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GPS-tracking reveals annual variation in home-range and sedentary behaviour in Common Kestrels breeding in central Italy

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Abstract - We studied the movements of Common Kestrels *Falco tinnunculus* in central Italy by GPS-tracking 10 individuals between 2019 and 2021. Our aim was to investigate the extent of movements during the breeding and non-breeding seasons. In the breeding season the mean home-range size increased from incubation (1.11 km^2) to the chick-rearing period (3.35 km^2), and the average home-range for the entire study period was 3.68 km^2. In winter, all tagged individuals remained within a few hundred meters of their nesting area, revealing for the first time a non-migratory behaviour for the species. In conclusion, our study provides novel data on the movement ecology of Kestrels during both the breeding and non-breeding seasons, and documented the resident behaviour of Kestrels in central Italy.

Keywords: home-range; GPS tracking, Kestrel; raptor migration; nest boxes; power lines.

INTRODUCTION

Research on movement ecology of birds provides important insights into species' responses to landscape structures or to environmental changes (e.g. Nathan et al. 2008; Fleming et al. 2014). Historically, collection of this type of data has been not only time consuming but also logistically challenging. In the last few decades, advances in technology, such as high-resolution GPS tracking, has enabled to collect remotely large datasets about activity of birds, opening new horizons for the study of home ranges, space use, or migratory behaviour (Tomkiewicz et al. 2010). GPS data may provide robust data to better describe changes in movements from the breeding to the non-reproductive season or to support the occurrence of both obligate migratory birds and resident birds over the whole distribution of particular bird species. For example, many birds of prey belonging to the genus *Falco* are described as partial migrants, but GPS data are not always available to strengthen direct field observations or data obtained from ringed birds (Miller et al. 2012).

The Common Kestrel *Falco tinnunculus* Linnaeus, 1758 (thereafter Kestrel), which is a small-size open-land bird of prey widespread across Europe, Africa, and Asia, has been described as partial migrant by several authors (e.g. Holte et al. 2016). The Kestrel is well-distributed in many environments, including grasslands, farmlands, and cities (Village 1990). Kestrels feed on a large variety of prey species with a wide latitudinal variation in diet composition (Costantini & Dell'Omo 2020). Kestrels breeding in the northern parts of their distribution mainly hunt on small mammals like voles (Yalden & Yalden 1985), which are abundant during spring and summer but not in winter. To face this seasonal decrease in prey and the harsh winter conditions, Kestrels of northern Europe are obligate migrants (Snow 1968; Newton & Dale 1996). In central or southern regions of Europe, Kestrels are partial migrants, meaning they can migrate, or even be resident, because of better climatic and food conditions (Adriaensen et al. 1998; Dhondt et al. 1997; Riegert & Fuchs 2011). Ringing programs across Europe, the main sources of data available about migratory behaviour (Adriaensen et al. 1997, The Eurasian African Bird Migration Atlas 2022), support the notion that the migratory strategy of this species varies in relation to latitude, being strongly influenced by prey abundance and weather conditions (Richardson 1990). In contrast to open-land environments, Kestrels tend to be resident in cities, probably because of the constant availability of avian prey (passerines) throughout the year (Kettel et al. 2018). However, even in cities, many studies conducted in Northern Europe highlight that Kestrels may show migratory habits (Riegert & Fuchs 2011; Sumasgutner et al. 2014), revealing that high latitudes can influence the migratory behaviour.

As compared to northern populations, there are limited systematic data on the migratory behaviour and movements of Kestrels in southern Europe. Moreover, data on movements of Kestrels have been collected with methods that present inherent limitations (e.g. visual observations: Village 1990; Brichetti & Fracasso 2003; VHF transmitters: Cunningham 2013; Riegert & Fuchs 2011; ringing programs: Adriaensen et al. 1997). In particular, the migratory behaviour has been investigated with data collected from recoveries of ringed birds (e.g. Sumrada & Hanzel 2012; Holte et al. 2016; Huchler et al. 2020), a technique that suffers unavoidable bias that may hinder interpretation. Small GPS devices represent an additional tool to record the movements of birds with precision. Within the kestrel species, GPS-data loggers have been successfully used on Lesser Kestrels *Falco naumanni* (Pliego et al. 2017, Cecere et al. 2020). Small VHF transmitters have been deployed on common Kestrels (Riegert et al. 2007), but so far to the best of our knowledge, there are no tracking studies on this species using GPS tags.

