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ORIGINAL ARTICLE

Factors affecting the reproductive performance of barbary partridges in cereal croplands of Northwestern Morocco: the role of timing of breeding and vegetation cover at fine-scale

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Abstract

In Morocco, the barbary partridge (*Alectoris barbara*) is the major game species, highly valued by the nation's hunters. Until recently little was known about factors affecting reproductive parameters of this species on cereal croplands in North Africa. In 2018, 51 nests were found and analyzed across two agricultural areas of Northwestrn Morocco (AGR_1 and AGR_2). In this work, I assessed the relevance of a set of environmental and anthropogenic variables in predicting the clutch size and number of chicks hatched per nest, by means of generalised linear mixed models (GLMM). The average clutch size and hatching success per nest were 12.26 (± 0.57) and 9.26 (± 0.95), respectively. In the two sites, clutch-size increased as the date advanced, but was significantly larger in AGR_1 (13.17 ± 0.84, $n = 26$) than in AGR_2 (11.20 ± 0.70, $n = 25$). The number of chicks hatched per nest increased over time but also with the increase of the vegetation cover at fine-scale. Barbary partridge reproductive parameters were neither affected by landscape nor anthropogenic variables. I discuss these findings and their ecological, and future research implications. I recommended to pursuit the investigations, while considering imperatively the age/sex ratios and predation pressure.

Keywords Gamebird species · Cereal croplands · Clutch size · Hatching success · Morocco

Introduction

Effective wildlife conservation requires: (i) knowing and quantifing factors affecting reproductive parameters for proper and effective management of breeding populations, (ii) understanding population conditions, and (iii) assessing the degree of persistence of existing habitats (Newton 1979; Steenhof and Newton 2007). Information on these parameters are important when considering management of wild populations.

In North Africa, the barbary partridge (*Alectoris barbara* Bonnaterre, 1792) is a common sedentary breeding bird (Isenmann and Moali 2000; Thévenot et al. 2003; Isenmann et al. 2005) that is distributed from the Canary Islands to north-eastern Egypt (Foronda et al. 2005). The population is declining due to a combination of factors (Hanane 2018): (i) poaching (Alaoui 2001), (ii) hunting pressure (Madge and McGowan 2002; BirdLife International 2004), (iii) habitat degradation (Alaoui 2001; Madge and McGowan 2002; BirdLife International 2004), and (iv) predation (Alaoui 2001). In Morocco, the barbary partridge is the major game species, highly valued by the nation's hunters (Hanane 2018). In North Africa, barbary partridges are closely associated with cereal crops (Maghnouj 1983, 1990; Akil 1998; Alaoui 2001) which provide nesting and feeding habitats for adults and chicks (Reitz et al. 2002; Rodriguez-Teijeiro et al. 2009; Setchfield and Peach 2016). This habitat covers 5.4 million hectares in Morocco (12% of the land area). This agricultural environment is nonetheless risky, because of several factors such as pesticide use, harvesting operations, and increased mechanization (Faria et al. 2016; Ponce et al. 2018; Stanton et al. 2018).

So far, most studies on barbary partridges focused on breeding biology (e.g. Maghnouj 1983; Alaoui 1992; Akil and Boudedja 1996; Akil 1998; Alaoui 2001; Boukrabouza 2011; Mezerdi 2011, 2015) and more recently on nest habitat selection (Hanane 2018). Little is known about factors affecting the nesting success of this game species in agricultural landscapes.

The main objective of this study was to document barbary partridge nest success in two agricultural areas in Northwestern Morocco. We investigate how clutch size and

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nest success vary through the breeding season. Barbary partridge breed over a prolonged period (i.e. from March to July) and that timing of breeding may be trade-offs between climate (precipitation content), vegetation cover, and availability of food resources.

