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Effects of rainfall and temperature on timing and breeding performances of a threatened large falcon: case study of the lanner falcon (*Falco biarmicus feldeggii*) in Italy

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Abstract

The use of environmental cues such as temperature and rainfall for the timing of breeding and as an indicator of plentiful food much later in the season is thought to have a great influence on breeding success and productivity rates. We tried to assess effects of such cues on timing and performance of the lanner falcon (*Falco biarmicus feldeggii*), a threatened large falcon in Italy. We ascertained success and productivity of 178 breeding attempts in 38 breeding sites distributed in central Eastern Sicily and along the Apennine peninsula. In Sicily alone, we checked each nest annually to ascertain the number and age of chicks and also post-hatching mortality. We overlaid nest locations in order to add attributes of temperature and rainfall for each month and year. Breeding populations from Sicily to the Apennine peninsula showed no significant difference in all breeding parameters except distribution of brood size. Annually, breeding pairs tried to synchronize the hatching in a precise favourable period that increased nestling survival. February rainfall was the main abiotic factor that greatly influenced all lanner falcon reproductive parameters with a positive effect as cues for breeding decisions by parents. Conversely, intense rainfall caused nesting failure through a delay in laying dates. Our study confirmed the importance of environmental cues such as temperature and rainfall on breeding decisions by lanner falcon pairs inhabiting the whole Italian territory. We discuss our results and compare them with prior studies in terms of their potential conservation implications for this threatened subspecies.

Keywords Avian predator · Environmental cues · Productivity · Post-hatching mortality

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Introduction

Reproduction is costly, and individuals that invest too much in a given reproductive bout pay with reduced reproductive output in the future (Sockman et al. 2006). To minimize the reproductive costs, the precise timing of reproduction is a crucial factor (Davies and Deviches 2014). The time-lag between the start of reproduction and the chick-rearing phase forces parents to begin the breeding period well before environmental conditions are optimal for feeding young (Dunn 2004; Davies and Deviches 2014). If the photoperiod synchronizes the endogenous system to lay within an annual reproductive window (Snelling 1973; Dunn 2004), other factors such as weather conditions (Meijer 1989; Daan et al. 1990; Meijer et al. 1992; Carrillo and González-Dávila 2010a) are probably involved too in tuning the timing more finely.

Several studies conducted in either cold or temperate regions have investigated the effects of local weather conditions on the reproductive performance of raptors (Olsen and Olsen 1988;

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1992; Kostrzewa and Kostrzewa 1990; Bradley et al. 1997; Rodríguez and Bustamante 2003; Anctil et al. 2014). Indeed, a significant direct relationship between local weather and average productivity rates of falcons was found only in a few cases (Olsen and Olsen 1989; Kostrzewa and Kostrzewa 1990; McDonald et al. 2004). Unpredictable adverse weather conditions may be a direct cause of nestling mortality, but indirect effects of temperature and rainfall seems to drive breeding population performances in many avian species (Kostrzewa and Kostrzewa 1990; Williams et al. 2015). Accordingly, rainfall and temperature oscillations between the egg-laying period and the first week after hatching appear to have a strong influence on the reproductive outcome (Olsen and Olsen 1988; Ratcliffe 1993; Jenkins 2000; Costantini et al. 2010; Mihoub et al. 2012). Environmental cues can be used to predict when food will be plentiful for the offspring much later in the season and to decide the onset of breeding accordingly (Mihoub et al. 2012; Williams et al. 2015; Imlay et al. 2018; Huchler et al. 2020).