Here we report the first GPS-tracking study on Common Kestrels in central Italy, which lies in the southern part of its European range. The aim of this study was to reveal circannual movements of Kestrels, to define home-range and to investigate the migratory behaviour of the species. We further analyzed the daily flying effort, by measuring the daily distances travelled per day in relation to sex and period of the year. Finally, we also described the space arrangement in which intraspecific interactions might occur, by comparing the home-ranges of neighboring breeding birds and measuring their overlap.

MATERIALS AND METHODS

Study population and GPS tracking

The Kestrels GPS-tracked in this study belong to a population breeding in nest boxes placed on high voltage power lines (Terna S.p.a., Rome, Italy) inside and outside the city of Rome, Italy. In 2019-2020 ten breeding individuals (seven females and three males) were captured to deploy small solar-powered GPS tags (GiPSy-Remote, Technosmart Europe, Rome, Italy). Tags weighed 3.5 g, which is 1.6% of the average bird's body mass (range: 1.5-1.9%), and thus lies within the recommended limits for tagging of wild birds (Casper 2009). Females were captured at their nest boxes during the early incubation period (i.e. after laying was completed and birds were regularly sitting on the eggs) using remotely triggered traps. Males were trapped when delivering food to the female inside the nest. There was no need to recapture the individuals since data could be downloaded via radio link up to a distance of 500 m using an automated base station placed in the vicinity of the nest.

All devices were deployed using a backpack Teflon harness crossed on the sternum (Rodriguez et al. 2012). The GPS were set to sample from 6:00 A.M. to 7:00 P.M. (local time), to avoid taking points during the night and draining the instruments battery. The instruments registered 1 fix/30 minutes from April to June, and 1 fix/120 minutes thereafter. The interval between fixes was increased to save battery during winter. Kestrel behaviour was sometimes an issue for solar recharging, as they perched most of their time with the solar panel not well exposed to the sun (Hernandez-Pliego et al. 2015). Moreover, during the breeding season females spent most of their time inside the nest, preventing solar recharge. Therefore, battery requirements forced us to decrease the sampling frequency in some cases, up to 1 fix/120 minutes, the settings of the GPS could be in fact remotely modified using the automated base station.

To investigate changes of the home-range size during the year, the study was divided in two seasons: the breeding season from April to September because in our study region egg laying starts in April and hatching continues until the end of June (Costantini et al. 2009; Costantini & Dell'Omo 2020), and the post-fledging dependence period is highly variable (even longer than one month), meaning that chicks from late breeders can potentially remain in the breeding area until late September (Costantini & Dell'Omo 2020); the non-breeding season between October and March. In addition, the reproductive season was further divided in three periods according to the reproductive ecology of the species (Costantini & Dell'Omo 2020): 1) incubation-brooding, from laying of the first egg to one week after hatching, during which the female spends most of their time inside the nest; 2) chick-rearing, from the first week after hatching to the second week after fledging (ca. 45 days after hatching) during which both parents hunt and provide food to the offspring; to be conservative we chose a post-fledging period of 15 days because it is approximately the period during which young Kestrels learn how to hover and hunt (e.g. Bustamente et al. 1994; Boileau & Bretagnolle 2014); 3) post-reproductive period, during which fledglings are more independent from their parents, even if they can still be seen in the breeding area. Some individuals have been tracked for more than a year, allowing us to analyze multi-year tracking home ranges.

Home range

Home range (HR) was calculated for each individual and for each period by using the 95% autocorrelated kernel density estimate (AKDE) following Fleming et al. (2015). Briefly, different continuous-time movement models were calculated from GPS data from each individual, then the model with lowest AICc was used to produce an AKDE (R package ctmm v. 0.6.1, Fleming and Calabrese 2021). All AKDEs were projected on a planar coordinate system (WGS 84 – UTM zone 33N) to measure areas. To investigate possible differences in HR depending on period, AKDE areas were regressed against period and number of sampling days using a linear mixed-effects model with bird identity (ID) included as a random factor. Whether to include sex as a factor was decided through AICc-based model selection. Differences between factor levels were tested post-hoc (R function glth, package multcomp v. 1.4.19). To account for high variability in sampling periods, only AKDEs estimated from at least 5 days of GPS tracking were considered in the model. We calculated the General Overlap Index (GOI, Ferrarini et al. 2021) between HRs of the individuals belonging to the same pair (four individuals in total), to gather information on HR overlap change during the breeding season and throughout the year. We also calculated the GOI for the four individuals which were tracked for two years, to compare HR from one year to the other. To compare our results with those of previous studies, we calculated also the 95% KDE using normal scale bandwidth (package ks v. 1.11.7).