Materials and methods

Study areas

The study was conducted in two agricultural areas (hereafter "AGR_1" and "AGR_2") in Northwestern Morocco. These areas [AGR_1 (3000 ha) and AGR_2 (2139 ha)], 27.8 km apart from each other, are known to support important breeding populations of barbary partridges (Maghnouj 1983; Alaoui 2001). The climate is typically Mediterranean, with cool, rainy winters, and hot, dry summers (reaching, at times, 44 °C). The two sites receive 410 mm of mean annual rain, most of which falls during the winter rainy season (November–January). In these areas, the altitude ranges from 317 to 443 m a.s.l.. The landscape is mainly composed of two macrohabitats: cereal crops (80% in AGR_1 and 65% in AGR_2) and olive *Olea europaea* plantations (20% in AGR_1 and 10.6% in AGR_2). AGR_2 is also composed by 10% of bare ground, 8% of vegetable crops, while the rest (6%) is occupied by a cork oak forest *Quercus suber.* Cereal crops are dominated by wheat (*Triticum turgidum* and *T. aestivum*), barley (*Hordeum vulgare*), and common oat (*Avena sativa*). In this agricultural mosaic, single-family houses, mostly distant from each other (1.15 ± 0.41 km), are found in the vicinity of patches of cereal crops and olive orchards. In the two studied agricultural areas, the harvesting of cereal crops is conducted in May and June.

Data collection

Monitoring took place from the beginning of March to the end of August, during the breeding season in 2018. This period was chosen because most pairs are nesting at this time (Thévenot et al. 2003; Hanane 2018). Because the species is patchily distributed across the landscape and highly secretive, the nests were located with the help of local people (gamekeepers, game managers, wheat harvesters and shepherds). This choice was based on 3 criteria: (i) availability and agreement to collaborate; (ii) homogeneous distribution and daily presence in the field; and (iii) large knowledge of barbary partridge nesting habitats. Potential nest sites were therefore identified by field collaborators based on the daily research by recording all signs of partridges' presence (e.g., droppings, frequently used passages to enter the cereal vegetation, hissing of males). Once one of the signs found, further and deeper research allows locating nests. For each nest, I georeferenced the location and elevation using a portable GPS (Magellan eXploristXL). The overall clutch size was determined by checking the nest each week (to minimize observer induced disturbance), especially when the adult was not in the nest, until the stabilisation of the number of eggs. The laying date was determined by: (i) knowing the date of the first egg laid; and (ii) back-dating from the hatching date assuming that incubation lasts 25 days (Maghnouj 1983). The hatching date was determined by two ways: (i) presence of chicks at nests; and (ii) presence of recent (1–2 days) egg breaks (half-shells in each others). The number of chicks hatched per nest was determined by counting the number of chicks at hatching, and by dividing by 2 the number of recent half-shells found at nests. Eggs were considered abandoned when they are still present at nest after the expected hatching date. When eggs disappeared before this date with the presence of Eurasian magpie (*Pica pica* Linnaeus, 1758) in their vicinity, they were considered as collected by this corvid. In some cases, this was comfirmed by the direct observation of this collect.

Explanatory variables

In order to determine factors affecting the reproductive parameters of barbary partridges in cereal cropland landscapes, 16 variables were selected (Table 1) to be included as explanatory factors in the models. These variables were used because they can potentially influence the nest success of barbary partridges. For landscape scale, I used a 50 m-radius as demonstrated by Hanane (2018) in a Moroccan agroforestry system, while

Table 1 Description of variables used in the analyses of the breeding performance of barbary partridge in agricultural areas of Northwestern Morocco

Abbreviations	Descriptions
LD	Laying date
HD	Hatching date
DNT	Distance from nest to the nearest tree (m)
HVG	Maximum height of vegetation within 5-m plot (m)
VCV	% vegetation (cereals/herbaceous layer; estimated by the same investigator)
ELV	Elevation (m)
CCV	% Cereal fields (durum wheat, bread wheat and barley)
BCV	% Bare ground
OCV	% Permanent crops (olive orchards)
TCV	% Trees (others than fruit trees)
ECV	% Vegetation edge
UPCV	% Unpaved road (tracks)
DW	Distance from nest to the closest water point (natural or managed) (m)
DUP	Distance from nest to the closest unpaved road (m)
DH	Distance from nest to the closest human habitation (m)
DR	Distance from nest to the closest paved road (m)

for fine-scale, I used a 5 m-radius (Hanane 2018). At this latter scale, all variables were measured in the field at the moment when the nest was first located. This choice was dictated by the fact that vegetation height can drastically change during the nesting period. Landscape scale variables were all performed using QGIS except for the elevation, which was estimated using a global positioning system (GPS) device (Garmin eTrex HC).

