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Article *in* Wildlife Research · January 2019

DOI: 10.1071/WR18081

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Long-term changes in the breeding period diet of Bonelli's eagle (*Aquila fasciata*) in Sicily, Italy

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Abstract

Context. Dietary analyses are essential to achieve a better understanding of animal ecology. In the case of endangered species, assessing dietary requirements is crucial to improve their management and conservation. The Bonelli's eagle (*Aquila fasciata*) has experienced a severe decline throughout its breeding range in Europe and, in Italy, fewer than 50 pairs remain, and only in Sicily. This species is subject to major threats, including changes in landscape composition and, consequently, prey availability, which is further aggravated by the occurrence of viral diseases in the case of rabbits.

Aims. To provide current data on the diet of the Bonelli's eagle in Sicily during the breeding period and to examine dietary shifts with regard to previous studies conducted in the same study area. To discuss possible implications for conservation of the Italian population of this endangered species.

Methods. We used a combination of three methods, including pellet analysis, collection of prey remains, and imagery from camera-traps installed at nests, to examine the diet of 12 breeding pairs of Bonelli's eagle from 2011 to 2017. We compared this information with data collected between 1993 and 1998 in the same study area.

Key results. In number, birds were the most frequently predated items (61.6%), followed by mammals (36.88%) and reptiles (1.52%). However, in terms of biomass, mammals were the main prey (65.71%), followed by birds (34.12%) and reptiles (0.17%). There was a decrease over the course of the current decade in the consumption of European wild rabbit (*Oryctolagus cuniculus*), which was compensated for with an increase in both dietary diversity and breadth in bird consumption, a trend not observed in the earlier study in the same region.

Conclusions. Here, we provide an updated assessment of diet composition of Bonelli's eagle during the breeding period. Interestingly, we found significant differences within the study period (2011–2017) in terms of frequency of occurrence, percentage of biomass, dietary diversity and dietary breadth in a species at risk. Furthermore, we found significant differences between the two study periods in both frequency and percentage of biomass, with significant changes in the consumption of lagomorphs and birds.

Implications. Our results indicated that shifts in the diet are linked to changes in prey abundance, which may be contributing to population declines in the Bonelli's eagle population in Sicily. Overall, measures aimed at increasing main dietary prey should be promoted to favour occupation of new territories and enhance vital demographic parameters (i.e. breeding success and survival rate) of Bonelli's eagle across the species range. This would be particularly important for small isolated populations such as the Sicilian one.

Additional keywords: camera-trap, conservation, dietary composition, food, pellets.

Received 9 May 2018, accepted 15 April 2019, published online 1 August 2019

Introduction

Detailed knowledge of animals' diet is a crucial step in understanding their ecology (Newton 1979) and, consequently, this information can help improve their management and conservation. Despite their general importance, diet studies of threatened species are constrained by conflicting evidence on robustness of the methodology. Direct observations of hunting behaviour, analysis of pellets, and collection of prey remains are methods usually employed to study avian diet (e.g. Mersmann *et al*. 1992; Lewis *et al*. 2004; López-López *et al*. 2009). However, these methods may give conflicting results. For example, the exclusive use of pellets tends to overestimate small prey (Real 1996), whereas the use of prey remains tends to overestimate large prey (Rosenberg and Cooper 1990). For this reason, some authors recommend the combined use of different methods (i.e. analysis of pellets and prey remains; Oro and Tella 1995), as well as trail-camera imagery if possible (e.g. López-López and Urios 2010; García-Salgado *et al*. 2015), so as to provide the most accurate picture of the diet of the animals.

The Bonelli's eagle (*Aquila fasciata*) is a resident threatened raptor, with western Palaearctic populations ranging across the circum-Mediterranean area and southern Europe (Ferguson-Lees and Christie 2001). Starting by the second half of the 20th century, this species has decreased sharply throughout its European range as a result of habitat modification owing to rural abandonment and changes in agricultural practices, which have caused changes in prey availability. In parallel, also mortality has increased, mainly because of direct persecution (i.e. poaching, illegal harvest) and electrocution on electric pylons (Ontiveros *et al*. 2004; BirdLife International 2016; Di Vittorio *et al*. 2018). The European population is estimated at 1100–1200 breeding pairs, with 80–90% of them being located in the Iberian Peninsula (BirdLife International 2016). In Italy, the Bonelli's eagle was historically present in Sardinia and Sicily, and irregularly in the southern Apennines (Cortone and Mirabelli 1987). Currently, it breeds only in Sicily (Di Vittorio *et al*. 2012; López-López *et al*. 2012), with an estimated population of 44 breeding pairs (Di Vittorio *et al*. 2018) and, because of a low population size and reduced distribution, is currently listed as critically endangered in Italy (Rondinini *et al*. 2013).