Daily distance travelled

Estimation of daily distance travelled (DD) might depend on how frequently GPS fixes were taken. We verified that the most common time lag between fixes was 30 minutes and filtered our subset to only use data with a temporal resolution of 30 minutes, leaving 63% of the raw data set (7,467 points). Then, distance between fixes was calculated for each individual (R function deg.dist, package fossil v. 0.4.0) and averaged over days. Similarly, to AKDE area, DD was regressed against period, sex, number of sampling days, and day of year using a GLMM with a Gamma distribution and log link, and with year and bird ID as random factors. We expected an increase in foraging effort during chick rearing, therefore we included day of year as both a linear and a quadratic term. Assumptions of normality and equal variances were met for both home range and DD models. After fitting the linear mixed effects models, residual plots were checked to confirm these assumptions. All analyses were conducted with R version 4.0.3.

RESULTS

One male Kestrel lost the device shortly after the application; therefore, GPS data were gathered from nine individuals (seven females and two males). Overall, we considered 11,910 fixes (1,323 mean per ID, ranging from 73 to 6,710). Of the nine tagged individuals, we could monitor only six beyond the incubation period (four females and the two males). One couple abandoned the nest because eggs were predated ; we no longer received data from the female's device, probably because she did not return within the download range of the base station. Devices of two other females stopped to send data during chick rearing but both females successfully raised their chicks until fledging.

Home range

Mean home range area, for the entire study period, as calculated by AKDE, was 3.68 km^2 (range 0.11-19.71 km^2). This analysis does not consider home range of bird 1007, which exhibited a unique behaviour by performing a 20 km trip from her nest on three separate occasions during the post-reproductive period. This exclusion did not affect the linear mixed-effects model since bird 1007 was only tracked for 4 days during this period, and therefore was excluded by the GLMM model. Full information on AKDE area, sampling days and total number of GPS fixes can be found in Tab. 1. The LMM including sex as a factor showed a better fitting with our data (ΔAICc of model excluding sex = 24), although neither sex nor number of sampling days were found to have a significant effect on AKDE area. Period, instead, was significantly associated with AKDE: Kestrels had smaller home ranges during incubation with respect to all other periods ($Z = -3.12$, $p < 0.01$; Tab. 2).

HR were estimated during the non-breeding season for the four individuals which were tracked between October and March. The home-range mean size during winter was 0.749 km^2 (range 0.493 – 1.21 km^2). No long-distance movements (> 20 km from nest area) from the breeding area were registered during the study period, especially during winter, except for irregular daily movements.

Although these results are purely descriptive since they refer to only four individuals belonging to two couples, we found a tendency within each couple to exhibit a higher GOI during incubation (Tab. 3).

Finally, we also calculated the 95% kernel density estimate (KDE) per individual, without distinguishing between periods, using normal scale bandwidth (R package ks v. 1.11.7), that shows a mean home range size of 1.5 km^2.

Daily distance travelled

Kestrels travelled shorter distances per day during incubation (est = -0.71, SE = 0.17, $t = -4.15$, $p < 0.01$), and longer during the post-reproductive period (est = 0.34, SE = 0.08, $t = -1.46$, $p < 0.01$). We found a

Table 1. Home range size by individual (ID) and breeding phase. Only home ranges estimated from at least 5 sampling days were used in the LMM model of AKDE area regressed against breeding period, sex, and sampling days with bird ID as a random factor. AKDE models correspond to the following: IID identically and independently distributed Gaussian model; OU Ornstein-Uhlenbeck model; OUf/OUF Ornstein-Uhlenbeck model restricted to a finite home range; letters ‘i’ or ‘a’ in the model specifications stand for isotropic or anisotropic.