Lanner falcon is an Afro-tropical and Mediterranean polytypic species with five recognized subspecies including the threatened European *Falco biarmicus feldeggii* Schlegel, 1843 (del Hoyo and Collar 2014; Gill et al. 2021). Listed as an endangered species in Annex I of the Birds Directive and classified as endangered in the Red List of European Birds, *Falco biarmicus feldeggii* has its European stronghold in Italy (Andreotti and Leonardi 2007; Birdlife International 2015). In this country, lanner falcons breed exclusively on cliffs and its whole breeding population consists of ca. 60 breeding pairs (bps) in the Apennine peninsula and ca. 70 bps in Sicily (Nardelli et al. 2015). One of the most controversial aspects regarding lanner falcon biology is the size of population demes and especially their resilience in response to human disturbances and adverse environmental conditions (Andreotti and Leonardi 2007). In fact, traditionally, the apparent size of the Sicilian population was greatly overemphasized when compared to the Apennine peninsula (Andreotti and Leonardi 2007). Recent studies on this island revealed that population density is non-random, indicating a preference for arable lowlands and grasslands (Amato et al. 2014; Sarà 2014, Di Vittorio et al. 2015). Indeed, breeding sites with high frequency of occupancy and low terrain complexity showed a significant increase in productivity (Amato et al. 2014). Inversely, other studies emphasized a strong decrease in productivity in the last years (also attributed to eggs and chicks theft; Pezzo et al. 2016; Di Vittorio et al. 2017). Nevertheless, a lack of a comprehensive review on breeding performance and potential environmental constraints on breeding distribution in Apennine peninsula persist until today.

The main aims of this study are: (1) to evaluate possible differences in breeding parameters in relation to different lanner falcon population sizes, (2) to ascertain post-hatching mortality and (3) effects of temperature and rainfall on breeding decisions made by breeding pairs. Finally, we compare the results with those of previous studies for their potential conservation implications.

Materials and methods

Study areas

Along 15 years of surveys (2000–2014), we collected data on the breeding parameters of 38 nest-sites of the lanner falcon in two large sample areas in Italy (Online resource 1: Fig. S1; Table 1). In the Apennine peninsula (central Italy 43°45'-41°42' N, 12°02'-15°91' E, Online resource 1: Fig. S1, B1-B3), we monitored three sub-sample areas: B1 (Marche) 5 sites during 2000–2013 (average 10.2 years per site), B2 (Latium) 7 sites during 2000–2014 (average 6.3 years per site) and B3 (Molise and Gargano) 10 sites during 2006–2014 (average 3.8 years *per* site). In central eastern Sicily (southern Italy, 37°82'-37°17' N, 13°80'-14°96' E, Online resource1: Fig. S1, A), we checked 16 sites during 2003–2006 (average 2.8 years per site; Table 1).

Overall, our sample size represents ca. 19 % of the lowest estimate of the whole Italian population (ca. 130–150 bps), accounting for 18 and 23 % of the pairs breeding in the Apennine peninsula and in Sicily, respectively (Andreotti et al. 2008; Leonardi 2015).

These sample areas are characterised by different habitat composition. In the Apennine peninsula the three sub-sample areas lie at a lower altitude, ranging from 107 to 768 m above sea level. Most of the breeding sites are surrounded by fragmented deciduous forests with relatively few open areas, especially abandoned grazing lands and badlands, whereas others are located on scrubland moors or non-irrigated arable land (De Lisio et al. 2006; Brunelli and Sarrocco 2012; De Rosa et al. 2015). In Sicily, the study area consists of flat terrains alternating with moderately steep hills ranging from 209 to 1062 m above sea level. Dominant habitats consist of pasturelands and extensive cereal fields, giving way to shrubs and wood remnants at higher elevations (Sarà 2014). Throughout the Sicilian range there are several different orchards, comprising mainly olive and citrus groves (Amato et al. 2014).

Nest monitoring and breeding productivity data

We monitored each site annually to ascertain nest-site occupation, the number of fledged young and, where possible, of nestlings, through nest site visits. A breeding pair was considered successful only when at least one young fledged (Hardey

Table 1 Nesting attempts by the lanner falcons in the two study areas

Study areas	Years	Checked nesting attempts
Apennine peninsula	2000—2014	133
Eastern Sicily	2003—2006	45
Total		178

et al. 2006). Thus, each breeding attempt was classified as either successful (S) or unsuccessful (U). We considered the number of fledged young per checked pair (productivity) as the most reliable dependent variable for evaluating influences of weather conditions on breeding performances (Steenhof and Kochert 1982). In fact, productivity is an integrated measure made up of sequential components that in birds includes clutch size, hatchability, and chick survival (Rockwell et al. 1993; Robinson et al. 2007). In addition, in order to compare our results with other studies on lanner falcon, we recomputed productivity rates as the proportion of young of all birds (young + adults) where the adult number (from territorial pairs) is considered as an estimate for the population size (Meller et al. 2018).