The diet of Bonelli's eagle has been studied in western Europe since the 1980s (see e.g. Cheylan 1977; Simeon and Wilhelm 1988; Real 1996; Di Vittorio *et al*. 2001; Moleón *et al*. 2009, 2012). This raptor preys on a wide range of species, including mammals, birds and reptiles, usually in relation to habitat suitability and prey availability (Cheylan 1977; Simeon and Wilhelm 1988). In southern Europe, European wild rabbits (*Oryctolagus cuniculus*) and pigeons (*Columba* spp.) represent its main prey, particularly during the breeding season (Gil-Sánchez *et al*. 1998; Resano-Mayor *et al*. 2016; Rollan *et al*. 2016). However, wild rabbits, a keystone species in Mediterranean landscapes (Villafuerte *et al*. 1995), have substantially declined in several parts of its current range in Europe. In particular, until the 1920s, the wild rabbit was abundant and spread all over Sicily. However, from the 1950s onward, local extinctions occurred in some areas of Sicily. This issue was aggravated between the 1980s and the 1990s because of the emergence of new viral diseases (e.g rabbit haemorrhagic disease virus variant strain 2 [RHDV2]; Camarda *et al*. 2014; Lo Valvo *et al*. 2014) and the reduction of suitable habitats for reproduction (Lo Valvo *et al*. 2017). Consequently, it has been classified as a near-threatened species on the Red List of Italian Vertebrates (Rondinini *et al*. 2013; http://www.iucn.it/) even though it is also considered an agricultural pest species in many areas (Lo Valvo *et al*. 2017). This could have a major impact on its main predators, including the scarce Bonelli's eagle (López-López *et al*. 2012).

In the present paper, we aimed to examine potential shifts in the diet of the threatened Bonelli's eagle in Sicily, by comparing data from two decades (1990s vs 2010s), across a variety of diet-estimation methodologies, to determine whether prey availability might be affecting population trends for this region. We also discuss possible implications for conservation of the Italian population of this threatened species.

Materials and methods

The present study used the same methodology and study area as that used in the 1990s study by Di Vittorio *et al*. (2001), so as to make the results directly comparable. Data were collected across 12 breeding pairs from February to May each year (corresponding with the breeding season) from 2011 to 2014 and from 2016 to 2017. We collected pellets, prey remains in the nests and below usual perches, and photographs from camera-traps installed on nests, but ensured that we avoided multiple counts of the same prey by only using one method at any given time at a particular nest site.

Regurgitated pellets were collected from nest sites and below usually used perches for five breeding pairs. Pellet and prey-remain searches were conducted throughout the breeding period, but different amounts of material were collected from each nesting area because of varying nest accessibility. Pellets were stored individually in plastic bags and dried before laboratory analysis (Marti 1987). For the identification of prey species contained in each pellet, we applied a comparison with feather, hair and bone collections at the Department of Animal Biology of the University of Palermo (Italy), applying a standard methodology (see Litvaitis 2000; Milchev *et al*. 2012), as well as the use of specialised guides (Cohen and Serjeantson 1986; Desse *et al*. 1986). Prey remains were reconstructed to estimate the minimal number of individuals of each species to avoid over-representation biases (Real 1996; Milchev *et al*. 2012). In addition, we also analysed images obtained by six camera-traps and one webcam, which collected data from mid-April to June, located at the other seven nest sites.

To facilitate comparison of our results with those of other studies of the diet of Bonelli's eagle (e.g. Di Vittorio *et al*. 2001; Moleón *et al*. 2012; Resano-Mayor *et al*. 2016; Rollan *et al*. 2016), we calculated prey diversity and dietary breadth. Prey diversity was calculated using the Gini index of diversity (Gotelli and Ellison 2004). This index is valuable for comparison because, unlike other commonly used indexes of diversity (e.g. the Shannon–Weiner index), it does not confound species richness and evenness and it does not depend on sample size (Gotelli and Graves 1996; review in Magurran 2003). The index was computed at the species level, and, similarly to other indexes, the higher the index value is, the higher the diversity measure (Gotelli and Graves 1996). Dietary breadth was calculated using

the methods in Steenhof and Kochert (1985). This value is similar to the Gini prey diversity index, but, in this case, prey items are grouped by taxa higher than the species level (family level in our case). Values for this index range from 1 to ∞.