ID	Sex	Period	AKDE95 (km^2)	Sampling days	Tot fixes	AKDE model
1001	Female	Incubation	19.71	3	73	OU a
1002	Female	All data	0.59	257	985	IID a
		Incubation	0.02	9	97	OU a
		Rearing	1.00	23	132	IID i
		Post-breeding	0.58	225	756	IID a
1003	Female	Incubation	0.11	11	161	OU a
1004	Female	All data	1.52	210	1061	OUF a
		Incubation	0.42	16	201	OU a
		Rearing	2.05	35	292	OU a
		Post-breeding	1.18	159	568	IID a
1005	Female	All data	1.22	45	528	OUf a
		Incubation	0.49	9	142	OU a
		Rearing	1.58	27	323	OUf a
		Post-breeding	1.08	9	63	IID a
1006	Male	All data	1.43	407	6710	OU a
		Incubation	1.23	11	252	OU a
		Rearing	1.45	30	595	OU a
		Post-breeding	1.74	227	2293	OU a
1007	Female	All data	5,438.24	30	487	OUF a
		Incubation	*	1	1	
		Rearing	0.009	25	429	IID a
		Post-breeding	57.28	4	57	OUf a
1008	Male	All data	1.53	160	1642	OUF i
		Incubation	1.52	20	513	OU a
		Rearing	1.67	30	619	OU a
		Post-breeding	1.24	110	510	IID a
1010	Female	Incubation	3.35	19	263	OUF a

(*) AKDE of bird 1007 was not calculated during incubation because of lack of data. Note that the bird 1007 has an extremely wide home range, due to overestimation of the AKDE. The bird 1007, in fact, made several excursions outside the home range that increased its extension. The home range calculated with 95% KDE is 0.17 km^2, which is a more plausible value.

Table 2. Summary of LMM model of AKDE area against breeding period, sex, and number of sampling days.

	Value	SE	t-value	p-value
Intercept	1,521,853.0	529,657.0	1.50	0.18
Period = Chick rearing	731,234.5	234,080.3	3.12	<0.01
Period = Post-breeding	-540,275.5	370,117.2	0.48	0.63
Sex = Male	350,684.9	1,002,336.0	0.35	0.74
N. sampling days	111,418.9	179,849.3	0.62	0.54

Table 3. General Overlap Index (% GOI) of male and female HR within the same couple during the reproductive periods.

Period	Couple 1004-1006	Couple 1005-1008
Incubation	59.0%	74.3%
Chick rearing	39.5%	71%
Post breeding	51.7%	66%

negative association with squared day of the year (est = -0.09, SE = 0.02, t = -2.24, $p < 0.01$), indicating a non-linear relationship between DD and period of the year. Males tended to fly longer distances per day than females (est = 1.26, SE = 0.43, t = 2.96, $p < 0.01$), although with greater variation among individuals. The model summary is reported in Tab. 4.

Multi-year tracking

Females 1002 and 1004, and males 1006 and 1008 were monitored for two years. Although device performance deteriorated with time, and the number of fixes was lower, it is clear that each of the four individuals occupied the same home-range area (Fig. 1) and the same nest for breeding, and none of them showed migratory behaviour. Finally, the reoccupation of the same area is also confirmed by the GOI calculated between years: 93% for 1002, 63% for 1004, 98% for 1006, and 100% for 1008.

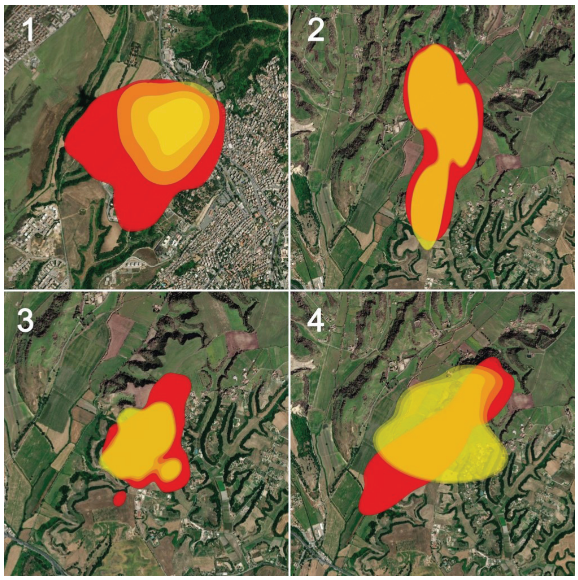

Figure 1. Multi-year tracking of individuals followed for multiple breeding seasons. AKDE home - ranges are provided per year: in red the first year of monitoring, in yellow the following year. 1: years 2019 (red) and 2020 (yellow) of the 1008 (male). 2: years 2020 (red) and 2021(yellow) of 1006 (male). 3: years 2019 (red) and 2020 (yellow) of 1002 (female). 4: years 2019 (red) and 2020 (yellow) of 1004 (female).