Every year in Sicily, we ascertained also hatching dates and chick mortality by visiting nests following a rigorously field protocol aimed at reducing disturbance (Leonardi et al. 2007). We determined the approximate nestling age by week through a photographic guide and the growth curve made by Kemp (1975). Then, we estimated the most probable week when eggs hatched considering an average incubation period of 32–35 days (Amato et al. 2014; Leonardi 2015).

Weather data

For each year of our study, we inferred monthly temperature (°C) and precipitation (mm) from the national system for the collection, processing and dissemination of climatic data of environmental interest (SCIA) set up by the National Institute for Environmental Research and Protection (ISPRA) (http://www.scia.isprambiente.it/).

Raster images were converted from ASCII format (cell size x = 1000 m; y = 1000 m) WGS 84 UTM Zone 32 N into shape files (polygons) by ArcGis 10.0 (ESRI, Redlands, CA). Then we overlaid the layer with nest positions to the polygons in order to attribute monthly temperature and rainfall values to each breeding site. At the end of this process, we obtained monthly values of temperature and rainfall, from January to May, per each breeding attempt. In fact, local environmental factors vary by year and nest-site and, consequently, cues useful for parental decisions varied during each breeding attempt (Williams et al. 2015, Imlay et al. 2018).

For the in-depth analysis conducted in Eastern Sicily, we also used daily (and then week averages) temperature and rainfall data from the Sicilian agro-meteorological information service (SIAS; http://www.sias.regione.sicilia.it). An *a priori* analysis (GLMMs) revealed that weather variables in Eastern Sicily show a predictable trend across years without any significant differences.

In order to detect the exact time-slot in which reproduction is optimal, we did not log-transform weather predictors to obtain their linear and quadratic effects in the GLMM models.

Statistical analysis

We consider a breeding attempt by the lanner falcon as a sample unit by site and year (n = 178 attempts; Table 1). This dataset does not include single non-breeders (ca. 5 %) occurring sparsely during the study periods. Each attempt was characterized by individual nest monthly temperature and rainfall, number of fledging young and hatching date (the latter variable for the Sicilian population only).

Main events (egg incubation, hatching, nestlings and fledglings) of the breeding season in Eastern Sicily were defined by weeks. The frequency of the hatch week was calculated as residuals from the median in each breeding season as follow:

$$X_i - Median\ (X)$$

Thus, residuals span from values below to above 0 which correspond the case when X_i is identical to the Median (X). We analysed the relationship between the hatching week and monthly temperature and rainfall using a non-parametric Kruskall-Wallis test.

We ran Generalized linear models to ascertain differences between Eastern Sicily and the Apennine peninsula in lanner falcon productivity (Poisson distribution) and breeding success (binomial distribution). Brood size distributions from study areas were compared with Kruskall–Wallis tests.

We used the Generalized linear mixed model (GLMM) procedure to ascertain which weather factors (monthly rainfall and temperature) affects chick survival (binomial distribution, 0 = died, 1 = lived), productivity (Poisson distribution), breeding success (binomial distribution, 0 = unsuccessful, 1 = successful). We avoided pseudo-replication effects by the use of the nest-site ID and years as random factors with a normal distribution of errors and sub-sample areas as weights (Burnham and Anderson 2002; Anctil et al. 2014). Fixed factors include the relative hatch week (calculated as residuals) and each monthly temperature and rainfall from January to May (Online resource 1: Table S1). Six different combinations of fixed variables were tested with model-averaged parameter estimates at significance level of α = 0.05 (Online resource 1: Table S1). Statistical analyses were performed using SPSS 21.0 (IBM Corp., Armonk, NY).

Results

Breeding performances

Pooled data (Apennine peninsula and Eastern Sicily) revealed a mean productivity (fledged young/checked pairs) of 1.65 ± 1.29 (n = 178), a fledging rate (fledged young/successful pairs) of 2.44 ± 0.71 (n = 120) and a breeding success (successful pairs/checked pairs*100) of 67.4 %.

