Díez (2005) observed 73% emergence in their study. Low emergence values in our

324 study are probably a consequence of the dry spring, particularly in the few weeks after

325 seeding. This idea is supported by the emergence peak after a late spring rainy event and

326 by the fact that emergence was highest at the sites with northern exposure where soil

327 desiccation is ameliorated in agreement with our H2 (Montero et al. 2008). Acorns are

328 recalcitrant seeds with their viability dependent upon relatively high water content

329 (Villar-Salvador et al. 2013); hence, *in situ* desiccation is an important cause of acorn

330 mortality (Joët 2013).

331

332 *4.3. Lack of distance effects*

333 The distance to woodland islets at small scales did not affect acorn predation and

334 seedling performance. Lack of distance effect on acorn predation is probably due to the

335 fact that our longest seeding distance (10 m) can be easily reached by all

336 dispersers/predators that may shelter in the islets (Pons and Pausas 2007b; Gómez et al.

337 2008). Similarly, we did not find higher seedling emergence at closer distances to the

338 islets where we expected higher emergence due to micro-climate amelioration by islet

339 canopy shade. This contrasts with results in Smit et al. (2009) showing higher

340 emergence in shaded microsites than in open microsites and suggests a lack of "safe"

341 microsites for recruitment in our experimental field (Pulido and Díaz 2005). It is

342 possible that microclimatic amelioration by islet canopy was not enough to maintain

343 high soil moisture during the dry spring, but we did not measure soil water content to

344 assess this explanation. The lack of distance effect on seedling mortality from herbivory

345 could be due to the fact that separation between islets is too small to detect a difference

346 in rabbit and hare movement (Gómez et al. 2008), but our observations suggest that

347 consumption of herbs by rabbits is much higher within 0-2 m of the edge of the islets

348 (**Fig. 1**). It is possible that there is a neutral balance between counteracting effects of

349 established islets on seedling establishment, namely microclimate amelioration

350 facilitating establishment near islets and competition with mature trees and herbivory

351 favoring establishment further away. A final possible explanation for lack of distance

352 effect on seedling emergence and early seedling survival is that we had insufficient

353 power to detect interactive effects between distance and orientation due to low sample

354 size and unbalanced design, due to high predation

355

356 *4.4. Initial woodland regeneration*

357 We recorded a natural establishment rate of 3.3 oaks ha^{-1} yr^{-1} along the 21 years of our

358 experiment, which in comparison with the figure of natural establishment found after

359 the first dry season suggests strong future mortality of recently established seedlings in

360 our field site. However, our woodland islets started to produce acorns seven years after

361 oak seedling plantation and seed production in the first reproductive years was small.

362 This means that the rate above will likely be higher and increase in the future. Leverkus

363 et al. (2014) found a natural establishment rate of 4.18 oaks ha^{-1} yr^{-1} at a post-fire

364 regeneration site in a Mediterranean mountainous environment with higher

365 precipitation.

366   We have investigated one case study to address the complex issue of outcomes

367 of relevant techniques, methods and approaches for large scale and long-term efforts for

368 landscape forest restoration (Stanturf et al. 2014). Three limitations of this study are that

369 it was conducted in only one site of 1 ha with planted oak islets, included only one year

370 of monitoring acorn removal/predation and seedling emergence/survival ,and did not

371 assess dispersal. On the other hand, the age of the introduced islets, the set of

372 recruitment stages and processes studied, and the singularity of the experimental design

373 provide relevant lessons for woodland restoration.

374   Acorn availability is a bottle-neck that limits vegetation establishment in

375 agricultural landscapes (Rey Benayas et al. 2008a; Rey Benayas and Bullock 2012,

376 2015), and this limitation was clearly overcome by the introduction of small woodland

377 islets that established successfully in our experimental field. These islets have triggered

378 holm oak regeneration that would have been high unlikely without nearby seed sources

379 (Gómez-Aparicio et al. 2009), but the rate of recruitment is limited by high acorn

380 predation, seedling herbivory, and stressful microclimatic conditions. Using tree

381 shelters against herbivores that also ameliorate climate harshness (Puértolas et al. 2010)

382 of the naturally established seedlings from acorns dispersed from planted woodland

383 islets would accelerate passive restoration of former cropland and pastureland. Thus,

384 planting woodland islets without further intervention seems not be sufficient to catalyze

385 "fast" initial recovery of Mediterranean woodland on abandoned farmland and

386 restoration will be resource intensive. "Success" or "failure" in restoration efforts like

387 the one investigated here nonetheless depends on the time frame of evaluation,

388 particularly in Mediterranean ecosystems where recruitment is notoriously episodic

389 (Moreno et al. 2011). Overall, we suggest that the woodland islet approach is a low cost

390 and useful technique to speed up woodland restoration in agricultural landscapes.

