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RESEARCH

Factors affecting hunting efficiency in the case of golden jackal

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Abstract
In recent decades, the golden jackal *Canis aureus* has experienced a population increase in many European countries, including Croatia. As a result, human-jackal conflicts (e.g., damage to livestock and wildlife, general nuisance in (sub)urban areas) have increased dramatically, and there is an urgent need to develop and use a range of mitigation tools that also aim to control population growth. Hunting is one of the well-known tools for population control; therefore, the aim of this study was to determine the effects of habitat type and weather conditions on jackal hunting success. From 2019 to 2023, a total of 217 jackals were culled during 106 hunting events in an approximately 10,500 ha lowland habitat along the Sava River in central Croatia. All jackals (56% males and 44% females) were culled using small calibre rifle (222 Remington) with night vision scope. Based on age structure, 16% juveniles and 84% adults were shot, and the average catch per unit effort (CPUE) was 2.0 animals/day. The best hunting success was obtained by attracting jackals with a calling method, i.e., by playing the sound of a wounded hare. Regarding the type of habitat, 56% of the culls were in cultivated, non-forested areas. It was confirmed that weather conditions, i.e., daily temperature and precipitation, influence hunting success, especially for males. Hunting success of adult males was lower on days with higher temperatures and on days with more precipitation. We can state that individual hunting with using calling method is an effective tool for successful golden jackals harvesting; moreover, jackal hunting can minimize the conflict with gamekeepers and farmers and would help to improve public perception of jackals.

Keywords *Canis aureus* · Calling method · Hunting success · Mesocarnivore · Moon phase · Weather conditions · Wildlife management

Introduction

In recent decades, the problems resulting from increasing abundance of several wildlife species, whether ungulates (e.g., Valente et al. 2020; Carpio et al. 2021) or small predators/mesocarnivores (e.g., Cove and O'Connell 2022), have increased worldwide. When a native species becomes abundant and causes conflicts, wildlife managers have the difficult task of developing socially acceptable management strategies (Garrott et al. 1993; Whisson and Ashman 2020). This is particularly evident in the case of predators, as carnivores are a particularly sensitive and complex issue due to public concern and attitudes towards them, animal welfare, and frequent human-related conflicts (Nunny 2020). One of the most well-known practices for managing abundant wildlife populations is lethal control, such as culling/hunting (Bengsen et al. 2020). Culling has been successfully used in a variety of ways to reduce population size or negative impacts of many mammals (Rosa et al. 2018; Gürtler and Cohen 2022), including predators, around the world (Nunny 2020). However, predator control is nowadays increasingly the subject of public concern, and there is a particular need to justify culling as a suitable management practice (Baker and Harris 2006). Many case studies have shown that culling can be effective, either alone or in combination with other

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methods such as trapping (Bengsen et al. 2020). Considering mesocarnivores, positive management experiences and hunting methods for population control exist so far, for example, for red fox (*Vulpes vulpes*) (Tryjanowski et al. 2009; Lieury et al. 2015). It is also important that data collected during hunting are often used in scientific studies and can significantly contribute to better management guidelines (Ewald et al. 2006).

In the second half of the 20th century, the population of the golden jackal *Canis aureus* increased simultaneously in many European countries, spreading from south-eastern to western and northern Europe (Potočnik et al. 2019; Stronen et al. 2021; Cunze and Klimpel 2022). One of the most striking examples of this population increase is Hungary, where jackal hunting bag increased from 80 individuals in 2002 to 12,126 individuals in 2022, which represents > 150-folds increase in only 20 years (Anonymous 2022). In Croatia, where our study took place, the existence of jackals was first mentioned (as one of the very first evidence of the species presence in Europe) at the end of fifteenth century (year 1491), when the species was introduced on the island of Korčula (Vuletić-Vukasović 1908; Kühn 1935; reviewed in Potočnik et al. 2019). However, the distribution range of the species in Croatia was limited to the coastal region (Dalmatia) until the end of the 19th century (Kryštufek and Tvrtković 1990), when first (but sporadic) reports appeared from the continental part of the country; there, the species has been permanently present and increasing in numbers since 1998 only (Bošković 2012). Since then, golden jackal in Croatia has faced rapid increase in population size as indicated by the acceleration of the annual cull (e.g., by 27.5% between 2011 and 2015; reviewed in Potočnik et al. 2019) and distribution range (by 5.6% in the same period, i.e., inhabiting > 35% of the country surface in 2015; Gomerčić et al. 2018). Recently, the population size was estimated at around 8,000 individuals (Ranc et al. 2018), with population densities reaching up to 2.4 territorial groups/1000 ha (Mladenovič 2016). In view of the continuous increase in its population density, the golden jackal's range is increasingly overlapping with that of humans, resulting in a steady increase in conflicts (Nikitović et al. 2023).

The golden jackal is an opportunistic mesocarnivore with high plasticity in human-dominated landscapes (Fenton et al. 2021). To date, it is still unclear what the main reasons are for the sudden and rapid range expansion throughout Europe (Cunze and Klimpel 2022), starting from the highest population densities in the Balkan Peninsula (Penezić and Ćirović 2015; Potočnik et al. 2019). However, evolutionary and environmental changes, including climate, habitat factors, and persecution of competing predator, the grey wolf *Canis lupus* (although also this species has exhibited very fast and continuous increase both in abundance and geographic range; Chapron et al. 2014), are thought to be one of the main causes of the recent dramatic expansion of the jackals across the European continent (Trouwborst et al. 2015; Krofel et al. 2017). Moreover, a high dispersal potential is also very important for a fast spread of jackal in Europe (Lanszki et al. 2018a; Potočnik et al. 2019; Stronen et al. 2021; Kojola et al. 2023).