The breeding success rates were 71 and 58 % in the Apennine peninsula and in Eastern Sicily respectively but not statistically different (χ^2 = 2.575, *df* = 1; *p* = 0.109). Accordingly, mean productivity did not differ significantly among study areas (Apennine peninsula = 1.68 ± 1.22; *n* = 133; Eastern Sicily = 1.34 ± 1.40; *n* = 45; χ^2 = 0.316, *df* = 1, *p* = 0.574). In fact, Sicilian lanner falcon successful pairs fledged an average of 2.69 ± 0.78 young (*n* = 26), not differing significantly from those on the Apennine peninsula (*n* = 94) with 2.37 ± 0.68 young per successful attempt (χ^2 = 0.857, *df* = 1; *p* = 0.354).

The frequency distribution of brood size was statistically different (*H* = 12.058, *df* = 3, *p* = 0.007) but no annual difference subsists within each sub-sample area (Table 2). Stepwise comparisons recognized two homogeneous subsets of study areas characterized by the same quartile range (2–3) but different medians: (1) = 2 and (2) = 3 (Table 2). Interestingly, subsets do not follow the original latitudinal partition (Apennine peninsula and Eastern Sicily).

Timing of breeding

In the Sicilian study area, egg deposition started from the third week of February to the first week of March and the hatching occurred, from the third week of March to the second week of April (Fig. 1a). The majority of young fledged in the second and third week of May (Fig. 1a).

In Eastern Sicily, different peaks of hatching frequency characterized each breeding season (*n* = 4; Fig. 1b). Residuals show that the main peak of hatching (ca. 28 %) occurs in the first week after the median (0.5 value; Fig. 2a). Lower frequencies occur at 0 value (median) (ca. 20 %), in the early and late hatching stages (ca. 16 % each) and the very early attempts (two weeks before the relative median) (ca. 4 %) (Fig. 2a).

Post-hatching survival

Overall a relative small percentage of chicks died after hatching in Eastern Sicily during 2003–2006 (9.5 %; *n* = 73 chicks, 66 of which fledged and 7 died, from 26 nests).

The distribution of survival rates was affected by the hatching week (Table 3; Fig. 2a). As shown by residuals, a relevant fraction of fledged nestlings (47 %) were born during the hatching peaks (48 %; Fig. 2a). Although early nests represented only 20 % of all breeding attempts, they produced 26 % of surviving nestlings (Fig. 2a). Inversely, late nests (16 %) produced 11 % of nestlings only (Fig. 2a). Weather parameters did not affects the surviving rates of nestlings significantly (Online resource 1: Table S1).

Effects of temperature and rainfalls on breeding performance

The used models suggest that the breeding performance of lanner falcon pairs are influenced by weather conditions (Table 3; Online resource 1: Table S1). In particular, February rainfall influence both breeding success (Table 3 and Online resource 1: Table S1; % CI 0.033–0.006) and productivity (Table 3 and Online resource 1: Table S1; % CI 0.003–0.011). Temperatures in May have a slight influence on breeding success only (Table 3 and Online resource 1: Table S1; % CI 0.065–0.804).

The relative hatching week in Eastern Sicily depends, again, on rainfall in February (*H* = 14.035, *df* = 5, *p* = 0.015) and slightly on those in January (*H* = 12.538, *df* = 5, *p* = 0.028) and March (*H* = 12.917, *df* = 5, *p* = 0.024). As well as breeding success, the sole temperature in May, when young fledge, seems to be related with the hatch week (*H* = 14.392, *df* = 5, *p* = 0.013).

Discussion

Reproductive parameters of lanner falcon populations in Italy

This study, to our knowledge, is the first on the lanner falcon to use a considerable number of breeding attempts throughout Italy (*n* = 178). Previous studies referred only to local regions which included demes with a small number of breeding pairs

Table 2 Frequencies of brood size of the lanner falcons in the study area

	Eastern Sicily	Apennine peninsula
Brood size	*N*	*N*
1	1	5
2	10	55
3	11	28
4	4	6
Sample size	26	94
Median	3	2
Quartile range	2–3	2–3

