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Using miniaturized GPS archival tags to assess home range features of a small plunge-diving bird: the European Kingfisher (*Alcedo atthis*)

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Abstract

Background: The European Kingfisher (*Alcedo atthis*) is a small plunge-diving bird, today considered a species of conservation concern in Europe given its rapid population decline observed across the continent. We implemented a pilot study aimed at providing first data allowing to: (1) assess home range features of the European Kingfisher for populations with unevenly distributed feeding habitats; (2) define conservation implications for habitats exploited by such populations; and (3) evaluate possibilities for developing GPS tracking schemes dedicated to home range studies for this species that could be possibly applied to other small plunge-diving birds.

Methods: In 2018 and 2019, we equipped 16 breeding European Kingfishers sampled within the marshes of the Gironde Estuary (France), with miniaturized and waterproof GPS archival tags deployed with leg-loop harnesses (total equipment mass = 1.4 g; average bird mass = 40.18 ± 1.12 g).

Results: On average, we collected 35.31 ± 6.66 locations usable for analyses, without a significant effect on bird body condition ($n = 13$ tags retrieved). Data analyses highlighted rather limited home ranges exploited by birds (average = 2.50 ± 0.55 ha), composed on average by 2.78 ± 0.40 location nuclei. Our results also underscore: (1) a rather important home range fragmentation index (0.36 ± 0.08); and (2) the use by birds of different types of small wetlands (wet ditches, small ponds or small waterholes), often exploited in addition to habitats encompassing nest locations.

Conclusions: Our study reveals interesting GPS tracking possibilities for small plunge-diving birds such as the European Kingfisher. For this species, today classified as vulnerable in Europe, our results underline the importance of developing conservation and ecological restoration policies for wetland networks that would integrate small wetlands particularly sensitive to global change.

Keywords: GPS tracking, Habitat connectivity, Small wetlands, Waterbirds, Wetland ecological networks

Background

Listed in Annex I of the European Union's "Birds Directive", the European Kingfisher (*Alcedo atthis*) is a small plunge-diving bird, today considered as a species of conservation concern in Europe given its rapid decline observed across the continent (BirdLife International 2004). In 2015, the European population was estimated to be decreasing by 30–49% over three generations (BirdLife International 2021). This significant decrease has led to the classification of the European population as "vulnerable" under the IUCN's criterion "A" (BirdLife International 2015). The European Kingfisher, a specialized

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species breeding within freshwater environments (Brooks et al. 1985), is particularly subject to water pollution or perturbation of its habitats that are likely to significantly impact population conservation conditions (Tucker and Heath 1994).

Given the declining and alarming population trend of the European Kingfisher in Europe and the possible relationship between this decline and the management or perturbations of the habitats exploited by the species, studies are needed to characterize its home range features. Until now, most studies dedicated to habitat features of the European Kingfisher have focused on environmental factors explaining the distribution of breeding pairs such as the bed stream features (Peris and Rodriguez 1996; Bonnington et al. 2007), the quality of riparian vegetation (Peris and Rodriguez 1996), the availability of food (Campos et al. 2000) or the water quality (Meadows 1972), but few studies considered combinations of potential factors affecting the distribution of the species along watercourses (Bonnington et al. 2007; Vilches et al. 2012). To examine the possible overlap of bird territories along the Meuse River (Belgium), Hürner and Libois (2005) radio-tracked two European Kingfisher males during the breeding period. Since this limited study, no work has characterized home range features of the species. Such data are nevertheless important, particularly for populations breeding within sites where access to trophic resources may be unevenly distributed and for which small water bodies, particularly sensitive to global change, may be relevant to population conservation.

Characterization of home range features of birds involves radio or GPS (Global Positioning System) tracking schemes that are particularly challenging to implement for small plunge-diving birds such as the European Kingfisher. Kingfishers of the genus *Alcedo* generally fly low over water and perch close to the water surface (Bonnington et al. 2007), inducing low detection probability of miniaturized VHF radio tags on equipped birds. Thus, GPS tracking, which constitutes the most revolutionary advance in assessing home range animal features (Tomkiewicz et al. 2010), appears as the best technical means to monitor home range characteristics of the European Kingfisher. Today, the latest technical advances allow the use of GPS devices (archival tags) weighing about 1 g (Hallworth and Marra 2015; Fraser et al. 2016). Such tags can be easily deployed on birds weighing about 35 g, following the rule of 3% of animal body mass to determine whether the deployment of tracking devices is appropriate or not (Kenward 2001). Nevertheless, the potential use of such miniaturized devices remains largely uncertain for species like the European Kingfisher, particularly regarding bird tolerance to tags and to the equipping method chosen. For diving birds, the use of tracking devices is particularly difficult given the high risk of notable impact on animal behaviour (Spiegel et al. 2017). For the European Kingfisher, the deployment of tracking devices is constrained by the bird's plunge-diver behaviour and its limited size, as well as by characteristics of the nests built by the species: tight burrows dug in the soil or within brittle stones. For their study, Hürner and Libois (2005) glued the tags under the tail feathers of birds, but this technique is not possible for GPS tags nearly five times heavier and bulkier than VHF radio tags. As a result, methods used to attach miniaturized GPS devices that would minimize the impact on the health and behaviour of birds while limiting poor tag retention remain to be identified.

