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Benefits of incorporating a scat-detection dog into wildlife monitoring: a case study of Pyrenean brown bear

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Abstract. In the Pyrenees, brown bear population abundance is estimated from non-invasive genetic analyses of scat and hair samples. Although such analyses are highly beneficial for population monitoring and research, it can be especially difficult for humans to locate bear scats in the field. To address this, we have incorporated a dog (trained from an early age to detect bear scats) into these efforts since 2014. Here, we compared the effectiveness of the scat-detection dog/handler and human-only teams to locate bear scats using our work in the Pyrenees as a case study. A species validation was systematically carried out, either genetically or visually using a microscope, based on the presence of bear hair, for all scats collected from 2010 to 2019. From 2014 to 2019, the use of the dog/handler team in addition to human-only teams increased the average number of bear scats collected annually by four times in comparison with the 2010-2013 period when only humans were searching for scats. This temporal augmentation could not be explained by the increase in bear population size. From 2014 to 2019, the annual percentage of outings during which at least one bear scat was found was 17 times higher for the dog than for humans. The use of the dog also resulted indirectly in a better genotyping success and genetic identification of more individuals due to a larger choice of viable samples that could be sent to the molecular laboratory, as well as a larger number of cub scats detected by the dog. We found that even the use of a single scat-detection dog can greatly improve the efficiency of detecting target scats in challenging monitoring conditions.

Key words: conservation dogs, faecal samples, genetic identification, large carnivores, non-invasive population monitoring

Introduction

Monitoring wildlife can be challenging, especially when animals are rare, elusive, solitary, largely nocturnal, highly mobile, far-ranging, and/or inhabiting remote or rugged habitats. The critically endangered Pyrenean brown bear (*Ursus arctos* Linnaeus, 1758) population is one such example, living in a mountain range peaking at 3,404 m above sea-level on the border of France, Spain and Andorra. Human persecution pushed this population to the edge of extinction in the mid-1990s with only five individuals present (Taberlet et al. 1997). The successful reintroduction of 11 bears, originating from Slovenia, from 1996 to 2018 (Quenette et al. 2001, 2006, 2019) has allowed the population to attain a minimum of 52 individuals in 2019, ranging over 10,400 km² (Sentilles et al. 2020).

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To date, the Pyrenean brown bear population abundance has mainly been estimated from non-invasive genetic analysis of hair and scat samples, field-collected either opportunistically or using systematic monitoring approaches (Sentilles et al. 2020). Between 2010 and 2019, more than 400 professionals and volunteers from the Brown Bear Network (ROB) gathered bear sign data in the French Pyrenees, comprising hair (42.6%), tracks (17.1%), photos and videos from camera traps (15.9%), attacks on livestock and beehives (15.2%), and other cues (e.g. visual observations, scratches on trees, 5%), with a relatively small proportion being scats (4.1%, J. Sentilles et al., unpublished data). Bear scats are not easily detected by humans in steep habitats with dense understory of the kind in this region, nor are they readily visually distinguishable in the field from scats of other mammal species with similar diet. In the Pyrenees, bear cub scats, in particular, can be easily confused with those of red foxes (*Vulpes vulpes* Linnaeus, 1758) and European badgers (*Meles meles* Linnaeus, 1758). In North America, it has been fairly well established that large carnivore scat detection can be improved through the use of scat detection dogs (see references in Orkin et al. 2016, Grimm-Seyfarth et al. 2019). In 2013, we therefore decided to incorporate this technique in future efforts to monitor the Pyrenean brown bear population, by training a dog from an early age to detect bear scats.

In this paper, we report on the effectiveness of the scat-detection dog/handler team compared with human-only teams to detect brown bear scats in the Pyrenees. We predicted that the dog/handler team would outperform the human-only teams in finding bear scats. We also compared the dog/handler and human-only teams' success in collecting viable samples for genotyping and detecting different individuals.

Material and Methods

Study area

Our study site is located in the French Pyrenees, on the border of Spain and Andorra where brown bears are present in the major part of the mountain range extending east-west for 430 km (Fig. 1). The Pyrenees Mountains are characterized by alternating large massifs and valleys with relatively steep slopes and elevations ranging from 500 to 3,400 meters. Forests of deciduous and coniferous