In recent years, questions and facts have increasingly been raised about the potential ecosystem values and impacts of jackals in areas with high population densities. Considering recognized benefits, through their scavenging behaviour jackals may provide important ecosystem services in the form of acceleration of nutrient recycling (Moleón et al. 2014), and by predating upon agricultural pests (e.g., rodents), they contribute to mitigate agricultural damages and ensuing economic losses (Ćirović et al. 2016). At the same time, during the spread of African swine fever, jackals can play a positive role, but for now, their role is recognized as ambivalent (Kemenszky et al. 2022). On the other hand, there are several concerns about negative impacts of this newcomer species in Europe, particularly considering interspecific interactions (i.e., predation, competition, and disease transmission). There are several reports and systematic scientific reviews (e.g., Hayward et al. 2017; Lanszki et al. 2018b; Potočnik et al. 2019; Lange et al. 2021) revealing depredation of many animal species; for example, 81 mammalian, 50 invertebrate, 31 bird, 8 reptile, 5 fish, and 3 amphibian species were found in the review of golden jackal nutrition across species distribution range (Lanszki et al. 2018b). Moreover, some studies indicated high predation rate and possible impacts on game species, e.g., brown hare *Lepus europaeus* across whole jackal distribution range (Hayward et al. 2017), and wild ungulates in Bulgaria due to depredation of roe deer *Capreolus capreolus*, fallow deer *Dama*, and European mouflon *Ovis gmelini musimon* (Markov 2012). On the contrary, some other studies across Europe (e.g., Hungary) indicated that decrease in deer species should still be debated in relation to possible (insignificant) impact of jackals (Hatlauf et al. 2021). Considering interspecific competition, Farkas et al. (2017) found that the high nutritional niche overlap between golden jackal and red fox affects the body mass of juvenile foxes. A possible negative impact of jackals is seen also in attacks on livestock (Yom-Tov et al. 1995; Kryštufek 2011; Fanin et al. 2018; Marinov et al. 2022), hybridization with domestic dogs and consequent higher conflict rate between hybrids and humans (Galov et al. 2015). From a sanitary point of view, the jackal is a possible vector of several diseases, including zoonotic diseases, in non-endemic areas (reviewed in Gherman and Mihalca 2017; Potočnik et al. 2019). In addition, even some sporadic jackal attacks on humans have been reported, as in the case of Croatia (Vodopija et al. 2016).

As golden jackal numbers are increasing in many European countries, reaching in some areas very high population

densities (territorial pairs/1000 ha: up to 4.8 in Serbia (Šálek et al. 2014), 5.0 in Greece (Giannatos et al. 2005), and even 5.7–7.0 in Bulgaria (Acosta-Pankov et al. 2018)), their impacts are also increasing. Therefore, mitigating human-jackal conflicts has become a major challenge in wildlife management these days (Marinov et al. 2022). Indeed, due to these impacts, the golden jackal is a top priority species in many European countries as the public, stakeholders, and policy makers advocate for the adoption of legal frameworks to best sustainably manage the population (Trouwborst et al. 2015; Potočnik et al. 2019; Fenton et al. 2021; Hatlauf et al. 2021). Therefore, the aims of this study were to determine: (i) the effect of culling on jackal population structure considering the sex ratio of culled individuals, (ii) the effect of habitat type, and (iii) the effect of weather conditions on hunting success.

Material and methods

Study area

The study was conducted on approximately 10,500 ha in the lowland floodplain forests around the Sava River in Croatia (45°16′15″ N, 16°54′41″ E). The study area consists of 60% agricultural land, 30% forests, and about 10% urban area at elevations between 90 and 110 m (Abramović 2016). The forests consist mainly of pedunculate oak *Quercus robur*, narrow leaf ash *Fraxinus angustifolia*, and black alder *Alnus glutinosa*. The area is interspersed with a mosaic of cultivated non-forest areas, grasslands, thickets, and forests, next to which there are some smaller inhabited places. Most of the local human population is engaged in agriculture and animal husbandry, traditionally raising pigs and cattle in free-range systems based on low food inputs and using natural food sources (Šprem et al. 2014). The climate is continental, moderately warm and humid with a mean annual air temperature of 11.3 °C and a mean annual precipitation of 959 mm (Ugarković et al. 2022). The main ungulate species in the study area are red deer *Cervus elaphus*, roe deer, and wild boar *Sus scrofa*. In addition to the golden jackal, the study area is also inhabited by red foxes and wild cats *Felis silvestris* (Ugarković et al. 2020).

Data collection

The legal status of jackal hunting across Europe is very diverse (Potočnik et al. 2019; Hatlauf et al. 2021). According to the Croatian hunting law (Anonymous 2018), jackal hunting is allowed in the form of single and driven hunts, and there is no strict hunting season, except that hunting of pregnant females or when they are carrying small offspring is prohibited. Hunting is allowed also at night with the help of night vision and thermal imaging devices (Anonymous 2018). Acoustic method of calling jackals by the hunter is allowed. According to the hunting management plans, the maximum number of jackals per 1000 ha of their natural habitat is set at 1 individual (Anonymous 2015).