To test for statistical differences in prey composition among years within the current study period (2011–2017), we used a Kruskal–Wallis test and Monte Carlo randomisations (9999 simulations; Gotelli and Graves 1996). To test for differences in the frequency and percentage of biomass contributions in the dietary habits of Bonelli's eagles between the current time (i.e. hereafter referred to as 'current' data) and the 1990s (data from 1993 to 1998; Di Vittorio *et al*. 2001; hereafter referred to as 'previous'), we used a Mann–Whitney *U*-test with 9999 random permutations of the original raw data implemented in Ecosim software (Gotelli and Ellison 2013). Nevertheless, we recognise that our small sample size of nests limits our ability to infer trend in eagle diet and, therefore, our results should be interpreted with caution. Statistical tests were considered significant if *P*-value was <0.05 and marginally significant if *P*-value was <0.10.

Results

In total, 98 pellets and 13 960 pictures taken from camera-traps were analysed. Overall, 263 prey items were identified, including 103 from pellets, 105 from prey remains and 55 from camera-traps. Prey remains were taxonomically classified, and included mammals, birds and reptiles, across 22 different species (Table 1). The mean number of prey identified per year was 49.83 ± 19.91 and there were marginal differences in prey frequency among years (Kruskal–Wallis test: $\chi^2 = 7.75$, Monte Carlo: $P = 0.087$).

Table 1. Dietary composition of Bonelli's eagle in Sicily during the breeding period

n, number of prey items recorded. Data from Di Vittorio *et al*. (2001) span from 1993 to 1998; current data were obtained from 2011 to 2017

Group	Taxon	Di Vittorio *et al*. (2001)			Present study		
		N	Number (%)	Biomass (%)	*N*	Number (%)	Biomass (%)
Mammals			39.07	69.84		36.88	65.71
	Leporidae		37.09	69.43		36.50	65.64
	European rabbit (*Oryctolagus cuniculus*)	56	37.09	69.43	88	33.46	56.08
	Italian hare (*Lepus corsicanus*)		0.00	0.00	8	3.04	9.56
	Muridae		1.99	0.41		0.38	0.07
	Rattus sp.	3	1.99	0.41	1	0.38	0.07
Birds			57.62	29.55		61.60	34.12
	Corvidae		18.54	7.16		15.59	5.80
	Hooded crow (*Corvus cornix*)	2	1.32	0.90	10	3.80	2.31
	Jackdaw (*Coloeus monedula*)	22	14.57	5.50	15	5.70	1.93
	Eurasian Magpie (*Pica pica*)	4	2.65	0.76	16	6.08	1.56
	Columbidae		38.41	22.18		34.22	19.54
	Common wood pigeon (*Columba palumbus*)	10	6.62	4.90	45	17.11	11.33
	Rock dove (*Columba livia*)	48	31.79	17.28	44	16.73	8.14
	European turtle dove (*Streptopelia turtur*)		0.00	0.00	1	0.38	0.07
	Turdidae		0.00	0.00		1.14	0.15
	Common blackbird (*Turdus merula*)		0.00	0.00	3	1.14	0.15
	Sturnidae		0.00	0.00		2.28	0.26
	Spotless starling (*Sturnus unicolor*)		0.00	0.00	6	2.28	0.26
	Phasianidae		0.00	0.00		3.04	3.34
	Rock partridge (*Alectoris graeca*)		0.00	0.00	5	1.90	1.41
	Chicken (*Gallus gallus domesticus*)		0.00	0.00	3	1.14	1.93
	Falconidae		0.66	0.21		2.66	0.75
	Common kestrel (*Falco tinnunculus*)	1	0.66	0.21	5	1.90	0.54
	Cesser kestrel (*Falco naumanni*)		0.00	0.00	2	0.76	0.21
	Accipitridae		0.00	0.00		0.38	0.49
	Common buzzard (*Buteo buteo*)		0.00	0.00	1	0.38	0.49
	Burhinidae		0.00	0.00		0.38	0.40
	Eurasian stone curlew (*Burhinus oedicnemus*)		0.00	0.00	1	0.38	0.40
	Phalacrocoracidae		0.00	0.00		0.38	1.54
	Great cormorant (*Phalacrocorax carbo*)		0.00	0.00	1	0.38	1.54
	Ardeidae		0.00	0.00		0.76	1.54
	Grey heron (*Ardea cinerea*)		0.00	0.00	2	0.76	1.54
	Laridae		0.00	0.00		0.76	0.31
	Black-headed gull (*Chroicocephalus ridibundus*)		0.00	0.00	2	0.76	0.31
Reptiles			3.31	0.62		1.52	0.17
	Colubridae		2.65	0.60		0.76	0.15
	Green whip snake (*Hierophis viridiflavus*)	4	2.65	0.60	2	0.76	0.15
	Lacertidae		0.66	0.02		0.76	0.02
	Western green lizard (*Lacerta bilineata*)	1	0.66	0.02	2	0.76	0.02
Total		151			263		