Statistical analyses

As a first step, I checked for possible correlations among variables by using variance inflation factors (VIFs). To prevent multi–colinearity, the variables were tested with Variance Inflation Factor (VIF) Analysis (Quinn and Keough 2002). Variables with a VIF > 5 were removed as recomanded by Zuur et al. (2009).

To examine how clutch size and number of chicks at hatching vary according to explanatory variables, I used Generalized Linear Mixed Model (GLMM) with a Poisson error distribution and log link function. Sampling plot [15 squares (1000 x 1000 m) among the 30 available were randomly chosen in AGR_1 and AGR_2] was included as a random factor in the model to avoid pseudo-replication. The number of chicks hatched was fitted to models by including the log of clutch size as an offset in the model. GLMM models were ordered by increasing Akaike information criterion corrected for small sample sizes using AICc (Burnham and Anderson 2002). I considered all models with ΔAICc lower than 2 to be equally good (Burnham and Anderson 2002). Variance explained was calculated using the methods of Nakagawa and Schielzeth (2013). I therefore calculated marginal R^2 (which describes the variance explained by fixed effects) and conditional R^2 (which describes variance explained by the full model).

One of the assumptions of parametric statistics is that observations are independent of each other [mean distance to the nearest nest was 65.07 m (± 5.51)]. This assumption is often violated with spatial data, so it is important to test for and, where present, subsequently address spatial autocorrelation in data prior to data analysis (e.g. Cherkaoui and Hanane 2018). Nugget to total sill ratio (NSR) was expressed as the percentage of total semivariance and was used to define spatial dependency in the data: NSR < 0.25 indicated strong spatial dependence, 0.25 < NSR < 0.75 indicated moderate spatial dependence, and NSR > 0.75 indicated weak spatial dependence (Cambardella et al. 1994). When spatial autocorrelation was encountered, we used spatial generalised linearmixed models, fitted via penalised quasilikelihood (glmmPQL). glmmPQL enables the building of spatial models with dependent data that are not normally distributed, and is among the best techniques for this kind of data (Dormann 2007). We adopted a Gaussian spatial correlation structure, but tests with exponential and spherical structures led to the same results.

All statistical analyses were performed in R-3.0.2 software (R Development Core Team 2013). I used the package 'lme4' for fitting GLMMs (Bates et al. 2014), and package 'MuMIn' to calculate AICc (Bartoń 2015). The same package was used to calculate marginal and conditional R^2 via the function 'rsquared.glmm'. Packages 'sp', 'lattice' and 'gstat' were carried out to draw semivariograms (Pebesma 2006). The package 'MASS' was used to fit glmmPQL models (Venables and Ripley 2002). Finally, the package 'visreg' was used to plot graphs (Breheny and Burchett 2012). Means are quoted ± standard errors.

Results

During the 2018 breeding season, 51 barbary partridge's nests were located (descriptive statistics of the measured variables are summarized in Table 2). 26 nests were located in the AGR_1 and 25 in AGR_2. In these agricultural areas, the average clutch size and number of chicks hatched per nest were 12.26 (± 0.57, min = 7, max = 18) and 9.26 (± 0.95, min = 0, max = 18), respectively. The proportion of hatched nests was 70.6% (min = 0; max =100). 15.7% of nests have been predated by the Eurasian magpie, 9.8% abandoned due to cereal harvesting and 3.9% lost for unknown reasons.