Despite the recent miniaturization of electronic devices, studies up to now conducted by radio or GPS tracking on small plunge-diving birds remain rare and have been mainly conducted for species with a minimal body mass between 100 to 200 g such as terns (for example: the Sooty Tern *Onychoprion fuscatus*, Soanes et al. 2015; the Sandwich Tern *Thalasseus sandvicensis*, Fijn et al. 2017 and the Artic Tern *Sterna paradisaea*, Seward et al. 2021). Thus, the critical limits of radio or GPS tracking techniques for small plunge-diving birds with a maximal mass that does not exceed 50 g remain unknown. This is particularly regrettable since the development of radio or GPS tracking schemes for small plunge-diving birds may provide important data for the conservation of habitats exploited by varied species such as the European Kingfisher, or other species of small plunge-diving birds such as the Blue-banded Kingfisher (*Alcedo euryzona*), a critically endangered species endemic to the Indonesian island of Java (Birdlife International 2018).

Given the importance in monitoring home range features of the European Kingfisher for population conservation, and the interest in documenting potential effects of radio or GPS tracking techniques in the framework of research conservation schemes dedicated to small plunge-diving birds, we implemented a pilot study aimed at providing first data allowing to: (1) assess home range features of the European Kingfisher populations with unevenly distributed feeding habitats; (2) define conservation implications for habitats exploited by such populations; and (3) evaluate opportunities for developing GPS tracking schemes dedicated to home range studies for this species of conservation concern that could be applied to other small plunge-diving species.

Methods

Our study was focused on a breeding population located along the right bank of the Gironde estuary (mid-French Atlantic coast) within the Special Protection Area "Estuaire de la Gironde – marais de la rive nord" (SPA

No. FR5412011; Fig. 1). Breeding birds were sampled over a linear range of approximately 30 km (between 45° 33′ 14″ N, 00° 57′ 10″ W–North and 45° 19′ 35″ N, 00° 42′ 58″ W–South) and over a width of approximately 6 km from the shore of the estuary. The sampled population (estimated between 25 to 30 pairs, R. Musseau, unpublished data) breeds within different habitats (alluvial woodlands with varied water levels, small water basins or small rivers), and is characterized by unevenly distributed feeding locations exploitable by birds: patches of small water bodies, rivers or channels. Birds were captured and recaptured using "Japanese" mist nets (height: 2.50 m; mesh: 16 mm and 5 shelves; length: 3 to 12 m) produced by Ecotone®. Mist nets were positioned as close as possible to the nests (located beforehand), directly in front of bird nests or close to the nests, across axes used by birds to access the nests. Nests were selected after confirming their occupation by birds, but without being able to determine the stage of broods within the nests. Indeed, the burrows of the European Kingfisher can be particularly convoluted, which often render ineffective the use of endoscopes to explore the breeding chamber located at the end of the burrows. After capture, birds were aged and sexed according to the criteria detailed by Demongin (2016), ringed with a metal "Museum Paris" ring engraved with a unique number, measured, GPS tagged and released at the capture site. Measures included: (1) wing length (flattened straightened method, Svensson 1992); (2) head length, measured from the tip of the bill to the back of the head using an electronic caliper; and (3) body mass, measured with an electronic scale to the nearest 0.1 g.