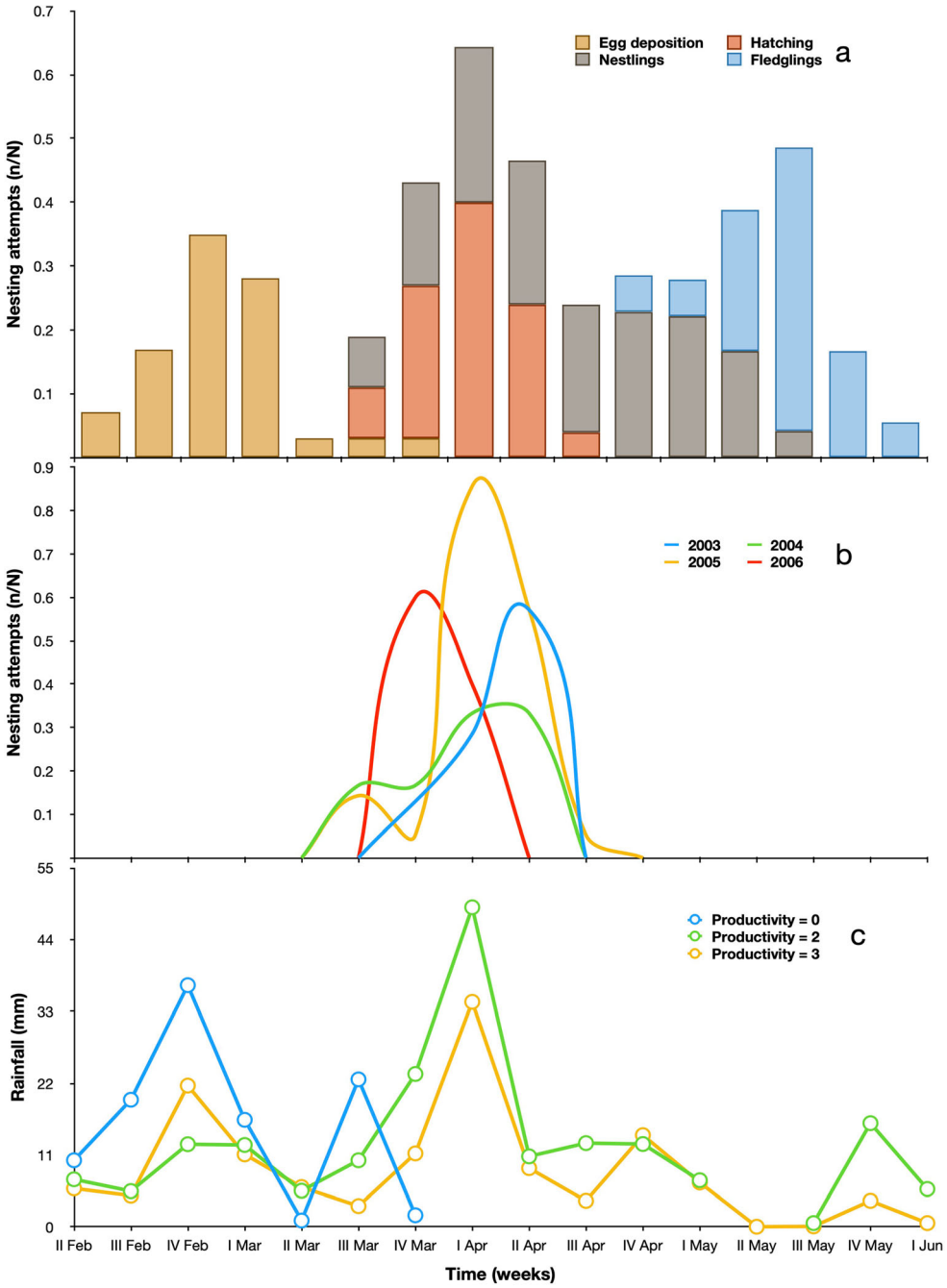

Fig. 1 **a** Frequency (n/N) distribution by week of main events (egg deposition, hatching, nestlings and fledglings) during breeding seasons of the lanner falcon in Sicily in 2003–2006 (nesting attempts = 26). **b** Hatching frequencies (n/N) per year of study. There is a statistically significant difference between the mean of the sampled population and the hypothesized population mean (One-sample Student's test $t_{25} = 14{,}541$, $p < 0.001$). **c** Average weekly rainfalls during unsuccessful (Brood size = 0) and successful (Brood size = 2 and 3) attempts made by lanner falcons in Sicily. Although February and March rainfalls follow a unique pattern, peaks used as cues by successful pairs are less intensive than those of unsuccessful pairs (successful pairs = 26, unsuccessful pairs = 19)

(Sigismondi et al. 2003; De Sanctis et al. 2009; Brunelli 2012). On the other hand, the apparent size of the Sicilian population and its resilience was overemphasized when compared to those of the Apennine peninsula (Leonardi 2001; Salvo 2001; Sarà 2014). Indeed, this study has shown that there are no significant differences among reproductive parameters of the lanner falcon inhabiting different territorial contexts. Accordingly, the rates fledglings/population size (adults + fledglings) are quite correspondent among areas (Eastern Sicily = 0.44; Marche = 0.46; Molise and Gargano = 0.45; Latium = 0.49).