391

Acknowledgements

399

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Fig. 1. In our 21-yr-old experiment, it is noticeable that the planted islets have increased in volume, exported acorns and produced new established oaks (e.g. the one with red arrow to the right of the figure) but are confined to the original planted surface. Also note the area with minimal herbaceous vegetation immediately outside the islets edge (red arrow in the centre of the figure).
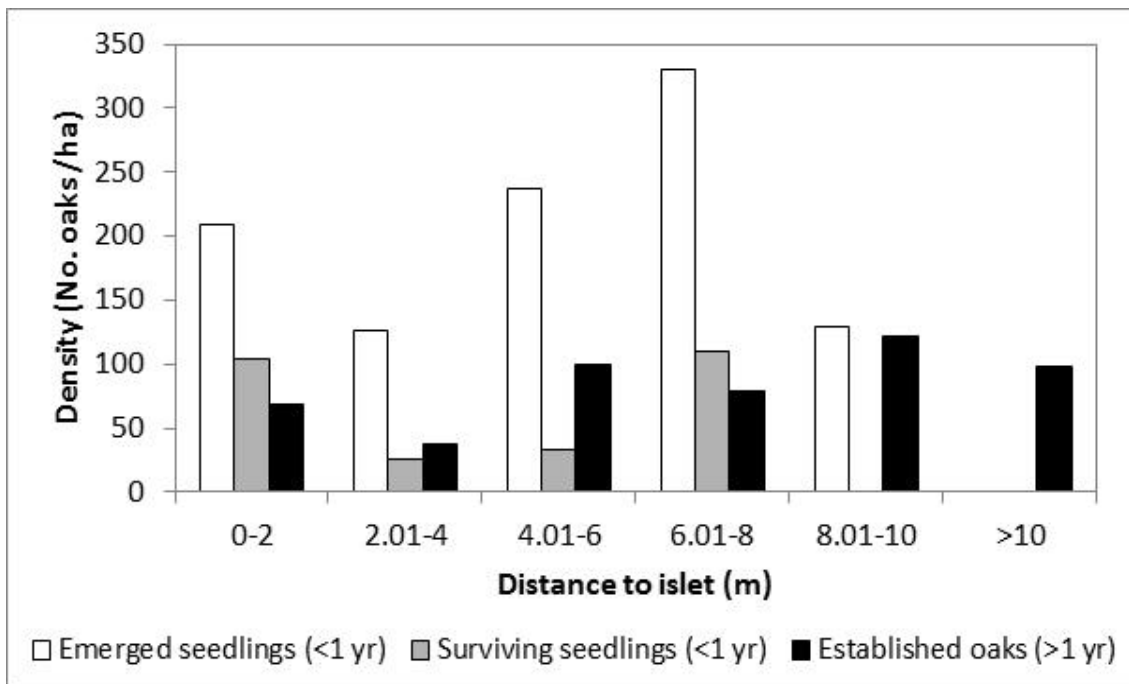
Fig. 2. Oak density (emerged seedlings in 2014, surviving seedlings after the first dry season, and established oaks > 1 year old) in 2-m width bands at different distance to the woodland islets.