The model that best described variation in clutch-size included the laying date (mean = 62.3 ± 3.84; min = 10, max = 110) and site (Tables 3 and 4, Fig. 1a). The average number of eggs per nest increased gradually as the date advanced in both sites. However, and although having a same pattern of increase, the clutch size was significantly larger in AGR_1 (13.17 ± 0.84, $n = 26$, min = 7, max = 18) than in AGR_2 (mean = 11.20 ± 0.70, $n = 25$, min = 7, max = 18) (Table 4,

Table 2 Descriptive statistics for variables (mean ± SE) measured at barbary partridge nests in agricultural areas of Northwestern Morocco

Variable	Min.	Max.	Mean ± SE
DNT	0.31	333.96	43.67 ± 11.39
HVG	0.44	2.98	1.09 ± 0.06
VCV	42.00	98.00	83.66 ± 2.17
ELV	317.03	443.10	389.97 ± 5.11
CCV	15.10	100.00	73.01 ± 4.65
BCV	0.00	10.15	0.58 ± 0.32
OCV	0.25	83.00	23.21 ± 4.90
TCV	0.00	20.11	1.26 ± 0.65
ECV	0.00	15.35	1.21 ± 0.51
UPCV	0.00	10.00	0.73 ± 0.24
DW	11.45	786.06	163.45 ± 24.28
DUP	3.228	500.81	108.31 ± 16.29
DH	43.59	797.71	214.01 ± 29.13
DR	596.10	4343.26	1504.40 ± 142.74

Table 3 Summary of the GLMM models describing barbary partridge breeding performance in agricultural areas of Northwestern Morocco. For variable acronyms, see Table 1

Breeding parameters	Models^a	k	logLik	AICc	ΔAICc	*wi*	R^2_{GLMMm}	R^2_{GLMMc}
Clutch size	Site + LD	4	−98.318	205.00	0.00	0.94	0.492	0.566
	LD	3	−101.132	211.30	6.39	0.04		
	Null model	1	−111.371	215.20	10.29	0.00		
Number of chicks hatched/nest	HD + log (VCV)	3	– 120.552	250.30	0.00	0.90	0.228	0.408
	Log (HVG)	2	– 123.240	255.70	5.40	0.06		
	Null model	1	−138.623	281.60	31.30	0.00		

Fig. 1a). The semi variogram, established from the residuals of the best GLMM model, indicates a spatial pattern in the data (Table 4). When I explicitly considered spatial autocorrelation in the modeling through the glmmPQL models, the effects of laying date and site were still significant (Table 4).

In accordance with the ΔAICc values, the most parsimonious model of hatching success included as explanatory variables the hatching date and local vegetation cover. The number of chicks hatched per nest was positively related to date (mean hatching date = 87.3 ± 4.35; min = 31, max = 135) (Tables 3 and 4, Fig. 1b) and local vegetion cover (Tables 3 and 4, Fig. 1c). Conversely to clutch size, I found no evidence of spatial autocorrelation in model's residuals (Table 4), which suggests that nearby nests have not the same hatching performance.

Discussion

In the present study I investigated the effects of local and landscape variables on the reproductive performance of barbary partridges in two agricultural areas in Northwestern Morocco. The results revealed that (i) clutch size was increasing over time in the two agricultural areas, but was larger at AGR$_1$ compared to AGR$_2$, and (ii) hatching performance (number of chicks per nest) was increasing over time, but also with the vegetation cover at fine-scale.

In these North African agricultural areas, we are in the presence of a gradually increase of barbary partridges clutch size over time. This pattern would be related to the presence of good breeding conditions during the months of May, June and July compared to March and April. In 2018, these two last months were relatively rainy with a total of precipitations of 156 and 128 mm, respectively. These climatic conditions would undoubtedly affect the adult conditions in the pre-reproductive period (Montagna and Meriggi 1991), thereby limiting the number of eggs lay per nest. In return, it is admitted that higher resources availability also lead to larger clutch sizes (Clifford and Anderson 2001; Evans et al. 2005; Spottiswoode 2009; Ong-in et al. 2016; Liu et al. 2018). This is the case of the majority of Moroccan agricultural areas where cereal harvests usually take places during May and June. This agricultural activity has however caused the abandonment of some nests (five in our case).