All hunting events, from which we used data in our study, were conducted in 2019–2023 during 106 hunting events by the one/same hunter using a small calibre rifle (222 Remington) and a night vision rifle scope, with the use of a thermal imaging device for better observation. The hunter used the calling method and imitation of various sounds that attract jackals. After each culling event, the following data were recorded: time and date of culling, time spent in hunting, sex and age of the shot jackal, GPS coordinate, weather conditions, moon phase, and call sound. Age was determined by the growth pattern/stage and attrition rate (tooth wear) of incisors in the upper jaw (Raychev et al. 1999), and jackals were divided into two age groups: juveniles (less than one year old) and adults (older than one year), respectively. Weather conditions, air temperature (°C), precipitation (mm), air pressure (kPa), wind degree (°), wind speed (Beaufort), and moon phase (first quarter; full moon; third quarter; new moon) for each hunting day were obtained from the Croatian Hydrological and Meteorological Service.

Data analysis

Using QGIS 3.4 software and the Habitat Map for Croatia (https://www.bioportal.hr/gis/), we determined the type of habitat where culling occurred and classified it into four land use classes: (i) cultivated non-forest, (ii) pasture, (iii) underbrush, and (iv) forest.

Descriptive statistics were obtained for all variables analysed. A significance level of 5% was considered statistically significant for all statistical analyses. Independence of the frequency of harvested animals' age classes (juvenile and adult) with wind speed, wind direction, moon phase, habitat type and calling sound were tested using the chi-square test. When the expected frequency per cell was < 5, we used Fisher's exact test instead. In addition, the Cochran-Mantel-Haenszel test was used to test whether there was a statistically significant difference between frequencies of both sexes of harvested animals. To estimate the effects of all selected predictor variables (full model) on the probability of culling of adult vs. juvenile jackals logistic regression with a binary outcome (adult/juvenile) was used (Eq. 1) (Hosmer and Lemeshow 1989). Our aim was to compare full model by gender.

$$\begin{aligned}\text{logit}(p) = \log(p/1-p) = {} & \beta 0 + \beta 1 * \text{temperature} + \beta 2 * \text{rain fall} + \beta 3 * \text{wind speed} \\ & + \beta 4 * \text{air pressure} + \beta 5 * \text{E} + \beta 6 * \text{S} + \beta 7 * \text{first quarter} \\ & + \beta 8 * \text{full moon} + \beta 9 * \text{new moon} + \beta 10 * \text{pastures} + \beta 11 * \text{underbrush} \\ & + \beta 12 * \text{forest} + \beta 13 * \text{bird} + \beta 14 * \text{hare} + \beta 15 * \text{wild boar} \\ & + \beta 16 * \text{mouse} + \beta 17 * \text{roe deer}\end{aligned} \quad (1)$$

where p is the probability of an event (culling adult jackal); $1-p$ is the probability that no adult jackal is culled (culling of juvenile).

Categorical variables, i.e., wind direction, moon phase, and habitat type, were used in the logistic regression model as dummy variables, with the category with the highest frequency assumed to be the base category. For wind direction, this was the category "west" (north wind was excluded from the analyses because no single juvenile was culled then); for moon phase, the base category was "third quarter"; and for habitat type, "cultivated non-forested areas" was selected as a base category. Lastly, the category "without calling sound" was used as the baseline for the variable calling sound.

We computed the Variance Inflation Factor (VIF) to verify the multicollinearity assumption made for the independent variables. VIF values over 10 might be a sign of multicollinearity. In order to find the best model (model with as few explanatory variables as possible), we used the residual analysis (stepwise method) for male and female models separately. The full variable (together with all of its dummy variables) should be incorporated into the model if any of the dummy variables show statistical significance in the stepwise method (SAS/STAT). Stepwise method first estimates parameters for variables forced into the model. These variables are the intercepts and the first explanatory variables in the model. Next, the procedure computes the score chi-square statistic for each variable not in the model and examines the largest of these statistics. If it is significant at the corresponding variable is added to the model. Variables already in the model do not necessarily remain. Variables are entered into and removed from the model (Furnival and Wilson 1974).

The area under the receiver operating characteristic (AUC) curve that we used to quantify the overall performance of the logistic regression model is a single scalar value that ranges between [0.5–1.0], where the lowest value corresponds to the performance of a random classifier and the highest value would be associated with an error-free classifier. All statistical analyses and graphical representations were performed using the SAS 9.4 statistical package (SAS Institute Inc.).

Results

From 2019 to 2023, a total of 217 jackals (95 females and 122 males) were culled during 106 hunting events with 95% confidence interval for sex ratio (female/male) (0.723/0.834). Based on the age structure, 16% juveniles and 84% adults were culled, and the overall index of catch per unit effort (CPUE) was ~2 animals per hunting day. The maximum number of culled jackals per hunting event was 5 individuals. Descriptive statistics for continuous variables (temperature, rainfall, air pressure and wind speed) is presented in Table 1. The best hunting success was achieved by attracting jackals with a calling method, i.e., by playing the sound of a hare (82 jackals; 37.8%), bird (28 jackals; 12.9%), roe deer (27 jackals; 12.4%), mouse (21 jackals; 9.7%), and wild boar (8 jackals; 3.7%). The total number of jackals culled without using a calling method was 51 (23.5%). Regarding habitat type, 56.1% of individuals were harvested in cultivated non-forested areas, 24.8% at pastures, 11.2% in underbrush, and 7.9% in forest. The moon phase also affected hunting success: 39.7% of all culls occurred during the third quarter, 26.9% during the full moon, 17.8% during the first quarter, and 15.5% during the new moon (Fig. 1a–d).

We found a statistically significant difference in the number of jackals culled according to habitat type and age for both sexes separately, i.e., for males ($p=0.019$) and females ($p=0.0058$), and also for all individuals regardless the sex ($p=0.0003$). There was also a statistically significant difference in the number of jackals culled by moon phases and age, also for males and females. On the contrary, we found no statistically significant differences in the number of jackals culled by age and wind direction, and by calling sound and age for either sex (Table 2).