Birds were equipped with archival GPS tags (Fig. 2). As recommended by Kenward (2001), we used GPS tags with a mass (including attachment elements) as close as possible to 3% of the bird mean mass expected. We used "PinPoint-10" archival GPS tags (1.0 g, produced by Lotek Wireless Inc.), which at our request, were adapted for the European Kingfisher (adaptations necessary due to regular immersion in water and the circulation of birds within the burrows of their nests). The adapted devices used for our study had the following features: length ~ 25 mm; width ~ 12 mm; height ~ 4 mm. Given their small size, the devices were not equipped with solar panels. Devices were fitted with a smooth and thin "whip" antenna in plaited steel (~ 40 mm in length and 0.5 mm in diameter). Waterproofing was achieved by an addition of a liquid synthetic elastomer coating that dries on contact with

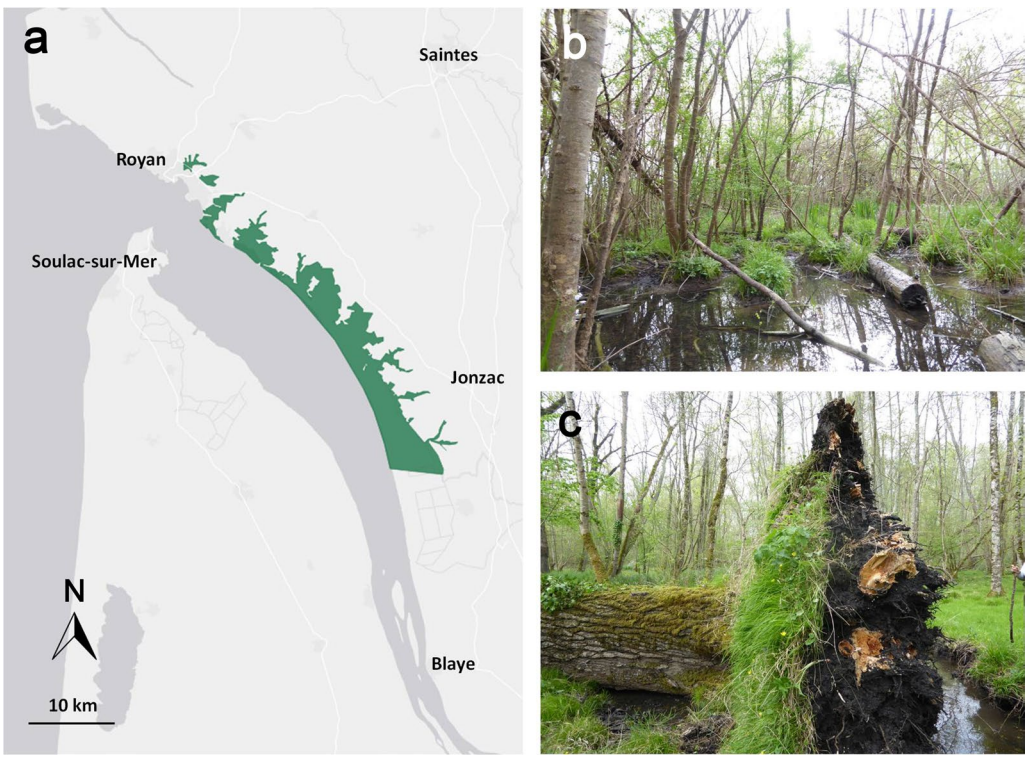

Fig. 1 **a** study site (green: Special Protection Area "Estuaire de la Gironde—marais de la rive nord" SPA No. FR5412011). **b**, **c** typical habitats exploited by the population of European Kingfisher (*Alcedo atthis*) breeding within the marshes of the right bank of the Gironde estuary. Map: © INPN (https://inpn.mnhn.fr). Pictures: © BioSphère Environnement

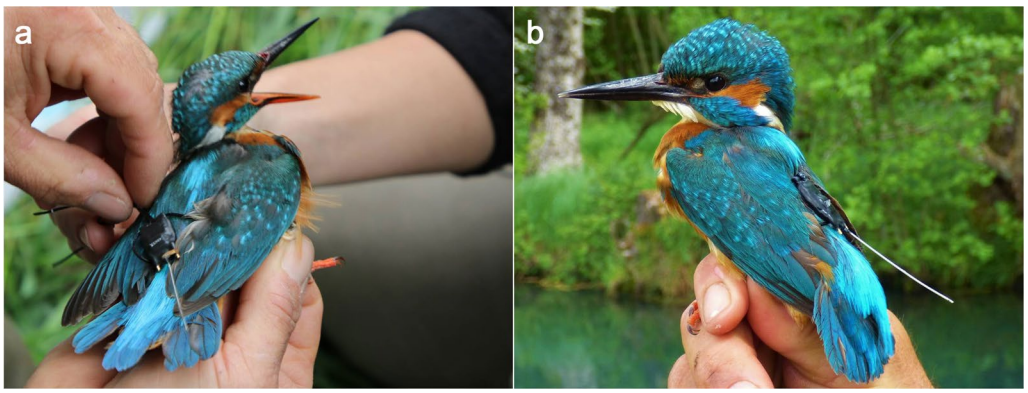

Fig. 2 **a** equipping a European Kingfisher (*Alcedo atthis*) with a miniaturized and waterproofed GPS archival tag. **b** European Kingfisher equipped with the GPS device