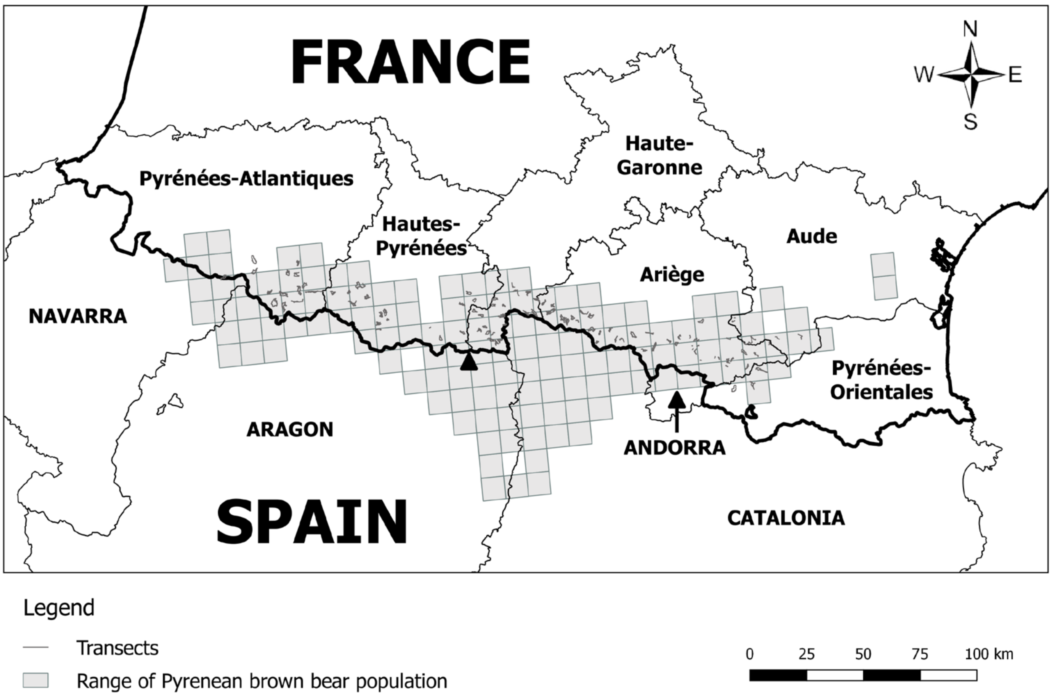

Fig. 1. Cumulative annual Pyrenean brown bear range area for the period 2010-2019. Note: In each of the 10 × 10 km light grey squares at least one confirmed bear clue was found between 2010 and 2019. Black lines represent administrative limits (French administrative departments, Spanish provinces, and Andorran borders between France, Spain and Andorra). Dark grey lines represent transects used in France between 2010 and 2019 within the framework of the systematic monitoring of the Pyrenean brown bear population.

trees cover more than 40% of the landscape (Martin et al. 2012). Above 1,800 meters, rhododendron (*Rhododendron ferrugineum*) and bilberry (*Vaccinium myrtillus*) form dense heaths, with alpine pasture and rocks dominating at the summits.

Scat-detection dog selection and training

In 2013, we selected a female purebred Belgian malinois puppy aged three months with a calm demeanour to facilitate home life with the handler and allow work among livestock and other working dogs. Early on, the puppy expressed enthusiasm for a toy then learned to associate brown bear scats with the reward of playing with this toy (Sentilles et al. 2016). The dog training consisted of hiding bear scats in vegetation and bringing the dog to the area and allowing it to search off leash, so that searching was not biased towards a particular location by the handler (Grimm-Seyfarth et al. 2019). The dog was taught to lie down facing the scat and bark after locating a brown bear scat. It was rewarded only if it detected a brown bear scat. All brown bear scats used during the training were provided either by captive facilities or collected in the field and validated to species using molecular tools. The dog was ultimately trained to specifically identify brown bear scats regardless of its content or age, exposure to sun or weather, and among scats from other animal species, as well as to work in a range of environmental conditions (e.g. indoor, outside at home or work place, outside in the mountains) and regardless of humans and animal presence, weather, and habitat type. In 2014, at ten-months of age, this Belgian Malinois became the first scat-detection dog in France.

Population monitoring

In the French Pyrenees, monitoring of the brown bear population relies primarily on non-invasive field methods. These can be based on monitoring in a manner that is systematic (i.e. transect sampling combined with baited hair traps and automatically triggered camera traps, and specific planned operations) or opportunistic (i.e. collection of bear data or samples by any mountain users such as hikers with no specific sampling design, as well as all reported putative bear damages on livestock and beehives; Bellemain et al. 2005, De Barba et al. 2010b, Sentilles et al. 2020). Individual identification of bears is accomplished by the genetic analysis of hair and scats (see below), as well as visual evidence (colouration, scars, GPS collars, or VHF ear tag transmitters) obtained by remote cameras (Sentilles et al. 2020).