Table 1 Descriptive statistics for continuous variables

Variable	*N*	Mean	Std Dev	Min	Max
Temperature (°C)	217	15.9	6.7	−0.2	29.2
Rainfall (mm)	217	0.51	1.48	0.00	9.00
Air pressure (kPa)	217	1.43	0.95	0.06	3.36
Wind speed (Beaufort)	217	2.43	0.63	2.00	4.00

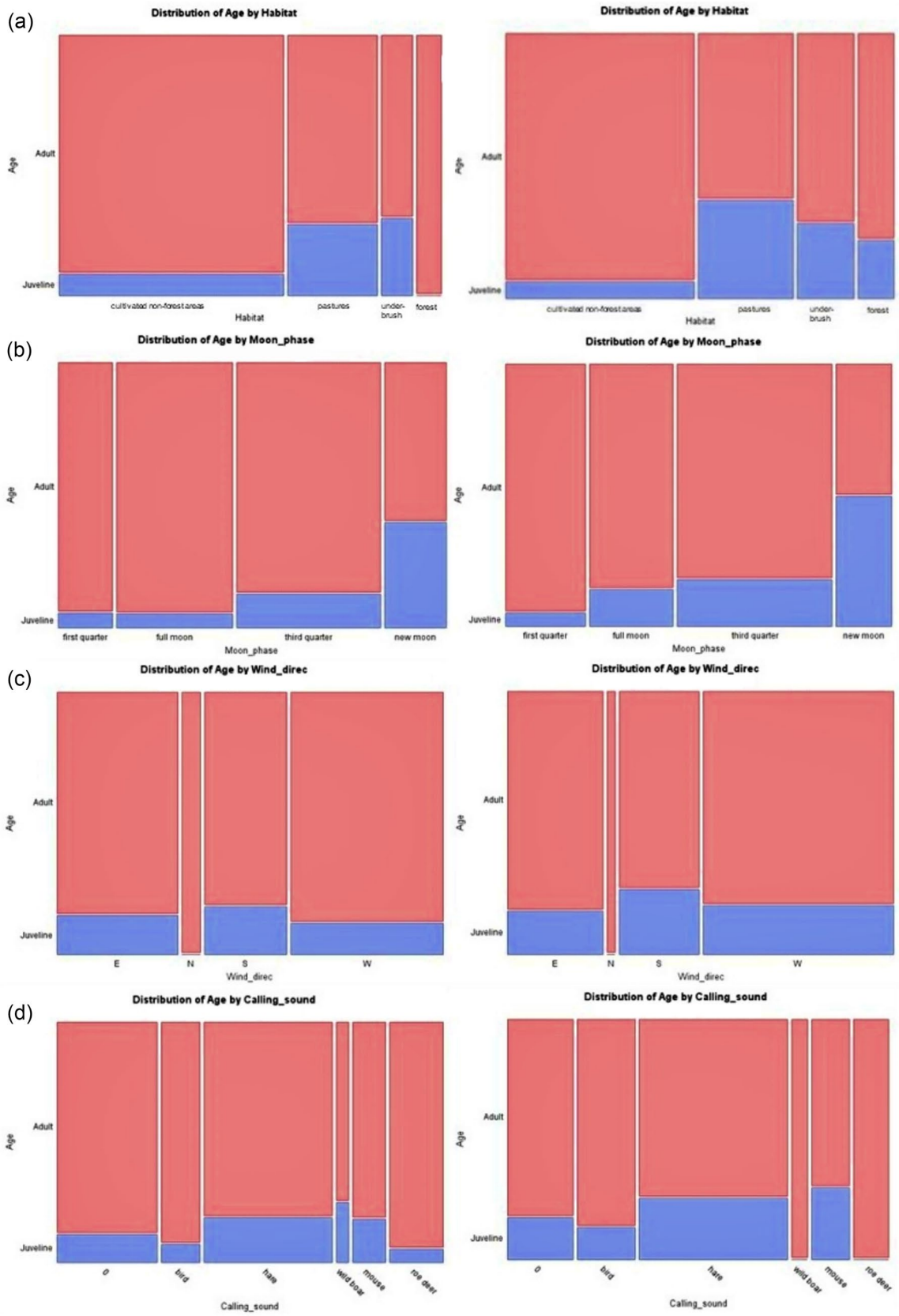

Fig. 1 Mosaic plots representing relative frequencies of age classes of harvested jackals for both sexes, i.e., males on the left and females on the right: **a** habitat type, **b** moon phase, **c** wind direction, and **d** calling sound

Table 2 Frequency table for categorical variables and results of Fisher exact and Cochran-Mantel-Haenszel tests