Birds were the most frequent prey item, followed by mammals and reptiles (Table 1). However, mammals constituted the majority of consumed biomass, followed by birds and reptiles (Table 1). European wild rabbits (*Oryctolagus cuniculus*) and pigeons (*Columba* spp.) were the main components of the diet of Bonelli's eagle, and rabbits were the most important consumed prey in terms of biomass (Table 1). In general, the contribution of reptiles was generally very low (Table 1). Throughout the current study period (i.e. from 2011 to 2017), diet frequency of wild rabbit declined by 66.67% ($\beta = -0.87$; $R^2 = 0.76$; $P = 0.022$), whereas there was no observed change in pigeon consumption ($\beta = 0.20$; $R^2 = 0.04$; $P = 0.710$; Fig. 1).

There were major differences between previous and current data in both frequency ($z = -2.224$; Monte Carlo: $P = 0.023$, $n = 22$) and percentage of biomass ($z = -2.430$; Monte Carlo: $P = 0.013$, $n = 22$), with the main differences being attributed to changes in the consumption of lagomorphs and birds. Additionally, in the current study, there was a greater diet diversity (Gini index: previous data = 0.734; current data = 0.820) and dietary breadth (previous data = 3.119; current data = 3.607) than there was in the previous study.

Discussion

Diet composition

Wild rabbits and pigeon species were the main prey of Bonelli's eagles in both the present study and previous studies for this species across its breeding range (e.g. Ontiveros and Pleguezuelos 2000; Moleón *et al.* 2009; Resano-Mayor *et al.* 2014). However, diet diversity was lower than that reported in other literature (e.g. Moleón *et al.* 2009; Caro *et al.* 2011; Resano-Mayor *et al.* 2016), likely because of regional differences in prey richness (Gasc 1997; Hagemeijer and Blair 1997). Our results confirmed that Bonelli's eagle in Sicily concentrates its predation effort on birds (Massa 1981; Salvo 1988; Di Vittorio *et al.* 2001) and, in accordance with previous work in the area, the European wild rabbit represented the main source of dietary biomass.

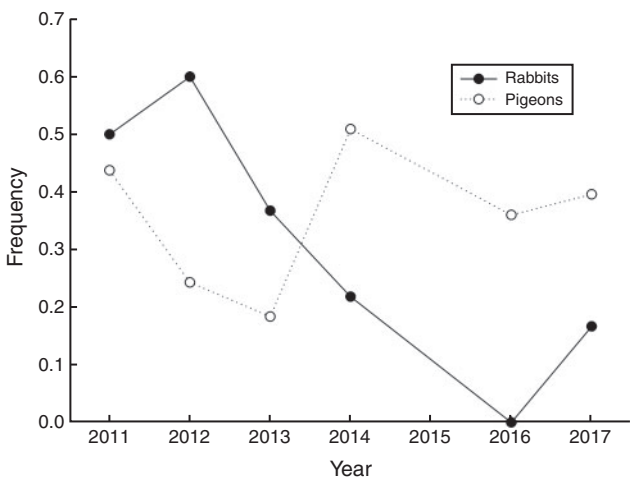

Fig. 1. Frequency of wild rabbit (*Oryctolagus cuniculus*) and pigeons (*Columba* spp.) in the diet of Bonelli's eagle in Sicily (Italy) during the study period.

However, of particular concern is that wild rabbit consumption was reduced over the course of the current study period, which was likely compensated for by increases in the amount of birds in the diet. Similar trends in compensation for a reduction in rabbits in the diet of Bonelli's eagles have been reported elsewhere (Ontiveros and Pleguezuelos 2000; Moleón *et al.* 2009, 2012). This implies a recent decrease in the availability of wild rabbits in Sicily (Lo Valvo *et al.* 2014, 2017). This is likely, given that, in recent decades, the wild rabbit has undergone a progressive decline in abundance throughout Italy (Lo Valvo *et al.* 2014) because of new viral diseases (e.g. RHDV2; Camarda *et al.* 2014) and a loss of suitable habitat (Lo Valvo *et al.* 2017). Similar reductions in wild rabbit availability are likely to be affecting Bonelli's eagle in other European regions such as the Iberian Peninsula (Villafuerte *et al.* 1995; Moleón *et al.* 2007; Caro *et al.* 2011; Resano-Mayor *et al.* 2014). In particular, this raptor may select alternative prey species (pigeons and other birds), particularly in areas where rabbit haemorrhagic disease has drastically reduced rabbit abundances (Moleón *et al.* 2009, 2012; Caro *et al.* 2011; Resano-Mayor *et al.* 2014).