In addition, in summer, the weather is more settled than in March and April, thus insect availability is greater (Montagna and Meriggi 1991). These insects will serve as a feeding support for chicks at hatching (Enck 1987; Potts 2013). Generally, it seems that under good breeding conditions (less precipitations and availability of cereals) females of barbary partridge laid more eggs. Furthermore, it is also possible that breeding experience and age of partridges could play a role in this clutch size pattern. Indeed, young birds reproduce less well because they are limited by incomplete acquisition of

Table 4 Estimates of the best GLMM models fitted for barbary partridge breeding performance in agricultural areas of Northwestern Morocco. See Table 1 for variable acronyms

Breeding parameters	NSR		Non-spatial model (GLMM)				Spatial model (glmmPQL)			
			β-coefficient	SE	*z*-value	*p*	*β*-coefficient	SE	*t*-value	*p*
Clutch size	0.432	Intercept	1.400	0.301	4.652	<0.0001	1.350	0.295	4.576	0.0002
		AGR1	1.400	0.301	4.652	<0.0001*	1.350	0.295	4.576	0.0002*
		AGR2	−0.305	0.103	−2.949	0.0032*	−0.305	0.097	−3.142	0.0054*
		LD	0.008	0.002	3.468	0.0005*	0.008	0.002	3.696	0.0015*
Number of chicks hatched/nest	1.000	Intercept	−8.315	1.841	−4.516	<0.0001				
		HD	0.009	0.002	3.115	0.002*				
		Log (VCV)	1.619	0.415	3.898	<0.0001*				

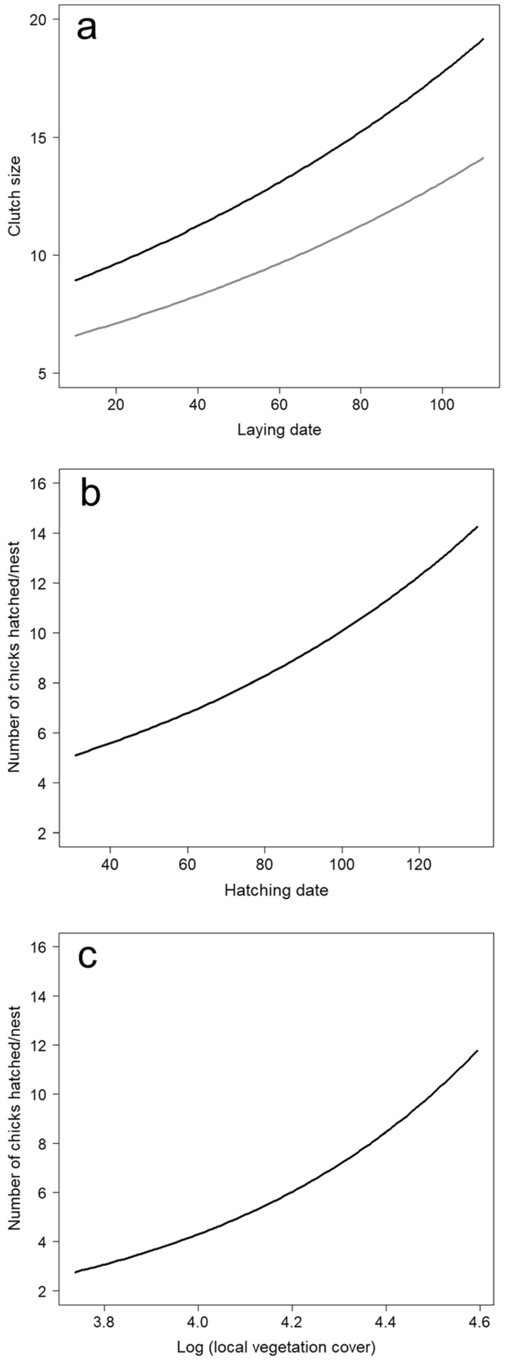

Fig. 1 **a** Relationship between the clutch size and laying date in AGR1 (black line) and AGR2 (grey line). **b** Relationship between the number of chicks hatched per nest and hatching date. **c** Relationship between the number of chicks hatched per nest and vegetation cover at fine-scale

necessary skills (such as foraging), or incomplete physiological maturation (Fowler 1995). Juvenile individuals are more vulnerable than adults to various threats probably because of their inexperience (e.g. hunting, predation, Guillemain et al. 2013; Fox et al. 2015; Souchay et al. 2018). So it is likely that, in early season, those are mostly the young partridges (less experienced) that breed, while those are the old partridge (more experienced) that breed from the beginning of summer. These latters would thus wait until the presence of good conditions to invest in reproduction.