		Males Frequency/column percent				Females Frequency/column percent			
Variables		Adult	Juvenile	Total	Fisher chi^2 = 9.8; p = 0.0198	Adult	Juvenile	Total	Fisher chi^2 = 11.02; p = 0.0058
Habitat	Cultivated non-forest surfaces	67 65.05%	6 35.29%	73 60.83%		44 57.89%	3 16.67%	47 50.0%	
	Pastures	21 20.39%	8 47.06%	29 24.17%		15 19.74%	9 50.0%	24 25.53%	
	Underbrush	7 6.80%	3 17.65%	10 8.33%		10 13.16%	4 22.22%	14 14.89%	
	Forest	8 7.77%	0	8 6.67%		7 9.21%ž	2 11.11%	9 9.57%	
	Total *Raw percent*	103 *85.83%*	17 *14.17%*	120		76 *80.85%*	18 *19.15%*	94	
	Cochran-Mantel-Haenszel test; p = 0.0003								
Moon phase	First quarter	17 16.04%	1 5.88%	18 14.63%	Fisher chi^2 = 14.9; p = 0.0046	19 25.0%	1 5.56%	20 21.28%	Fisher chi^2 = 11.55; p = 0.0146
	Full moon	36 33.96%	2 11.76%	38 30.89%		18 23.68%	3 16.67%	21 22.34%	
	Third quarter	41 38.68%	6 35.29%	47 38.21%		32 42.11%	7 38.89%	39 41.49%	
	New moon	12 11.32%	8 47.06%	20 16.26%		7 9.21%	7 38.89%	14 14.89%	
	Total *Raw percent*	106 *86.18%*	17 *13.82%*	123		76 *80.85%*	18 *19.15%*	94	
	Cochran-Mantel-Haenszel test; p < 0.0001								
Wind direction	E	34 32.08%	6 35.29%	40 32.52%	Fisher chi^2 = 1.65; p = 0.7428	20 26.32%	4 22.22%	24 25.53%	Fisher chi^2 = 1.01; p = 0.8891
	N	6 5.66%	0	6 4.88%		2 2.63%	0	2 2.13%	
	S	22 20.75%	5 29.41%	27 21.95%		15 19.74%	5 27.78%	20 21.28%	
	W	44 41.51%	6 35.29%	50 40.65%		39 51.32%	9 50.0%	48 51.06%	
	Total *Raw percent*	106 *86.18%*	17 *13.82%*	123		76 *80.85%*	18 *19.15%*	94	
	Cochran-Mantel-Haenszel test; p = 0.4843								
Calling sound	No calling sound	30 28.30%	4 23.53%	34 27.64%	Fisher chi^2 = 2.98; p = 0.6443	14 18.42%	3 16.67%	17 18.09%	Fisher chi^2 = 5.25; p = 0.4755
	Bird	12 11.32%	1 5.88%	13 10.57%		13 17.11%	2 11.11%	15 15.96%	
	Hare	35 33.02%	8 47.06%	43 34.96%		29 38.16%	10 55.56%	39 41.49%	
	Wild boar	3 2.83%	1 5.88%	4 3.25%		4 5.26%	0	4 4.26%	
	Mouse	9 8.49%	2 11.76%	11 8.94%		7 9.21%	3 16.67%	10 10.64%	
	Roe deer	17 16.04%	1 5.88%	18 14.63%		9 11.84%	0	9 9.57%	
	Total *Raw percent*	106 *86.18%*	17 *13.82%*	123		76 *80.85%*	18 *19.15%*	94	
	Cochran-Mantel-Haenszel test; p = 0.2357								

Both full models for males and females are statistically significant and have very good predictive power, and the AUC (area under curve) > 90% (Table 3). The VIF analysis shows that the only variables that are somewhat collinear are temperature (3.9) and air pressure (4.2) which makes sense and correlation coefficient for both sexes is

Table 3 Results of full logistic regression for culling adult vs. juvenile jackals according to the model in Eq. 1

		Males						Females					
		AIC = 84.442; −2logL = 48.442; AUC = 0.929						AIC = 86.275; −2logL = 50.275; AUC = 0.921					
	Variables	PE	SE	CHI2	pr > chi^2	OR	VIF	PE	SE	CHI2	pr > chi^2	OR	VIF
	Intercept	3.80	3.29	1.33	0.248			3.60	2.87	1.58	0.209		
Moon phase	Third quarter												
	First quarter	1.64	1.70	0.94	0.332	5.18	1.39	2.75	1.71	2.59	0.108	15.70	1.36
	Full moon	0.89	1.25	0.52	0.473	2.45	1.48	−1.15	1.19	0.94	0.332	0.32	1.51
	New moon	**−4.06**	**1.67**	**5.93**	**0.015**	0.02	1.34	−1.67	1.15	2.11	0.146	0.19	1.45
	Temperature	**−0.45**	**0.19**	**5.89**	**0.015**	0.64	3.88	−0.17	0.11	2.39	0.122	0.85	3.95
	Rainfall	**−0.45**	**0.22**	**4.47**	**0.034**	0.64	1.14	−0.09	0.23	0.15	0.698	0.91	1.29
Habitat	Cultivated non-forest surfaces												
	Pastures	−2.29	1.19	3.72	0.054	0.10	1.40	**−4.34**	**1.31**	**10.96**	**0.001**	0.01	1.46
	Underbrush	−1.46	1.27	1.32	0.251	0.23	1.17	−1.33	1.09	1.49	0.222	0.26	1.28
	Forest	17.51	385.70	0.00	0.964	> 500	1.13	−0.89	1.21	0.54	0.463	0.41	1.24
	Wind speed	2.07	1.40	2.19	0.139	7.94	1.44	1.13	0.98	1.33	0.249	3.10	1.82
	Air pressure	1.76	1.12	2.46	0.117	5.83	4.22	0.49	0.77	0.41	0.523	1.64	4.17
Wind direction	W												
	E	−1.48	1.25	1.39	0.239	0.23	1.73	−0.09	1.22	0.01	0.941	0.91	1.73
	S	−0.28	1.17	0.06	0.811	0.76	1.63	−0.96	1.18	0.66	0.417	0.38	1.44
Calling sound	No calling sound												
	Bird	5.22	2.81	3.45	0.063	184.64	1.42	0.23	1.55	0.02	0.881	1.26	1.97
	Hare	−0.48	1.21	0.15	0.694	0.62	1.66	−1.43	1.29	1.22	0.269	0.24	2.40
	Wild boar	0.88	4.40	0.04	0.842	2.41	1.16	9.64	411.60	0.00	0.981	> 500	1.39
	Mouse	3.13	2.36	1.76	0.184	22.86	1.38	−0.39	1.90	0.04	0.837	0.68	1.74
	Roe deer	2.44	1.87	1.69	0.193	11.43	1.62	14.38	231.90	0.00	0.951	> 500	1.72