Systematic bear scat surveys are mainly conducted on fixed 10-km-long transects, spread homogeneously over the area of known, regular bear presence, which covers about 3,000 km² in France (Sentilles et al. 2020, Vanpé et al. 2020; Fig. 1, Table S1). These transects are walked monthly between May and November each year in search of bear signs by teams of two members of the Brown Bear Network, or by the scat-detection dog/handler team. Planned operations are also initiated during the year, with or without the dog/handler team, in order to search for bear scats around dens, diurnal resting places, in areas where females with cubs have been recently observed, or potential feeding areas during mast years. In all cases except transect surveys, the scat prospection technique with the dog is more or less modelled on the one used for counting mountain Galliformes species with a pointing dog (Léonard 1992). Basically, the dog/handler team walks in zigzags, facing the wind, over a sample area ranging from five to ten hectares, over a period of three to four hours.

In opportunistic monitoring, scat searches are carried out where bears may be present, which encompasses approximately 6,000 km² in France (Sentilles et al. 2020, Vanpé et al. 2020; Fig. 1). This includes in particular the search of bear signs by professional damage inspectors or by the scat-detection dog/handler team investigating livestock injury or mortality when suspected by brown bears (hereafter named "damage investigations"). The scat search procedure for damage investigations is identical whenever it is performed, with or without the dog in attendance. More precisely, it is carried out within a radius of 100 to 200 meters around the reported damage for 30 minutes to an hour, depending on the topographic relief of the area, with the entire area systematically covered.

All scat searches involving the dog were conducted with the dog off-leash to maximize the area covered, but the dog had to remain as much as possible in sight of its handler. All putative bear scats found by dog/handler or human-only teams were collected, mapped and entered in the overall database. Importantly, because the detection dog is trained and rewarded for detecting the scat of target species, and not the living animal, and remains under the supervision of the handler, it poses no direct threat to free-living animals. This research was considered to be of low ethical risk to dogs, humans and wildlife involved.

The size of the Pyrenean brown bear population is annually estimated using the Minimum Detected Size (MDS) index, which corresponds to the total number of different individuals detected in the population during the year (Sentilles et al. 2020). The MDS of the current year is used every year to correct the MDS of previous years (e.g. to add bears which were not detected the previous years but detect the current year) and defined what we called the Minimum Retained Size (MRS; Sentilles et al. 2019). MRS thus corresponded to a reassessment of the EMD in the light of information collected in subsequent years.

Species validation

A species validation was systematically carried out, either genetically or visually using a microscope based on the presence of bear hair for all putative bear scats collected in the field from 2010 to 2019 either by the dog/handler or human-only teams. Hereafter, "bear scats" will refer to sole genetically or visually validated bear scats. Otherwise, "putative bear scats" will be used.

From 2014 to 2019, all putative bear scats collected in the field by human-only teams (n = 337) were presented to our scat-detection dog in standardised conditions in a scent box for the purpose of discrimination (as per Wasser et al. 2004), or visually confirmed on the basis of the presence of bear hair for species validation, before being sent to the molecular laboratory. The dog indicated on 239 of them (the 98 failing to be indicated on by the dog were not submitted for genetic analysis).

Genetic analyses

Due to financial constraints, only a subset of all collected scat samples were genetically analysed to evaluate their viability for determining genotypes or to identify different individuals. From 2010 to 2013, we selected scats for genetic analyses among those that were visually validated based on the presence of bear hair (n = 84). From 2014 to 2019, we selected scats among those detected by the dog or found by human-only teams, which the dog indicated during species validation tests (n = 102).

About 1 cm^3 of scat material was collected per sample and stored in 95% ethanol. Hair samples were collected and stored in paper envelopes. Genetic samples were sent to the Laboratoire d'Ecologie Alpine CNRS joint research unit