air (Plasti Dip®) up to the limit of ~ 1.3 g per device. GPS tags were attached to birds using leg loop harnesses, as described by Rappole and Tipton (1991), using braided nylon (0.8 mm in diameter) tied above the GPS tags with a reef knot consolidated by a point of glue (Loctite 454®). Given the possible difficulties in recapturing birds, we created a breaking point on the harness consisting of a few stitching marks made with a thin cotton thread, which allowed a trade-off between: (i) good tag retention and the lessening of discomfort risk for birds while they move through their burrows or during dive phases, and (ii) a possible break of the harness caused by the weakening of the cotton fibers in the short or medium term in the event of experiencing difficulties in recapturing birds. The total mass of the equipment (GPS tag + harness) was ~ 1.4 g. GPS devices were configured to collect one location every 30 min, between sunrise and sunset, calculated for the deployment location (i.e. approximately from 7:30 a.m. to 8:30 p.m. local time—for birds captured during the first half of April, and 6:20 a.m.to 9:45 p.m. local time—for birds captured during the first half of June). Given that the aim of our study was to characterize the home range of birds, focusing particularly on feeding habitats, we chose to collect data only during the day knowing that the European Kingfisher is a diurnal fisher, which catches its prey by recognizing their shapes and movements (Brooks et al. 1985). The interval between each collected location was chosen to minimize the autocorrelation risk among locations while maximizing the number of locations over the operating period of the tags (the potential number of locations being limited by battery capacities). Tags were programmed to initiate data collection one day after being deployed on birds, allowing animals a minimum period to adapt to the equipment. Five days after tag deployment, which represents the maximum operating period expected of the GPS tags given the frequency of data collection, birds were recaptured and the GPS tags removed. Data were transferred to a computer using a DLC-2 box (device produced by Lotek Wireless Inc., allowing communication between the GPS tags and the computer) and the "PinPoint host" interface also developed by Lotek Wireless Inc.

To evaluate possible impacts of tags on bird health condition, we analysed changes in bird body mass while comparing tagged and untagged birds. Non-tagged birds were unexpectedly captured during ringing operations implemented to capture juveniles in order to collect feathers within the framework of a study to analyse contamination levels of birds by trace metals. Considering the possibility of significant variation in female mass during the breeding period due to egg production, analyses were performed using only data collected from males. Given the small sample size, the comparison of bird body mass variation between groups (tagged and untagged) was performed using a Fisher-Pitman permutation test (FPP test) with 10,000 permutations, a powerful alternative to the Wilcoxon-Mann–Whitney rank-sum test (Kaiser 2007). Analyses were performed using the "coin" R package (Hothorn et al. 2008) run under the R software environment (version 4.0.0, R Core Team 2020). Home range size and fragmentation levels were assessed using a cluster analysis, following the multi-nuclear outlier-exclusive range core method defined by Kenward et al. (2001). Analyses were performed using the software "Ranges 8 v. 2.16" (Anatrack Ltd., Kenward et al. 2008). We defined cluster convex polygons (= nuclei) using the objective core method, integrating for calculation, as suggested by Kenward et al. (2001), a rescaling of x and y coordinates to equalize variance (Silverman 1993) and the Gaussian kernel function for density estimation introduced by Worton (1989). By analogy with plotting contours or 95% ellipses of the density distribution,

allowing the determination of the global home range of the animals monitored (Worton 1989), we chose to exclude from analysis locations in the largest 5% of the nearest-neighbor distance distribution. A fragmentation index (partial area—Cpart) was calculated adding areas of all clusters divided by the area of the single convex polygon encompassing all clusters. This index ranges from 0 to 1. A value close to 0 indicates a high fragmentation level of individual home range, while a value close to 1 corresponds to a single continuous cluster. Diversity indices of bird home ranges were calculated to estimate the diversity of use of the different clusters (DivLocs) and the diversity of cluster areas (DivArea). These metrics were calculated using the Simpson's index: $1/\Sigma p_i^2$, where DivLocs p_i is the proportion of the total n locations in cluster i and DivArea p_i is the proportion of the area of the cluster i relatively to the total area of the different clusters. The values of these metrics start at 1 if animals use a single nucleus and increase with the diversity of habitat use (DivLocs) or the diversity of nuclei areas (DivArea). Analyses were performed using GPS data with a Horizontal Dilution of Precision (HDOP) ≤ 5. In order to be analysed, collected GPS locations were transformed following Lambert Conformal Conic (LCC) projection by means of a data importation in the QGis software ("Free Software Foundation", version 2.14.12).