Significant values are indicate in bold

OR = exp(PE)

PE parameter estimate, *SE* standard error, *CHI2* Wald chi^2 statistics, *OR* odds ratio, *VIF* Variance Inflation Factor

approximately 0.78 (Table 3). Temperature was singled out as being more significant in the full model and after in stepwise procedure because it has a higher value score chi^2 statistics. For males, the effect of temperature and rainfall was statistically significant in assessing adult jackal culling compared to juveniles, i.e., the higher temperatures and rainfall caused a lower probability of culling the adult jackals (Table 3; Figs. 2 and 3). This tendency was also observed in females, but the result was not statistically significant. For wind direction, the estimated parameters indicated that during west winds the chance of culling juveniles is slightly (not statistically significant) higher than for adults. For moon phase, the new moon had statistically significant effect, and the probability of culling juveniles was higher during new moon than in the case of adults, with the third quarter as the baseline (Table 3). Analysis of habitat type indicated that the probability of culling juvenile jackals at pastures was higher than for adults in cultivated non-forested areas, and this result was statistically significant for females ($p = 0.001$) and for males at significant level of 5.4% (Table 3). It is important to note that in the case of males, no single individual was culled in the forest, so odd ratio (OR) could not be properly estimated because we have a complete separation of adults and juveniles (Fig. 1a). Similarly, OR for harvesting of female jackals in respect to calling sound was not estimated as no single juvenile female was culled when using wild boar or roe deer sound (Fig. 1d). For calling sounds, none of the categories proved to be statistically significant, but the probability of culling an adult is higher (close to the significance level, $p = 6.3\%$) than for juveniles when hunting without a calling (Table 3). We chose the best models after evaluating the complete models for both sexes and employing the stepwise procedure (Table 4). For males, the variables new moon ($p = 0.0003$) and temperature ($p = 0.011$) were singled out, while for females, new moon ($p = 0.0015$) and pastures ($p = 0.014$) were combined. By adding other dummy variables of the same parent variable to the model, we obtained the final (best) model (Table 4). Let us notice that by adding other dummy variables of the parent variable moon phase, new moon is no longer statistically significant at the significant level of 5% but 11%.

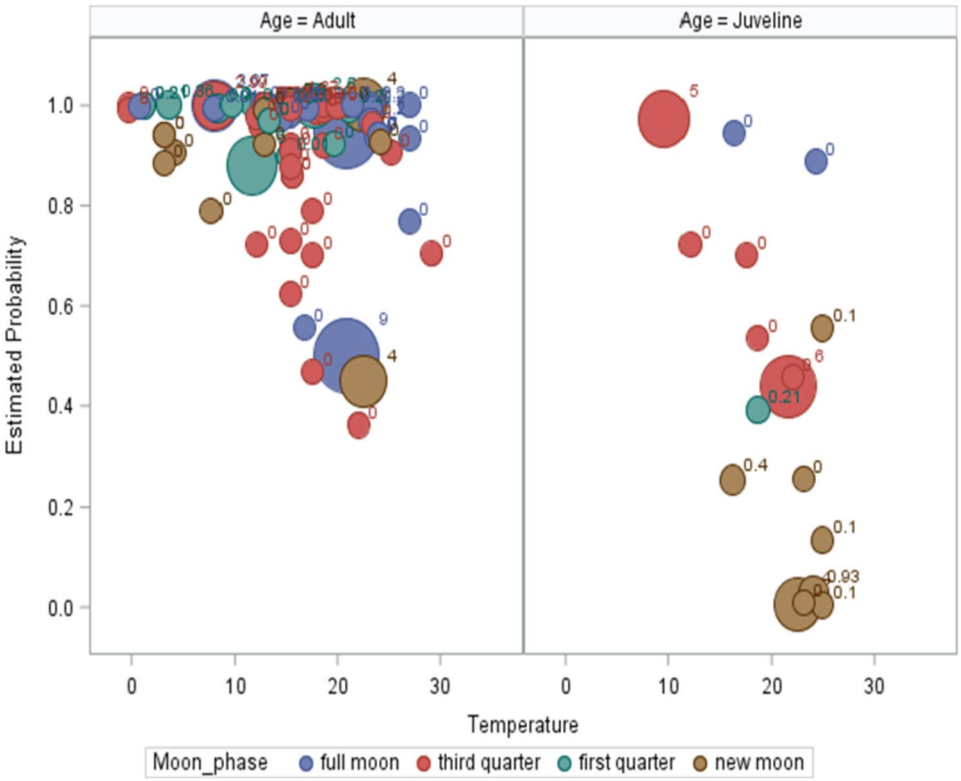

Fig. 2 Estimated probability of culling male jackals of both age classes at different moon phases, rainfalls and temperatures according to the logistic regression model. Bubble colour represents the moon phase and bubble size represents rainfall range 0–9 mm (values with bubbles)