Regarding the woodpigeon, we found a higher frequency of occurrence in the diet of this raptor than in previous studies in Sicily (Massa 1981; Salvo 1988; Di Vittorio *et al.* 2001), possibly because the distribution of woodpigeons in Sicily has increased by 39% (AA.VV 2008) over the past few decades (Lo Valvo *et al.* 1993). Considering the eclectic diet of this raptor, it is unlikely that the abundance of the main prey could limit its distribution (Caro *et al.* 2011). However, several studies have indicated that the abundance of rabbit in the diet may affect the productivity and mortality of this species, especially of young and immature birds (see e.g. Carrete *et al.* 2002; Balbontín *et al.* 2003). High consumption of optimal prey (i.e. rabbits) or moderate consumption of these species, complemented by alternative items (e.g. pigeons), could improve productivity, adult survival and nestling body condition (Resano-Mayor *et al.* 2014, 2016), whereas an increase in diet diversity has the opposite effect (Moleón *et al.* 2012; Resano-Mayor *et al.* 2016; Rollan *et al.* 2016).

Management implications

Some authors have proposed measures to increase prey availability to enhance the conservation of Bonelli's eagle (Resano-Mayor *et al.* 2014), including management guidelines to maintain high-density populations of rabbits, and enhance populations where they are scarce (Caro *et al.* 2011). Increasing prey availability in low-quality territories could be an adequate management measure for the recovery and conservation of the populations of Bonelli's eagle where prey scarcity affects breeding success throughout the species' range (Ontiveros *et al.* 2004; Ferrer *et al.* 2018). In addition, actions to improve prey populations, particularly rabbits, could also be an important conservation strategy in dispersal areas (i.e. areas where juvenile and non-breeding birds concentrate before they settle in a breeding territory; Cadahía *et al.* 2010; Rollan *et al.* 2016), and may eventually promote the establishment of new breeding pairs.

In general, the main management actions to recover and increase prey populations in the long term might include habitat restoration and implementation of sustainable hunting programs (Rollan *et al*. 2016). However, when local populations of Mediterranean raptors, such as the Sicilian population of Bonelli's eagle, are subjected to other factors that affect population persistence such as severe habitat degradation (Di Vittorio *et al*. 2012). This is further compounded by a severe and sharp reduction in prey species, especially wild rabbit (Lo Valvo *et al*. 2014, 2017). Thus, it may be advisable to provide supplementary feeding (Rollan *et al*. 2016) to increase productivity in occupied territories until habitats are restored and the stability of prey population has returned. For example, the ongoing LIFE ConRaSi project (Conservation of Raptors in Sicily) funded by the European Union, has supplemented food availability via the construction of several strategically located rabbit farms across eagles' territories. This management action has already had benefits for other threatened species such as the Spanish imperial eagle (*Aquila adalberti*; Blanco 2006; González *et al*. 2006; Ferrer *et al*. 2013, 2018) and the eastern imperial eagle (*Aquila heliacal*; Demerdzhiev *et al*. 2011). These structures, considered as temporary and maintained for a medium timespan (e.g. 5 years), provide safe places where rabbits can breed and find refuge from predators, increasing their survival and, therefore, their population size (Fernández-Olalla *et al*. 2010; Guil *et al*. 2014). This strategy could favour occupation of new territories and enhance demographic performance (i.e. breeding success and survival rate) of the Sicilian population of Bonelli's eagle (Di Vittorio *et al*. 2018) over the short term, until key factors attributed to population declines can be addressed.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgements

We thank all members of 'Gruppo Tutela Rapaci' for their support during the field activities. This project was supported by the LIFE Project 'ConRaSi -LIFE14 NAT/IT/001017 CUP H86J15000240006: Conservation of Raptors in Sicily'. Special thanks are due to two anonymous reviewers and Andrea Taylor, the Chief Editor, who made valuable suggestions to improve the original manuscript.

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