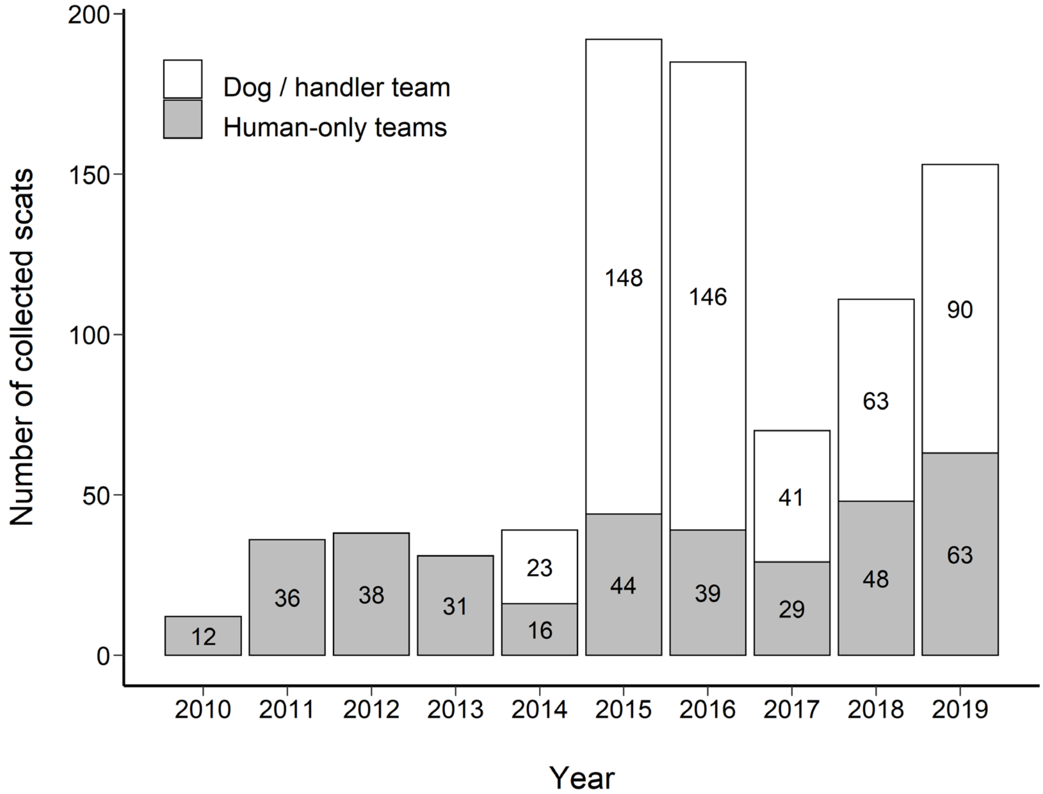

Fig. 2. Number of bear scats collected annually between 2010 and 2019 with (in grey, by the human-dog team) and without (in white, by human-only teams) the help of the scat-detection dog. The year 2014 corresponds to the first year of use of the scat-detection dog.

Table 1. Efficiency (mean ± SD) of the scat-detection dog/handler team (D), human-only teams (H), and both combined (D + H) in terms of number of bears scats detected per year, percentage of positive outings per year, number of bear scats detected per outing and per year, and number of bear scats detected per positive outing and per year, for the periods before (2010-2013) and after (2014-2019) the scat-detection dog was used, within the framework of the brown bear population monitoring (both periods) as well as the specific case of damage investigations (2014-2019 period only). Note: Bear scats are defined here as scats genetically validated or visually validated using a microscope based on the presence of bear hair. A positive outing is an outing yielding at least one bear scat.

	Population monitoring				Damage investigations only		
	2010-2013	2014-2019			2014-2019		
	H	D	H	D + H	D	H	D + H
# bear scats/year	29.25 ± 11.87	85.17 ± 52.88	39.83 ± 16.17	125.00 ± 62.43	22.83 ± 13.23	19.00 ± 10.00	41.83 ± 19.70
% positive outings/year	2.44 ± 1.32	36.89 ± 16.56	2.21 ± 0.98	3.74 ± 1.76	62.88 ±13.95	8.10 ± 4.65	13.06 ± 6.43
# bear scats/outing/year	0.03 ± 0.02	1.58 ± 0.89	0.03 ± 0.01	0.10 ± 0.07	1.43 ± 0.58	0.11 ± 0.06	0.24 ± 0.16
# bear scats/positive outing/year	1.27 ± 0.16	4.12 ± 1.43	1.54 ± 0.34	2.60 ± 0.79	2.28 ± 0.74	1.38 ± 0.21	1.79 ± 0.30

(LECA), or the ANTAGENE Company for analysis using a mitochondrial DNA (mtDNA) species identification test, as well as a Polymerase Chain Reaction (PCR) multi-tube approach, based on 13 microsatellite markers and one sex-specific marker for individual and sex identification. Extraction methods, PCR protocols, protocols for individual identification, molecular sexing, and distinguishing brown bear samples from other animal species' samples are described in detail in De Barba et al. (2010a, b).

Statistical analyses

We aimed to compare the effectiveness of dog/handler and human-only teams for collecting bear scats in the field. First, we investigated all bear scats collected within the framework of the Pyrenean brown bear population monitoring, comparing scats collected (i) before (2010-2013) *vs.* after (2014-2019) we started using the dog, and (ii) by the dog/handler *vs.* human-only teams for the 2014-2019 period (Fig. 2, Table S2). Second, we focused only on bear scats collected during damage investigations, for which a bear was implicated or could not be ruled out, comparing scats collected by the dog/handler *vs.* human-only teams for the 2014-2019 period (Fig. 2, Table S2). All comparisons were done in terms of average numbers of bear scats found annually, as well as percentages of outings yielding at least one bear scat annually (hereafter named "positive outings"). For the 2014-2019 period, we also compared the dog/handler and human-only teams' success in collecting viable samples for genotyping (genotyping success)

Table 2. Model selection for the effects of bear population size (PopSize, fitted as a continuous variable) and period (Period, fitted as a factor with two levels: 2014-2019 *vs.* 2010-2013) on the total number of scats collected annually in the field using a linear regression model. Note: K – number of parameters, AICc – Akaike Information Criterion corrected for small sample size, ΔAICc – difference in AICc between the given model and the selected model, AICcWt – Akaike weight, representing the ratio of ΔAICc values for each model relative to the set of candidate models. The selected model (smallest AICc value) is shown in bold. The annual estimation of the Pyrenean brown bear population size is based here on the Minimum Retained Size (MRS).