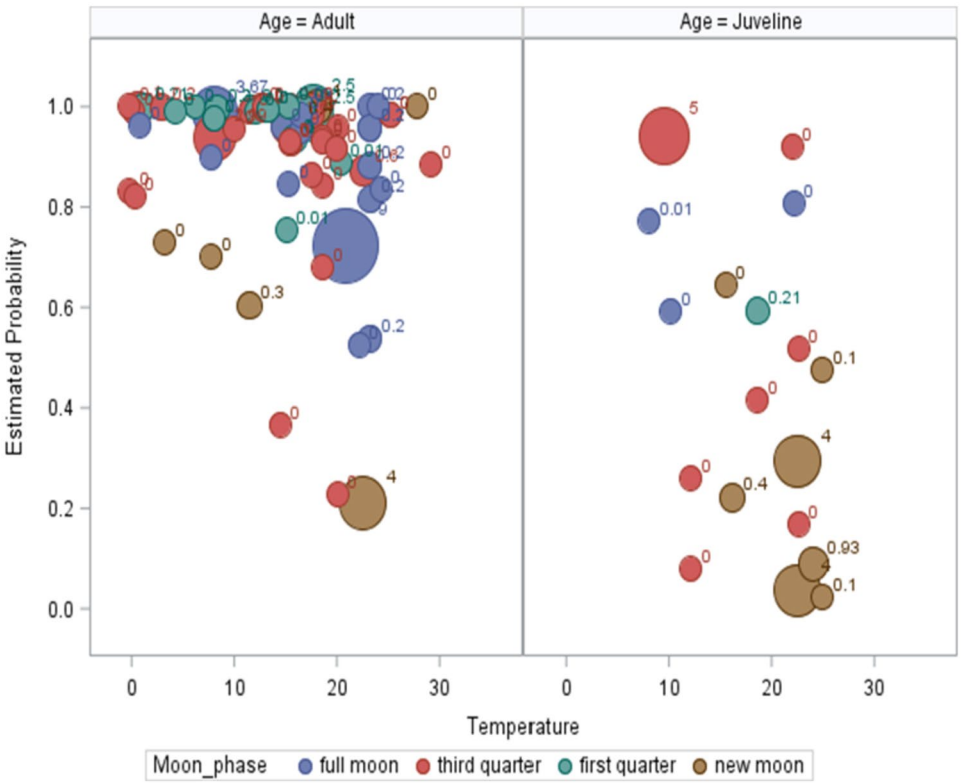

Fig. 3 Estimated probability of culling female jackals of both age classes at different moon phases, rainfalls and temperatures according to the logistic regression model. Bubble colour represents the moon phase and bubble size represents rainfall range 0–9 mm (values with bubbles)

Table 4 Results of logistic regression for culling adult vs. juvenile jackals after stepwise method

		Males						Females					
		AIC = 87.595; −2logL = 77.595; AUC = 0.787						AIC = 84.136; −2logL = 70.136; AUC = 0.828					
	Variables	PE	SE	CHI2	pr > chi^2	Score Chi2	OR	PE	SE	CHI2	pr > chi^2	Score Chi2	OR
	Intercept	4.50	1.16	15.06	< 0.001			2.74	0.71	14.98	< 0.001		
Moon phase	Third quarter												
	First quarter	0.49	1.14	0.18	0.668		1.63	2.06	1.16	3.12	0.077		7.84
	Full moon	1.44	0.89	2.60	0.107		4.20	−0.23	0.84	0.08	0.781		0.79
	New moon	**−1.37**	**0.69**	**3.96**	**0.047**	13.17	0.25	−1.21	0.76	2.55	0.110	10.11	0.29
	Temperature	**−0.15**	**0.06**	**6.53**	**0.011**	6.46	0.86						
	Rainfall												
Habitat	Cultivated non-forest surfaces												
	Pastures							**−2.52**	**0.82**	**9.31**	**0.002**	5.99	0.08
	Underbrush							−1.51	0.89	2.89	0.089		0.22
	Forest							−1.17	1.03	1.28	0.258		0.31

OR = exp(PE)

PE parameter estimate, *SE* standard error, *CHI2* Wald chi^2 statistics, *OR* odds ratio

Discussion

Managing wildlife populations is often challenging because in recent years hunters are decreasing in number, they are ageing, have less and less time as well as motivation (Massei et al. 2015; Bengsen et al. 2020). Management aiming to control population growth/abundance has the greatest effect when different methods/approaches are applied in parallel: for example, lethal control such as culling through hunting (Bengsen et al. 2020) should be accompanied by reducing the availability of one or more limiting factors (Dolev et al. 2022). To successfully control overabundant populations of different target species, many countries are changing their legislation and introducing new methods, techniques, and regulations. For example, in Europe, the use of silencers, night vision devices, and thermal scopes, as well as hunting during the night and without a specific hunting season (i.e., all year round), has been introduced recently for some game species. Some of these measures have proven to be successful in term of hunting efficacy, such as combining night vision rifle scope and thermal imaging device with acoustic calling method, as was also confirmed in our case study of hunting golden jackal in Croatia.

Culling is a traditional and commonly used method for controlling several large mammal species; however, in the case of golden jackal, it has been shown to be only locally effective in the short term, with significant "over culling" contributing to overcompensation of jackal populations growth, and up-following increase of densities to as much as four times above their pre-culling values (Dolev et al. 2022). The most likely explanation for this phenomenon in jackal populations is immigration from neighbouring areas with lower hunting pressure or even without hunting (Minnie et al. 2016), as has been described also for red foxes in the UK (Baker and Harris 2006). This claim can also be supported by the fact that golden jackal populations are spreading rapidly across Europe and have nowadays high population densities in a very great spectrum of ecosystem conditions (Potočnik et al. 2019; Cunze and Klimpel 2022).