Although having a same pattern in clutch size over time, this parameter was significantly larger in AGR$_1$ compared to AGR$_2$. The difference in clutch size between these two sites would likely be related to breeding conditions which, at first glance, would be better in AGR$_1$ compared to AGR$_2$. With the presence of the Eurasian magpie in both sites, it is more possible that we assist to a more pronounced predation pressure in AGR$_2$ compared to AGR$_1$. However, I doubt this is a sufficient explanation for the pattern in clutch size I found, to the extent that there is an increase in clutch size over time. Overall, the literature mentions the negative effect of predation pressure (nest predation rate) on the clutch size (Hořák et al. 2011) as well as on population's spatial dynamics (Fuller et al. 1995; Robinson et al. 1995; Gruychev 2012). Another possible explanation is that there is a difference in the population age structure between AGR$_2$ and AGR$_1$. This latter site would be occupied by more young than would be the AGR$_1$ (more adults) which can affect their physiology and behaviour (Nadal et al. 2018). Further studies should clarify this and consider the young/adult ratio variable in the analysis, which may improve the value of age ratio in explaining between sites variations in partridge clutch size.

Results of our modelling approach also reveals that the hatching performance increases as the breeding season advances in the two sites. The same hatching temporal pattern was also recorded for two other patridge species, the grey partridge (*Perdix perdix* Linnaeus, 1758) and red-legged partridge (*Alectoris rufa* Linnaeus, 1758), by Potts (1980). The food availability from May (after cereal harvest) but also the improvement of the climatic conditions would undounbtedly explain this upward trend in the number of chicks hatched per nest. Several authors (Green 1984; Potts 1986; Montagna and Meriggi 1991) have announced the presence of a high chick mortality in cold and rainy springs, and when the availability of insects is reduced. This fits perfectly with our case where March and April months were very rainy. The absence of the site effect in explaining hatching performance corroborates this hypothesis. It is very likely that both the intensity of predation and food resource availability were virtually identical in the two agricultural areas, not allowing thereby to bring out an effect of site. The hatching success was positively associated with vegetation cover at fine-scale. Vegetation cover is undeniably a key factor for barbary partrige's nesting success (Maghnouj 1983), but also in other partridge species such as the red-legged Partridge (Ricci 1985; Ricci et al. 1990; Casas et al. 2009), and grey partridge (Bro et al. 2000). In Finnish agricultural landscapes, Krüger et al. (2018) have reported an increase of nest survival as days passed in another galliform's species, the common pheasants (*Phasianus colchicus* Linnaeus, 1758). In studying nest survival of mixed-grass prairie passerines, Davis (2005) suggests that increased concealment due to vegetation growth may be a positive factor for certain species. The barbary partridge would a priori be one of these species that greatly benefit of vegetion cover at fine-scale. In addition, according to Ponce et al. (2018), the presence of high vegetation in the vicinity of the nest is a factor contributing to reduce nest predation. Overall, in birds, dense cover crop fields in spring may be an attractive breeding site (Wilcoxen et al. 2018).

In summary, the availability of cereals and the improvement of weather conditions would, at least partly, explain our results in both regarding the clutch size and hatching performance. However, the explication share of each of them is not known and quantified, as well as for other factors that could play a role such as the age/sex ratios and predation pressure. Research programs should be continued in order to deeply and urgently assess the role played by the population age/sex structure and predation pressure. This will be valuable in improving our understanding on the processes in which barbary partridges cope with prevailing abiotic and biotic conditions in North African cereal croplands to have good reproductive performances.

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Compliance with ethical standards

Conflict of interest The author declares that he has no conflicts of interest.

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