Models	K	AICc	ΔAICc	AICcWt
Period	**3**	**114.34**	**0.00**	**0.66**
PopSize	3	116.99	2.64	0.17
Constant	2	117.50	3.16	0.14
PopSize + Period	4	120.32	5.97	0.03
PopSize * Period	5	129.19	14.84	0.00

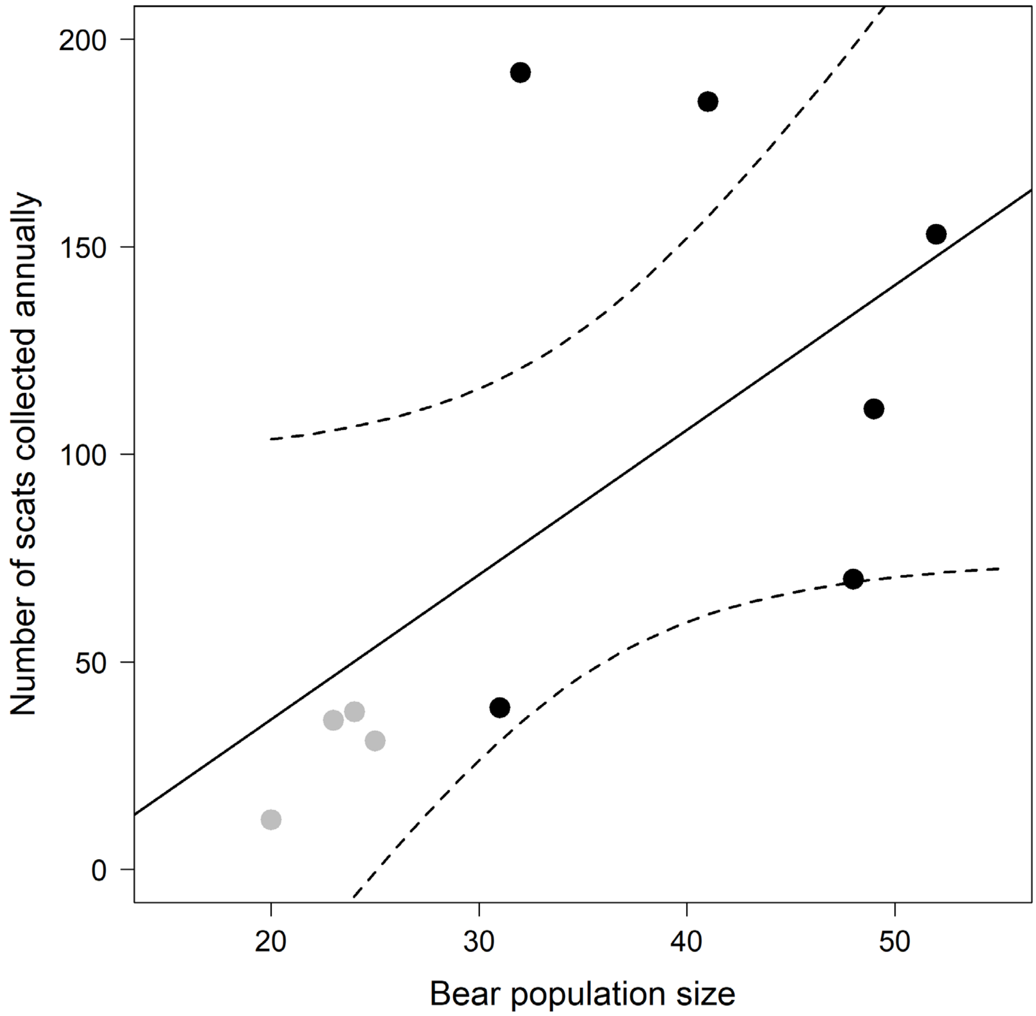

Fig. 3. Variation in the number of scats collected annually from 2010 to 2019 in the French Pyrenees as a function of Pyrenean brown bear population size and the use (blacks dots, 2014-2019 period) or (grey dots, 2010-2013 period) not of the scat-detection dog. Note: The black continuous line (y = 3.54 × −35.1) represents the non-significant linear regression model between the two variables and the black dashed line its 95% confidence interval. The annual estimation of the Pyrenean brown bear population size is based here on the Minimum Retained Size (MRS).

and detecting different individuals (population monitoring success).