Our results indicate a high proportion (84%) of adult jackals in the hunting bag, which can be attributed to the use of the calling method (Fig. 1d). Because adult jackals search for food items more intensively, they may respond more to the calling sound then juveniles. This indicates that such hunting method—even if hunting generally does not affect population size directly as revealed by previous study from Bulgaria (Stoyanov 2018)—may affect it indirectly, i.e., due to changed demographic (age) structure. The study of Stoyanov (2018) also confirmed an impact of jackal hunting on age structure of the population and that survival of subadults had important influence on jackal's population size because mainly 2–3 years old animals took part in the reproduction. However, as in our study, all individuals older than 1 year was classified as adults, we can assume that hunting pressure towards reproductive individuals was very high.

Several studies on different species have shown that various factors can strongly influence hunting success, such as habitat characteristics (Solberg et al. 1999; Lebel et al. 2012), weather conditions (Rösslova et al. 2020; Baur et al. 2021), and hunting methods (Tryjanowski et al. 2009; Hampton et al. 2021). Golden jackal as a species

shows remarkable habitat plasticity but prefers farmland where individuals find most of their food and meet their needs (Šálek et al. 2014; Fenton et al. 2021). This assertion is also supported by our results, as most jackals were culled in cultivated, non-forested areas and only a smaller percentage in underbrush or forested habitats. In addition, it is important to emphasize that no single male juvenile was culled in the forest habitat (Fig. 1a), which may indicate that this habitat is unacceptable for them primarily because of food selection (Bošković et al. 2013) or territorial distribution among individuals.

Weather, especially temperature, plays an important role in animal behaviour and thus affects hunting success (Baur et al. 2021). In our study, higher daily temperature leads to a lower probability of culling adult jackals (Table 3), which might be due to their lower activity during hot days. A similar result was obtained for rainfall, indicating a significant negative influence of rain on hunting success, again especially for adult male jackals (Table 3; Figs. 2 and 3). Regardless the target species, rainfall has a major influence on hunting success and is often the subject of scientific debate, with studies showing no effect (Diekert et al. 2016), a positive effect (Fobes 1945) as well as a negative effect (Rösslova et al. 2020; Baur et al. 2021).

Several other weather-related factors can also affect hunting success. Wind can be challenging because it affects regular animal movements (Wijers et al. 2022). Strong winds not only motivate animals to move from their usual habitats, but also interrupt successful hunting for humans, and consequently negatively impact hunting success (Baur et al. 2021). Even if animals move during the windy days, as soon as they smell human scent they return to a safe area. Our results show that hunting success increases with decreasing wind speed, but the influence of wind direction is even more pronounced (Fig. 1c; Tables 1 and 2). Although we cannot provide general conclusions because our study area is quite small and might be influenced by some local factors as terrain and microclimatic conditions, it is evident that during northern wind hunting success was extremely low and no juveniles of either sex was culled, whereas the greatest hunting success occurred when the wind came from the west (see Fig. 1c). Air pressure is known to be a factor that can influence animal behaviour (Tajchman et al. 2022) and thus indirectly affects hunting success. However, our results do not indicate a significant influence of atmospheric pressure on hunting success which is in accordance with previous findings on different game species, e.g., obtained by Rösslova et al. (2020) in the Czech Republic during eight hunting seasons. Moon phase is a known factor affecting predator activity, especially during periods of high visibility (e.g., full moon), when preys reduce their activity to minimise predation risk, while predators increase their activity in search of prey (Penteriani et al. 2013). This was confirmed by our study, since during periods of greater visibility (full moon and third quarter) jackals were obviously more active, therefore the opportunity of culling was greater (Fig. 1b). Interestingly, (adult) males were also more frequently culled during the new moon (Tables 3 and 4). Similar findings of moon affect were also confirmed in Africa with black-backed jackal *Canis mesomelas*; their activity increased from new moon to halfmoon and then decreased between halfmoon and gibbous (Botha et al. 2022; Wallin 2022).

Since this demographic category is probably the most active in searching for prey, this might be related to higher activity of males during the new moon when predators from Canidae family are more active and travelled more during darkness (responding to higher activity of prey species) as revealed for another Canidae species, i.e., maned wolf *Chrysocyon brachyurus* in South America (Sábato et al. 2006).

Different hunting methods play an important role considering hunting success. Our method was based on calling, i.e., imitation of different sounds that attract jackals. During the study, the five most common sounds of jackal's prey were imitated, none of which had statistical significance for hunting success (Table 3). Nevertheless, using the sounds of roe deer and wild boar did not result in culling of juvenile females (Fig. 1d), which is probably related to the size of the prey and the fact that juvenile females do not include this prey among their food (Bošković et al. 2013).

In conclusion, we can state that using night vision/thermal imaging devices in combination with calling method can be an effective tool for successful hunting of golden jackal. Although based on our results we cannot confirm that hunting affects jackal abundance/density, it is obvious that such a specific hunting approach can affect the population demographic (age) structure as also found previously related to general hunting (Stoyanov 2018). However, at the moment we cannot predict the consequence of such change in demographic structure on population abundance, i.e., either its decrease due to intensive cull of reproductive individuals or increase due to higher reproduction success of subadults and/or immigration of individuals from neighbouring areas (see also Minnie et al. 2016). Therefore, studies of the effect of (different methods) of hunting on the population structure as well as on life history traits of golden jackal should be encouraged in the future.

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Author contribution N.Š. and V.B. conceptualized the framework and wrote all drafts of the manuscript. B.P. and D.U. revised all drafts of the manuscript. A.J. did the statistical analyses. I.I. obtained and arranged raw data. All authors read, corrected, and approved the manuscript.

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Declarations

Competing interests The authors declare no competing interests.

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