For the different variables analysed, given the small size of data sets, standard errors and confidence intervals (95% CI) were calculated using a non-parametric bootstrap resampling method, consisting of 1500 random samples (with the same size as the original sample) generated by a random draw with replacement of the values in the original data set (Efron 1979; Efron and Tibshirani 1993). For 95% CI, we used the Bias Corrected and accelerated bootstrap method (BCa, detailed by Efron (1987) and Preacher and Selig (2012)). These parameters have been calculated using the "boot" R package (Canty and Ripley 2021) run under the R software environment (version 4.0.0, R Core Team 2020).

Results

We equipped a total of 16 breeding European Kingfishers with GPS loggers (7 individuals in 2018: 4 males + 3 females; and 9 individuals in 2019: 5 males + 4 females) captured in front or close to 9 different nests (7 potential pairs and 2 single individuals, see details in Table 1). We used 11 different tags (4 tags were reused after battery recharging). The average date of bird equipping, for the two years combined of the study, was April 22. On average, birds were recaptured 7.38 ± 1.30 days after being GPS tagged (95% CI 5.85–11.64 days; maximum = 23 days). Three individuals were never recaptured: 2 females that had been captured rather close to a targeted nest, but that were breeding in another nest; and 1 female we failed to recapture before the end of the occupation of its nest, and subsequently we were unable to recapture within its breeding site. Initial body mass of birds was on average 40.18 ± 1.12 g (95% CI 38.22–42.62 g). GPS loggers represented on average 3.52 ± 0.09% (95% CI 3.33–3.70%) of the initial bird body mass. For all tagged birds, the average body mass variation between capture and recapture was − 1.85 ± 2.41% (95% CI − 6.76–2.92%; maximal gain = + 16.38%; maximal loss = − 15.59%). Comparison of mass variation between capture and recapture for tagged and untagged males (years 2018 and 2019 pooled) revealed an average mass variation of: (i) − 2.40 ± 3.03% (95% CI − 7.67–4.65%; maximal gain = + 16.38%; maximal loss = − 15.59%) for tagged males ($n = 9$); and (ii) − 4.25 ± 1.70% (95% CI − 7.83– − 1.06%); maximal gain = + 1.64%; maximal loss = − 9.92%) for untagged males ($n = 5$). The FPP test did not reveal a significant difference between groups ($P = 0.60$). For the male recaptured after the longest period of equipment (23 days), the body mass variation was only – 2.73%, i.e. less than the average variation observed for untagged males.

For the 13 tags retrieved, we collected on average 41.92 ± 7.72 locations (95% CI 25.54–6.22; min = 21; max = 80) and 35.31 ± 6.66 locations usable for analyses (HDOP ≤ 5; 95% CI 21.46–47.54; min = 19; max = 74; see details in Table 1). Four tags failed (mainly due to waterproofing issues): 3 tags with no data collected and one that partially functioned (run time for only one day for a total of 21 locations collected). The 9 birds recaptured with enough data for analyses (≥ 31 locations) were sampled over an area of about 18 km in length within different wetland eco-complexes distributed along the study region. Six of these 9 birds were paired (i.e. sampled within the same location; Table 1). Home range analysed thus correspond to 6 different locations exploited by 6 paired birds and by 3 birds sampled without their mate. For these 9 birds, home range size was on average 2.50 ± 0.55 ha (95% CI 1.56–3.80 ha), with on average 2.78 ± 0.40 clusters (95% CI 2.00–3.56); Table 2 and Fig. 3. For 2 birds, probably due to a "burrow effect" (GPS tags that possibly did not receive satellite signals when the birds were in their burrows), the nest does not appear within any identified cluster. On average, fragmentation index (CPart) was 0.36 ± 0.08 (95% CI 0.24–0.61), DivLocs 2.03 ± 0.30 (95% CI 1.57–2.91) and DivArea 1.81 ± 0.27 (1.40–2.62); see details Table 2. The defined clusters corresponded to different types of small wetlands: small rivers (12%), water treatment plant basins (4%), small channels and wet ditches (28%), small ponds (8%), waterholes located within alluvial forests (40%) or water bodies (8%); Table 2 and Fig. 3. For the mates belonging to the