Given small sample sizes within groups (n ≤ 6 years per period), we used Wilcoxon rank sum tests (two-sided) to compare means of the two periods (2010-2013 *vs.* 2014-2019), and Wilcoxon signed rank test for paired samples (two-sided) to compare means of the two scat survey techniques within the 2014-2019 period (with *vs.* without the use of the dog). We used a simple linear regression model fitted using the "lm" function in the "nlme" R package (Pinheiro et al. 2020) for testing the effects of Pyrenean brown bear population size based here on MRS (fitted as a continuous variable) and period (fitted as a factor with two levels: 2014-2019 *vs.* 2010-2013) on the total number of scats collected annually in the French Pyrenees. We built all possible models (i.e. population size × period, population size + period, population size, period, constant; see Table 2) and compared them with the small sample size corrected Akaike information criterion (AICc) as recommended by Burnham & Anderson (2002). All statistical analyses were performed using R 3.4.2 software (R Core Team 2019). Unless otherwise stated, data are shown as mean ± SD.

Results

Comparison of all bear scats collected within the framework of population monitoring from 2010 to 2013 *vs.* from 2014 to 2019

The mean number of bear scats collected per year was four times lower before than after the use of the scat-detection dog (significant difference: W = 24, $P = 0.01$; Fig. 2, Table 1). The best model

Table 3. Parameter estimates of the selected model describing the effects of the period (Period, fitted as a factor with two levels: 2014-2019 *vs.* 2010-2013) on the total number of scats collected annually in the field using a linear regression model.

	Estimate	SE	t	*P*
Intercept	125.00	20.37	6.137	0.0003
Period (2010-2013)	–95.75	32.20	–2.973	0.0178

(i.e. with the lowest AICc) testing for the effects of bear population size and period on the total number of collected bear scats in the field annually was the model including the period only (AICc weight = 0.66; Table 2). Based on this model, the total number of bear scats collected annually was significantly higher after than before using the dog/handler team (mean difference ± SE = 95.75 ± 32.00, Adj. R^2 = 0.466, $F_{1,8}$ = 8.84, *P* = 0.018; Table 3, Fig. 3), but was not affected by bear population size.

The annual percentage of positive outings was slightly higher for the 2014-2019 period than for the 2010-2013 period (Fig. S1A, Table 1). We collected, on average, three times more bear scats per outing and per year between 2014 and 2019 than between 2010 and 2013 (significant difference: W = 22, *P* = 0.04; Table 1, Fig. S1B). In addition, the number of bear scats collected per positive outing each year was, on average, twice as large between 2014 and 2019 than between 2010 and 2013 (significant difference: W = 24, *P* = 0.01; Fig. S1C, Table 1).

Comparison of bear scats collected by the dog/handler *vs.* human-only teams within the framework of population monitoring from 2014 to 2019

From 2014 to 2019, the dog/handler team recovered 68% of the 750 bear scats collected in total over these six years (Fig. 2, Table S2). During this period, outings were significantly more successful in terms of yielding at least one bear scat when performed with the dog than without (significant difference: V = 21, *P* = 0.03; Fig. S1E, F, Table 1). The annual percentage of positive outings was on average 17 times higher when performed with than without the dog (significant difference: V = 21, *P* = 0.03; Fig. S1D, Table 1).

Among the 102 putative bear scats that the dog either found in the field or that was discriminated by the dog in the lab (during species validation tests) between 2014 and 2019, and from which samples were sent for genetic analyses, 84 provided DNA that could be amplified. All 84 samples were confirmed as bear scats by the mtDNA species identification test. The scats found by the dog/handler team enabled the identification of 46% of all genetically-identified bears or 70% of all genetically-identified cubs of the year (Table S3). Without the work of the dog/handler team, nine of the 20 genotyped cubs would not have been identified at all.

Comparison of bear scats collected by the dog/handler *vs.* human-only teams during damage investigations from 2014 to 2019

Although the damage investigations carried out with the scat-detection dog represented less than 8% of all investigations carried out between 2014 and 2019, they enabled us to collect more than 54% of all bear scats found during damage investigations (Table S2). The number of bear scats collected per damage investigation each year was, on average, 13 times higher for the dog/handler than for human-only teams (significant difference: V = 21, *P* = 0.03; Fig. S2A, Table 1). On average, the percentage of damage investigations carried out annually that resulted in the collection of at least one bear scat was eight times higher for the dog/handler than for human-only teams (significant difference: V = 21, *P* = 0.03; Fig. S2B, Table 1).