Clutch size

Lahoz-Monfort et al. (2013) stated that the probability of each potential egg being laid and surviving until fledging is mathematically equivalent to that of the mean number of fledglings. Thus, we can see effects of fecundity using the pattern of distribution of the mean number of fledglings among our breeding populations. All our study areas show the same quartile range (2–3) but different medians that characterized two main homogeneous subsets (Table 2). These subsets (Eastern Sicily and Latium; Marche and Molise) are grouped

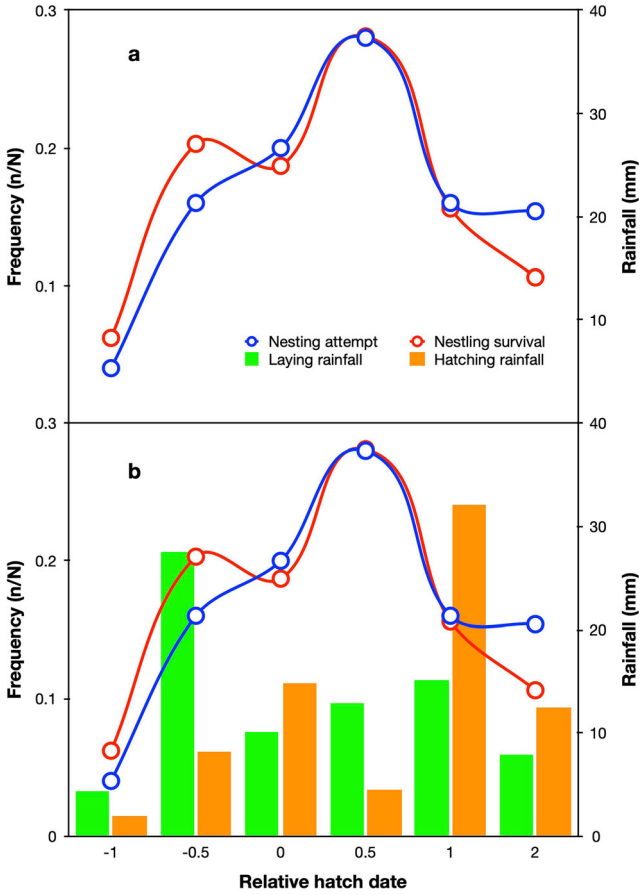

Fig. 2 Frequency distribution of nesting attempts and nestling survival in relation to their relative hatch date in Sicily (**a**). Rains are used by lanner falcon pairs as cues for decide when to lay their eggs (**b**). Consequently, the majority of hatches will take place under favourable conditions. Inversely, late nests faced with unfavourable rains for the new-born nestlings (**b**). Values are standardized relative to the yearly median (nesting attempts = 26; surviving nestlings = 73)

independently from their latitudinal position (Apennine peninsula and Eastern Sicily). Our results along with other studies on lanner falcon show a strong relationship among brood size rates and productivity. In fact, high or low contributions on population growth depend on frequencies of brood size of three or two nestlings respectively (Table 2). Therefore, independently from population size, the maintenance of a lanner falcon population is a function of the frequency of larger broods. Presumably, low median in brood size affected the breeding populations in the Apennine peninsula. In Eastern Sicily very few high productivity nests contribute up to 38 % of fledglings for the entire breeding population (Amato et al. 2014). Common kestrels (*F. tinnunculus*) showed the same annual fluctuations in brood size in different areas and in different years (Meijer et al. 1988). Several studies suggested that it is profitable for this falcon to breed early, since earlier broods are larger and more young fledge (Aparicio and Bonal 2002; Dunn 2004; Zellweger-Fischer et al. 2011). Thus, increasing brood sizes should depend on timing and egg-laying decisions made by parents during the breeding season.