DISCUSSION

Home range

Common Kestrels breeding in the area of Rome had an average home range, calculated by AKDE, of 3.68 km^2, which is approximately twice the estimate (1.5 km^2) obtained using the classic KDE method. Our AKDE estimate of the home range also differs from estimates of previous studies (e.g., Cunningham 2013; Village 1990), which relied on the KDE method, a common issue when comparing traditional KDE to AKDE.

The results of our work also show that males have a larger home-range than females during the reproductive season, which is in agreement with prior work based on direct observations (Tolonen & Korpimaki 1995). Females dramatically increased their home-range from incubation to chick-rearing period, as expected owing to their larger contribution to incubation as compared to males (Fig. 2). Prior work showed that variation of the home range of Kestrels is mainly determined by the brood's food requirements and by prey abundance (Casagrande et al. 2008) but can also depend on competition among neighbouring breeding individuals (Riegert et al. 2007).

The overlap of home ranges between partners was highest at the beginning of the breeding season. During incubation, females spent most of their time in the nest-box and movements, which were also restricted around the nest, were wholly included in the partner's larger home-range. The lowest overlap if considering the average between the couples (41.3%) occurred during the post-reproduction period, suggesting an increased trophic competition or an expansion of hunting territories (Village 1982).

Daily displacement

Like home range area, daily travelled distance increased from incubation to the chick-rearing period as well, as previously suggested for other Kestrel populations (Tolonen & Korpimaki 1994, Ramellini et