Of the bear scat samples genetically analysed, a lower proportion was found by the dog/handler than by human-only teams (47% *vs.* 63%, respectively) during damage investigations. However, the dog/handler team allowed us to identify, on average, 15 times more genotypes and 14 times more individuals per year and per damage investigation, compared to human-only teams (for both: significant difference: V = 21,

Table 4. Comparison of the dog/handler (D) *vs.* human-only (H) teams' success in collecting viable samples for genotyping (genotyping success) and detecting different individuals (population monitoring success) within the framework the specific case of damage investigations carried out between 2014 and 2019. Note: Data are shown as mean ± SD for the number of genotypes and the number of different individuals per outing and per year.

	D	H
# bear scats genetically analysed	64	72
# genotypes/outing/year	0.32 ± 0.12	0.02 ± 0.02
# different individuals/ outing/year	0.24 ± 0.06	0.02 ± 0.01
Total # different individuals	19	18

P = 0.03; Fig. S2C, D, Table 4). Finally, 70% of the 27 individual bears identified during damage investigations could be identified from scats found by the dog compared to 18 individuals for human-only teams (Table 4). Among these 27 individuals, nine (including six cubs of the year) were detected exclusively by the dog.

Discussion

Non-invasive genetic sampling techniques based on scats hold great promise for large carnivore conservation research. Applications include species and individual identification, population parameter estimation, diet and seed dispersal studies and population genetics analyses (Rodgers & Janečka 2013). But scat detection rates by humans are generally low, particularly in challenging steep habitats with dense understory. Our results clearly show, using the Pyrenean brown bear as a case study, that even using a single scat-detection dog/handler team (see de Oliveira et al. 2012 for a similar study) can greatly improve the efficacy of collecting target scats, and increase the probability of acquiring genotypes and detecting individuals from scat samples.

Since 2014, we have observed a great improvement in our efficiency of detecting bear scats in the field compared to the period when human-only teams were searching for scats (2010-2013). Our results show that those temporal variations cannot be explained by an increase in bear population size over time, but result mainly from the use of the dog since 2014. In addition, we have no reason to believe that human experience in detecting bear scats significantly changed over this time. Although we could not compare the efficiency of the dog against humans in rigorously similar conditions within the framework of population monitoring, for instance searching simultaneously scats on the same transects (Grimm-Seyfarth et al. 2019), our results from damage investigations clearly confirm that the scat-detection dog out-performed the abilities of humans to detect scats when placed under strictly similar scat searching protocols.

Furthermore, since the use of a scat-detection dog helped us to collect more bear scats per outing, we were able to select fresher scats (with less DNA degradation) to send to the molecular laboratory, allowing a better genotyping success and identifying more individuals genetically, which is essential to estimate population size reliably in the Pyrenees mountains. In particular, the use of the dog permitted better identification of the individuals involved in damage to livestock, which provides key information on inter- and intra-individual variability of predatory behaviour, and allows for better management of "problematic" bears. It also resulted in a significant saving of time, human resources and money (see the cost information section in the Appendix S1). Interestingly, most of the individuals detected by the dog/handler team were cubs < one year old and could not have been identified at all without the help of the dog. The scats from cubs are particularly difficult to find and identify by humans given their small size and their possible confusion with red fox scats. As such, the dog/handler team made an important contribution to estimating the reproduction parameters of the population.

The high inter-annual variability in the number of scats collected using the dog between 2014 and 2019 (85.17 ± 52.88) could be explained by the existence of two mast years (2015 and 2016), combined with an increasing experience of the dog at detecting bear scats over time (Fig. 2). During the autumn of mast years, bears commonly concentrate on areas of high seed availability in the forest, resulting in a concentration of bear scats over restricted areas. This situation facilitates scat detection by the dogs but not necessarily by humans. Indeed, because they operate largely by scent rather than sight, dogs assist in finding visually concealed targets, such as scats hidden below dead leaves, in grass or under dense understory (see also Grimm-Seyfarth et al. 2019). In addition, dogs help in minimizing sampling bias towards scats with traits that enhance their visibility (e.g. larger, more exposed, older and/or brighter scats; Long & MacKay 2012, Bonesi et al. 2013, Grimm-Seyfarth et al. 2019). During the fall of 2015 (a mast year for acorns) and 2016 (a mast year for beechnuts), up to four different bears could thus be identified in an area as small as one square kilometre due to the genotyping of nine scats found by the scat-detection dog (J. Sentilles, pers. comm.); representing a peak in the number of scats collected by the dog during these two mast years (147.00 ± 1.41) compared to other years (54.25 ± 28.91). Hence, in addition to obtaining a better insight into demographic parameters through genetics, the use of the scat-detection dog conferred a better understanding of the diet and habitat use of the Pyrenean brown bear during the hyperphagia period.