Timing and post-hatching survival

Mean laying dates of falcons varied significantly between years (Aparicio and Bonal 2002). An adaptive decline in average fertility, clutch size and hatchability with progressive date of laying is characteristic of most bird species with a single clutch of variable size per year such as falcons (Cavé 1968; Bird and Laguë 1982; Meijer 1989; Daan et al. 1990). Accordingly, model IV indicates that the survival chances of Sicilian lanner falcon nestlings depends on hatching date (Table 1; Fig. 2). In fact, the bulk of surviving nestlings always coincides with the peak of hatching regardless of the appreciable annual fluctuations (Fig. 1a). Presumably, there is a constant and significant contribution of factors relating also to the quality of parents and especially their reproductive decisions (Zabala and Zuberogoitia 2014; Williams et al. 2015). Outside the main peak, few early breeding attempts produced more surviving young than expected but late nests suffer the exact opposite effect (Fig. 2).

Weather effects

Negative correlations between rainfall and nestling survival have been observed in several raptor species (Potapov 1997; Steenhof et al. 1997; Bionda and Brambilla 2012; Anctil et al.

Table 3 Model-averaged parameter estimates tested at significance level of $\alpha = 0.05$

Models	Response variable	Terms	Slope	± se	df	*F*	*p*
I	Breeding success	February rainfalls	-0.019	0.007	1,145	7.862	0.006
	Productivity	February rainfalls	0.007	0.002	1,145	10.703	0.001
II	Breeding success	May temperatures	0.434	0.187	1,122	5.418	0.022
III	Productivity	Feb rains x Feb temp	0.001	0.000	1,113	4.278	0.041
IV	Chick survival	Hatch week	0.000	0.577	5,67	2.459	0.042

Nest-site ID and years are used as random factors to avoid pseudo-replication effects. Model I (fixed factor: rainfall), model II (fixed factor: temperature), model III (fixed factor: rainfall x temperature), model IV (fixed factor: Hatch week). Dependent variables: chick survival (binomial distribution, 0 = died, 1 = lived), productivity (Poisson distribution), breeding success (binomial distribution, 0 = unsuccessful, 1 = successful). Results from all models (I-VI) are listed in Online resource 1: Table S1

2014). Nevertheless, severe effects are stressed where the weather acts in an unpredictable way and especially where reproduction is restrained in a short time window (i.e. the Arctic; Bradley et al. 1997; Anctil et al. 2014). If the main goal of lanner falcon breeding pairs is to synchronize the hatching in a precise favourable period, that in turn increased survival chances of nestlings, post-hatching mortality should therefore be limited (Fig. 2). In fact, in seasonal environments, it might be advantageous to invest all available energy into one breeding attempt during a period of favourable conditions (Griebeler et al. 2010). Accordingly, in Eastern Sicily where weather conditions are seasonally and reasonably predictable, we found < 10 % of dead nestlings before fledging.

The main time window where parents should adjust their reproductive decisions is during the laying period. Unfortunately, egg laying can be temporally separated from the chick-rearing phase by several weeks due to the physiological and behavioural preparation of parents (Williams et al. 2015). Thus, the use of environmental cues (i.e. rainfall and temperature) for the timing of breeding should becomes fundamental for lanner falcon breeding success and productivity (Williams et al. 2015).

Temperature seems to have a marginal role on breeding parameters at this regional level. In fact, temperatures, as well as photoperiod, greatly affect laying dates of the lanner falcon but only at a large geographical scale (see Leonardi 2015 for a review). For instance, laying peaks in February and March characterize all lanner falcon populations of European Mediterranean countries (including all our study areas), whereas those of North Africa are shifted to March and April (Leonardi 2015). Nevertheless, a relationship with temperatures in May (when young fledge) mainly exists with the hatching week and breeding success. Presumably, pairs try to avoid that fledged nestlings may well face a decline in the food supply and harsh environmental conditions, such that they are unable to find enough food as well as less time to learn to hunt difficult prey (Olsen and George 1993; Smith 2004).