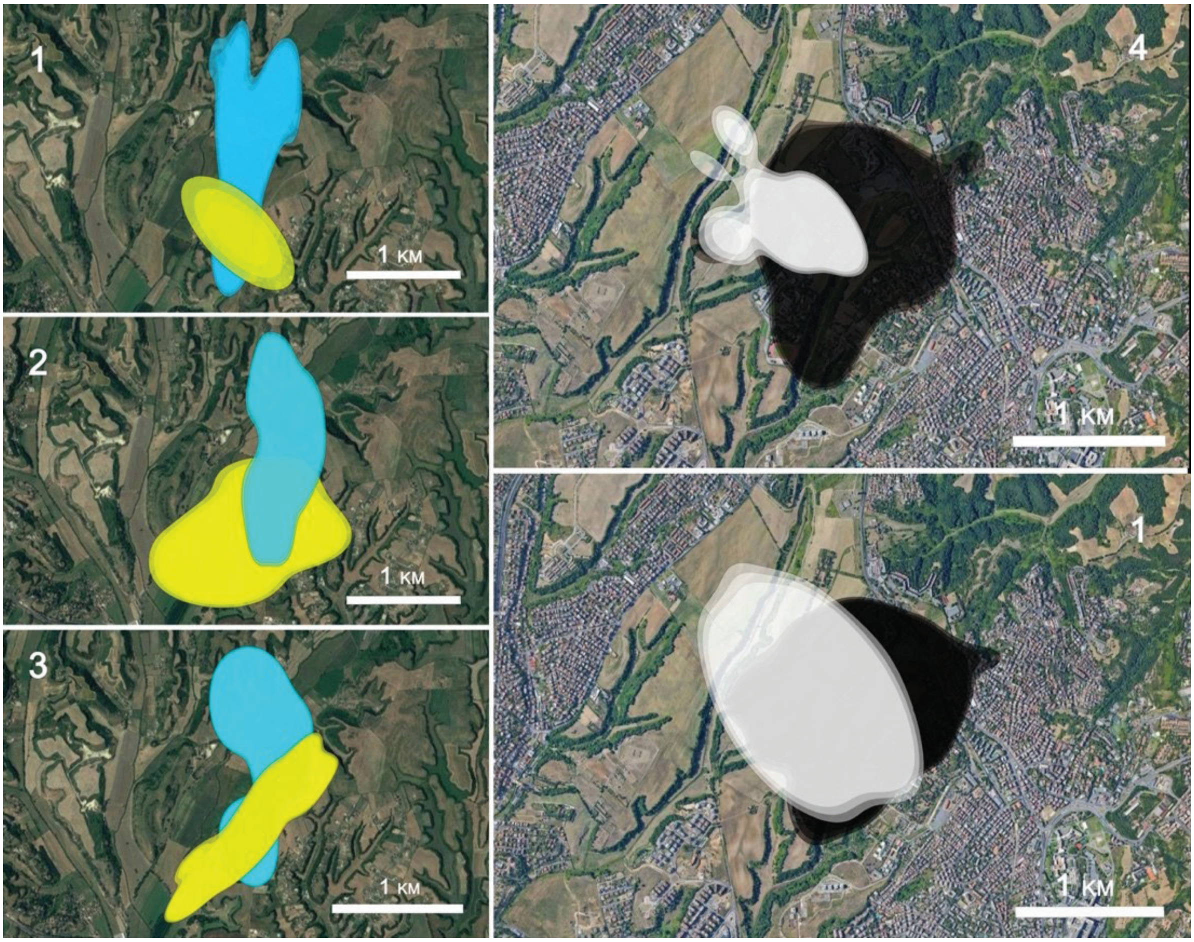

Figure 2. On the left: changes in overlap between male and female of the same couple. AKDE home - ranges of the couple 1004 (female, yellow) and 1006 (male, blue) from May 2019 to July 2021. 1: incubation period, 2 rearing-chick period, 3 post-reproduction period. On the right: overlap between male (1008) and female (1005) of the same couple, measured by AKDE home-ranges (white female, black male). 1 - Incubation period. 2 - Rearing-chick period.

al. 2022).

In winter, due to bad weather conditions and to a shift toward perch-hunting behaviour (e.g. Masman et al. 1988b) we expected reduced flight activity. This was the case in general, however, we also recorded a few events of extended daily displacements, with rapid flights up to 20 km from the breeding area and return within the day. This type of event was also observed during the late chick-rearing period in one individual, and seemed not to be related with foraging activity but more with an impulse to explore the surroundings. Further work is needed to clarify the meaning of this behaviour.

Migration and wintering area

Our data show that the four individuals that we could track for two consecutive winters (October-March) remained in the vicinity of the breeding site. Although these data are limited to a small number of individuals, they represent the first direct evidence of non-migratory behaviour of the Kestrels in the Mediterranean region, demonstrated with GPS instruments. In fact, return data of ringed individuals, which are abundant in central Europe and have helped to depict the winter movements of the species across countries (Costantini & Dell'Omo 2020), are almost missing for our study region, regardless of the fact that more than 6,500 Kestrels have been ringed in Italy since 2000 within the EURING framework (data analysis in preparation). One factor that could lead to a resident behaviour is the proximity to the city of Rome as previously suggested for other European cities (Huchler et al. 2020), as it might guarantee milder winter conditions and larger availability of prey. However, there is debate about whether cities are optimal environments for Common Kestrels, as results are contrasting (e.g. Sumasgutner et al. 2014; Kettel et al. 2018; Costantini & Dell'Omo 2020). This topic deserves further investigation.

In conclusion, the results of our multi-year GPS tracking show that the size of the home ranges, the overlap between partners, and the daily displacement of individuals vary in relation with the season. Our data also show that movements are performed in a very restricted area throughout the whole year, suggesting the occurrence of a non-migratory behaviour of Kestrels in our study area.

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Table 4. Summary of GLMM model of daily displacement against day of year, breeding period, sex, and number of sampling days.

	Value	SE	z-value	p-value
Intercept	3.99	0.62	6.49	<0.01
Day of year	-0.01	0.06	-0.14	0.89
Day of year ^{2}	-0.09	0.02	-3.71	<0.01
Period = Chick rearing	0.71	0.17	4.09	<0.01
Period = Post-breeding	1.05	0.17	6.22	<0.01
Sex = Male	1.26	0.43	2.96	<0.01
N. sampling days	-0.73	0.20	-3.67	<0.01

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