We used the scat-detection dog to discriminate scats collected by human-only teams. Through this process, we aimed to refine selection of scats sent to the molecular laboratory, and thus to save time and money (Grimm-Seyfarth et al. 2019), although it still requires processing time. Between 2014 and 2019, 98 scats were confirmed by the dog as non-bear scats and were not subsequently sent to the molecular laboratory, which allowed us to save almost €15,100 in laboratory fees. Although it might be possible that some bear scats were missed during this discrimination process (i.e. some false negatives may arise as a result of failure of the dog to detect the presence of the target odour, or a failure of the handler to identify the positive alert; Concha et al. 2014), we are confident that this would be rare. Indeed, interactions of non-target species with target scats via urine-marking, coprophagy, and moving scats with their mouths can affect a scat's genetic profile, rather than dog detection ability of the target odour (DeMatteo et al. 2018). In addition, we expect the dog to favour "false positives" rather than "false negatives" to obtain the reward, and the dog always reinforced the barking signal in cases when the handler did not appear to notice. Finally, as recommended by Concha et al. (2014), we used the sniffing behaviour of the dog to distinguish true from false negatives. A short single sniffing duration indicated a true negative, in contrast to false positives, true positives, and false negatives, which were characterized by a longer sniffing and/or a second sniffing episode (dogs tend to reinvestigate inconclusive odours before issuing a response). In the specific context of an increasingly pressing social demand for bear management in the Pyrenees, the dog's reliability and speed of species discrimination, associated with its efficiency in scat detection, are valuable. Furthermore, the scat-detection dog has become important in facilitating dialogue and discussions with livestock breeders in the field, acting as an 'ambassador' on a subject as sensitive as the presence of the brown bear in the Pyrenees.

The efficiency of the detection dog technique has encouraged us to extend the method to the detection of grey wolf (*Canis lupus* Linnaeus, 1758) scats using a different dog (Roda et al. 2020), as well as carcasses and poisoned baits in Catalonia and Andorra. Interestingly, the first tests carried out with our bear scat-detection dog during the winter of 2017-2018 confirmed the feasibility of using the same dog for the subsequent and simultaneous detection of scats from other species: European and American minks (*Mustela lutreola* Linnaeus, 1761 and *Neovison vison* Schreber, 1777, respectively; see Sentilles et al. 2019).

Overall, we recommend the integration of scat-detection dogs alongside human efforts to strengthen current work on large carnivore population monitoring, conservation and management. Our study suggests that even the use of a single scat-detection dog can greatly improve the cost-efficiency and reliability of detecting target scats, while minimizing sampling bias, especially in challenging remote conditions such as mountains and habitats with dense understory. Dogs are particularly valuable for improving offspring genetic identification and, as such, make an important contribution to estimating the reproduction parameters of the populations. In conclusion, even though the scat-detection dog technique focuses only on non-invasive scat sampling and cannot replace humans in many ways such as hair and camera trap surveys, visual observations and telemetry, it is a valuable complementary tool to human survey efforts to monitor target species.

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Supplementary online material

Appendix S1. Cost information.

Fig. S1. Comparison of the mean annual percentage of positive outings (i.e. outings for which at least one scat was collected) (A and D), the mean number of scats collected annually per outing (B and E), and the mean number of scats collected annually per positive outing (C and F) between 2010-2013 (before we started using the scat-detection dog) and 2014-2019 (after we started using the dog) periods (A, B and C), as well as between human-only and the scat-detection dog teams during the 2014-2019 period (D, E and F).

Fig. S2. Comparison of the mean number of scats collected annually per damage investigation (A), the mean annual percentage of damage investigation allowing to collect at least one scat (B), the mean number of genotypes obtained annually per damage investigation (C), and the mean number of different individuals detected annually per damage investigation (D), for human-only and the scat-detection dog teams during the 2014-2019 period.

Table S1. Annual brown bear population systematic monitoring effort (number and total length of transects) in the French Pyrenees from 2010 to 2019.

Table S2. Total number of outings carried out and total number of bear scats (genetically or visually validated using a microscope based on the presence of bear hair) detected each year by the scat-detection dog/handler team (D), by human-only teams (H), and in total (D + H) within the framework of the brown bear population monitoring as well as the specific case of damage investigations for the periods P1 from 2010 to 2013 before the scat-detection dog was used, and P2 from 2014 to 2019 after the scat-detection dog was used, as well as the whole study period from 2010 to 2019 (P1 + P2).

Table S3. Number of different individuals and cubs of the year genetically identified between 2014 and 2019 within the framework of brown bear population monitoring in the French Pyrenees as a result of scats detected by the dog/handler team (D), and all scat and hair samples detected by either the dog/handler or human-only teams (D + H).

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