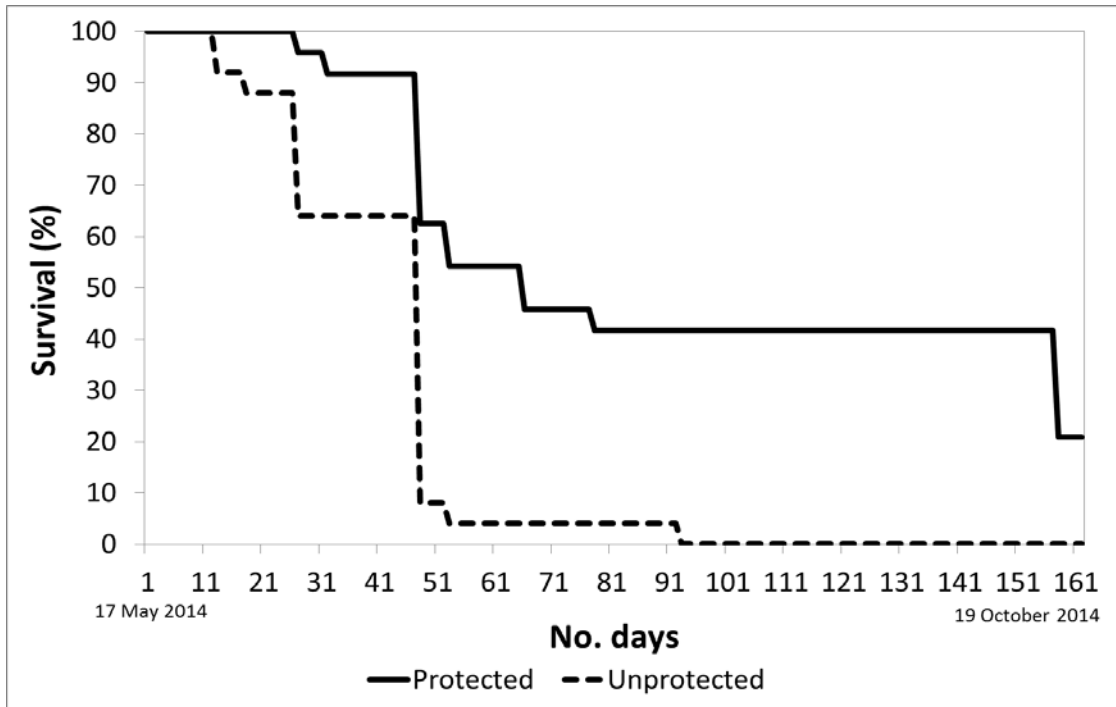
Fig. 3. Changes in survival probability of protected and unprotected *Q. ilex* seedlings through the summer and early fall of the first growing season. These graphs refer to the 31 emerged seedlings from seeded acorns that were monitored since May 17 2014 plus the 18 seedlings that emerged later.
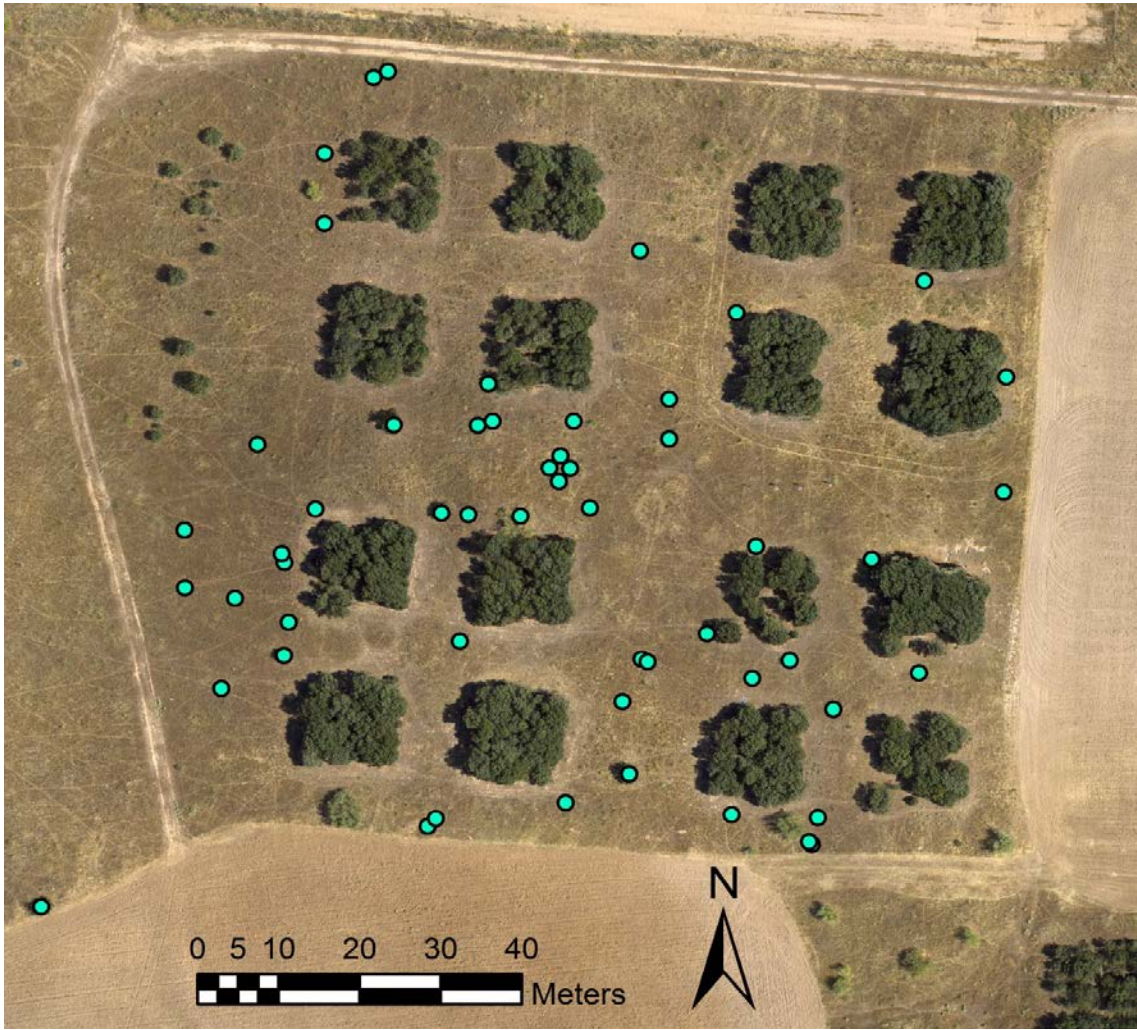
Fig. 4. Position of the 58 naturally established oaks > 1 yr old in the experimental field.
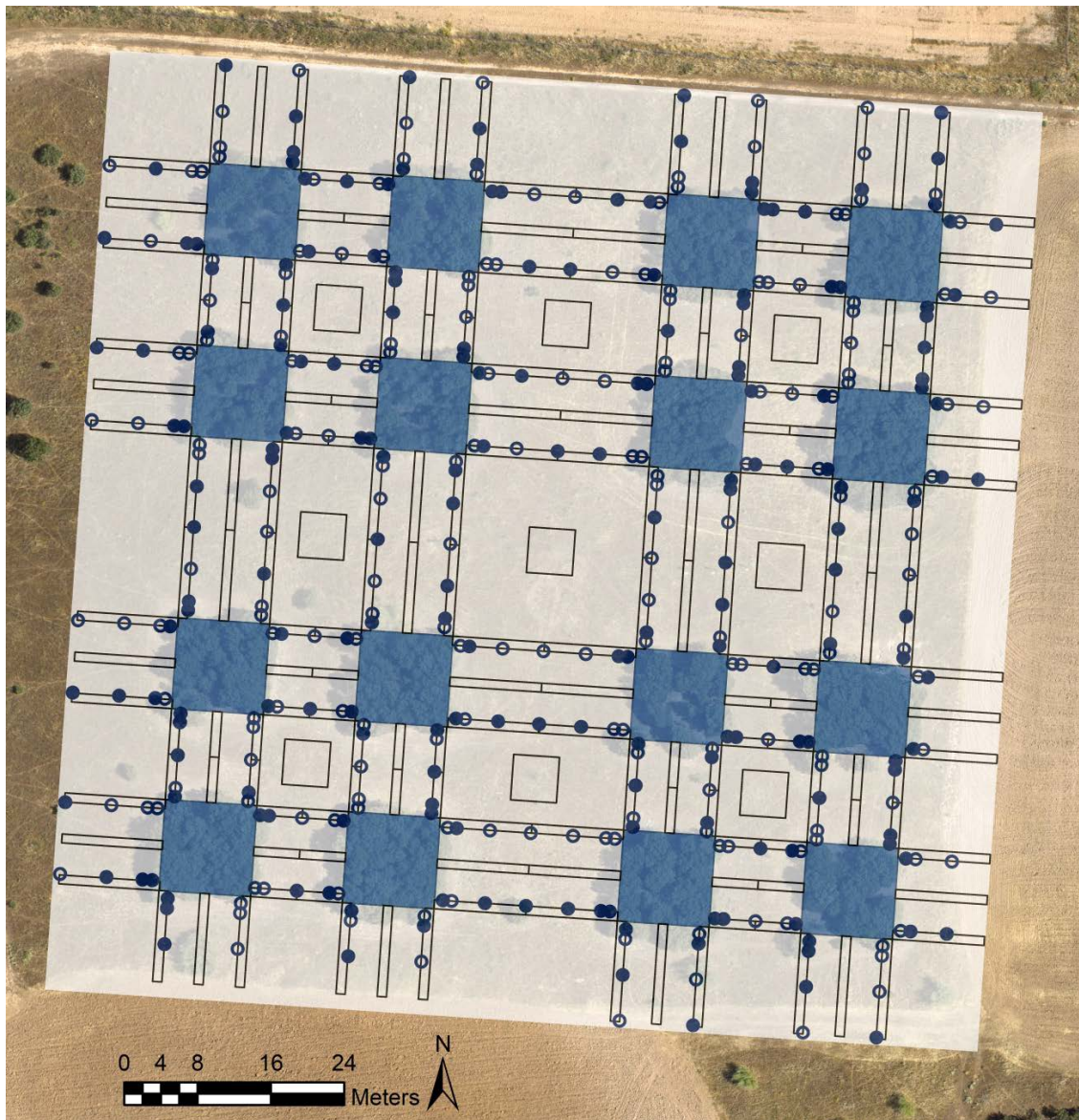
Supplemental material

Fig. 1S. Design of the seeding experiment and sampling for assessment of early natural establishment of oak seedlings. Position of (a) 386 acorn seeding points located along two 10-m long transects in each of the four corners of every woodland islet. Open and solid blue circles indicate unprotected and protected seeded acorns, respectively, at 0, 1, 5 and 10 m from the islet edge (see text for a few exceptions to these seeding distances); and (b) 192 rectangular plots and nine squared plots between the islets or between the islets and nearby active crops to count and monitor natural seedling emergence and early survival.