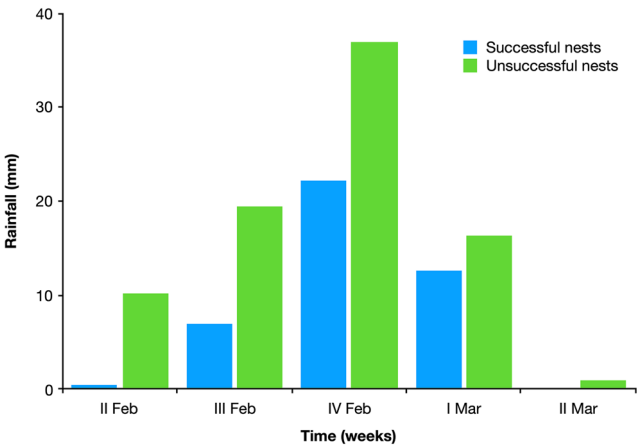

Fig. 3 Rainfalls (mm) during successful and unsuccessful laying attempts made by Lanner falcons in Sicily. Although February rainfalls follow a unique pattern (Online resource 1: Table S1), peaks used as cues by successful pairs are less intensive than those of unsuccessful pairs (successful pairs = 26, unsuccessful pairs = 19)

In all sample areas, February rainfall is the main abiotic factor that greatly influences all the lanner falcon reproductive parameters (hatching, productivity and success). We can try to explain this remarkable importance because it acts as the main factor on the decision when to lay eggs. In fact, February weekly rainfall in Eastern Sicily seems to be a cue for the majority of pairs to start laying (Fig. 2b). In addition, the use of this cue also avoids the occurrence of nestling mortality that could coincide with high rainfall during hatching (Fig. 2b). Similar effects of abundant rainfall prior to laying was observed in common kestrel populations inhabiting semi-arid environments (Carrillo and González-Dávila 2010b). Furthermore the Sub-Saharan African lanner falcon subspecies lays eggs during the dry season following heavy rains that favour egg production and the subsequent rearing of young due probably to a greater abundance of prey (Leonardi 2015). In fact, several studies show the influence of rainfall on brood size through food availability (Grant et al. 2000; Illera and Díaz 2006; Carrillo and González-Dávila 2010b). Perhaps, prey is likely to be affected by weather conditions both in terms of phenology and especially density (Newton 1979; Rodríguez et al. 2010). Accordingly, breeding success is likely to be linked to prey availability and thus reflect changes at lower trophic levels and in abiotic conditions (Frederiksen et al. 2007). Nevertheless, intense precipitation forces a delay in deposition and then to a drastic reduction in average productivity (Tolonen and Korpimäki 1995; McDonald et al. 2004; Carrillo and González-Dávila 2010b; Costantini et al. 2010). Conversely, we observed a positive effect with rainfall as a cue for lanner falcon breeding decisions (Fig. 2) but intense rainfall levels led to nest failure (Fig. 3) or loss in productivity (Fig. 1c). Negative effects should include a delay in laying dates, as demonstrated by this study, but also a possible detriment on the physical condition of parents (Hiraldo et al. 1990; Dawson and Bortolotti 2000). Further studies are needed to clarify the latter aspect.

Conclusions and conservation issues

Our study confirmed the importance of environmental cues such as temperature and rainfall on breeding decisions by lanner falcon pairs inhabiting the whole Italian territory. Thus each year, breeding pairs try to synchronize hatching in a precise favourable period through the decision of when to lay. Thereby, they can limit post-hatching mortality. On the other hand, more intense rainfall leads to failure or to a delay on laying that ultimately reduces brood size. In fact, high and low contributions of fledglings on population growth depends

on frequencies of brood size of three or two nestlings respectively.

The lanner falcon breeding population in Eastern Sicily and the Apennine peninsula represents a significant part of the whole population in the Western Palaearctic (Leonardi 2015). Thus, the viability of this population is crucial for preserving an important gene pool for this subspecies (Amato et al. 2014). Considering the expected climatic changes induced by global warming, this study could be the precursor of a predictive model on population dynamics and may explain factors that caused the population modifications of lanner falcon in Italy.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11756-021-00875-x.

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Declarations

Ethics approval All procedures followed by this study were in accordance with international ethical standards and were approved by the Italian Institute for Environmental Protection and Research (ISPRA) and the Sicilian Office for the wildlife management (Sicilian regional government). Authors accept all publication rights.

Conflict of interest The authors have no conflicts of competing interest to declare.

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