Table 1 Synthesis of capture and recapture data of European Kingfishers (*Alcedo atthis*) tracked by miniaturized GPS receivers within the Gironde marshes (France)

Bird ID	Nest ID	Tag number	Sex	Date of capture (mm/dd/yy)	Date of recapture (mm/dd/yy)	Intitial mass (g)	Mass at recapture (g)	Tag's run time (days + hours)	Nunber of locations collected	Number of usable locations (HDOP $\leq$ 5)
201	JU-18	48,657	M	04/06/18	04/13/18	37.2	37.7	3 d + 5.5 h	80	64
202	FO-18	48,658	M	04/18/18	04/26/18	34.5	33.4	14 h	21	19
203	FO-18	48,659	F	04/18/18	–	50.6	–	Not recaptured	–	–
208	CH-18	48,657 (reuse)	M	05/02/18	05/08/18	41.8	35.8	0 h	0	0
209	CH-18	48,655	F	05/08/18	–	41.5	–	Not recaptured	–	–
214	GP-18	48,746	F	05/29/18	06/03/18	40.7	44.2	3 d + 1 h	47	42
217	TR-18	48,974	M	06/11/18	07/04/18	36.7	35.7	0 h	0	0
216	GP-18	49,245	M	04/08/19	04/14/19	44.1	41.7	3 d + 4.5 h	40	31
258	MO-19	49,246	M	04/16/19	04/21/19	35.9	35.6	0 h	0	0
265	TR-19	48,746 (reuse)	M	04/08/19	04/15/19	35.4	41.2	3 d + 3 h	80	74
266	TR-19	49,243	F	04/08/19	04/15/19	43.0	37.3	3 d + 0.5 h	69	58
267	PP-19	49,247	F	04/09/19	04/15/19	45.8	45.3	3 d + 1.5 h	51	44
268	MO-19	49,244	F	10/04/19	16/04/19	39.0	40.3	3 d + 5 h	43	32
269	PP-19	49,245 (reuse)	M	15/04/19	20/04/19	41.7	35.2	3 d + 4.5 h	45	36
270	TA-19	49,243 (reuse)	F	24/04/19	–	39.5	–	Not recaptured	–	–
271	TA-19	48,746 (reuse)	M	24/04/19	29/04/19	35.5	36.5	2 d + 7.5 h	69	59

Bird ID corresponds to the last three ring numbers. Nest ID corresponds to the identification number of the nest used by each bird

Table 2 Home range features of European Kingfishers (*Alcedo atthis*) tracked by miniaturized GPS receivers in the Gironde marshes (France)

Bird ID	Sex	Nest location	Area (ha)	No. of clusters	CPart	DivLocs	DivArea	Rivers	BWTP	Channels & WD	Ponds	WAF	WB
201	M	River bank	1.99	4	0.13	2.64	2.40	1 NH + 1 FH	1 FH	1 FH			
214	F	Alluvial woodland	1.01	2	0.33	1.69	1.67				1 FH	1 NH	
216	M	Alluvial woodland	5.74	1	1.00	1.00	1.00					1 NH	
265	M	Water basin	3.24	4	0.16	2.23	1.86			3 FH			1 NH
266	F	Water basin	2.20	3	0.25	2.21	1.83			2 FH			1 NH
267	F	Alluvial woodland	0.45	5	0.18	4.26	3.82				1 FH	4 FH	
268	F	Alluvial woodland	1.09	2	0.49	1.87	1.94					2 FH	
269	M	Alluvial woodland	2.04	2	0.26	1.20	1.03			1 FH		1 NH	
271	M	River bank	4.70	2	0.47	1.21	1.21	1 NH				1 FH	

Bird ID corresponds to the last three ring numbers; Area = total area exploited by birds (ha); No. of clusters = number of clusters identified within an individual's home range; CPart = summed area of clusters divided by the single area encompassing all clusters; DivLocs = Simpson's index for diversity of locations across clusters; DivArea = Simpson's index for diversity of areas across clusters; BWTP = water treatment plant basins; WD = wet ditches; WAF = waterholes of alluvial forests, WB = water basins. Numbers indicate the number of clusters corresponding to NH (nesting and potential feeding habitats) or FH (feeding habitats)

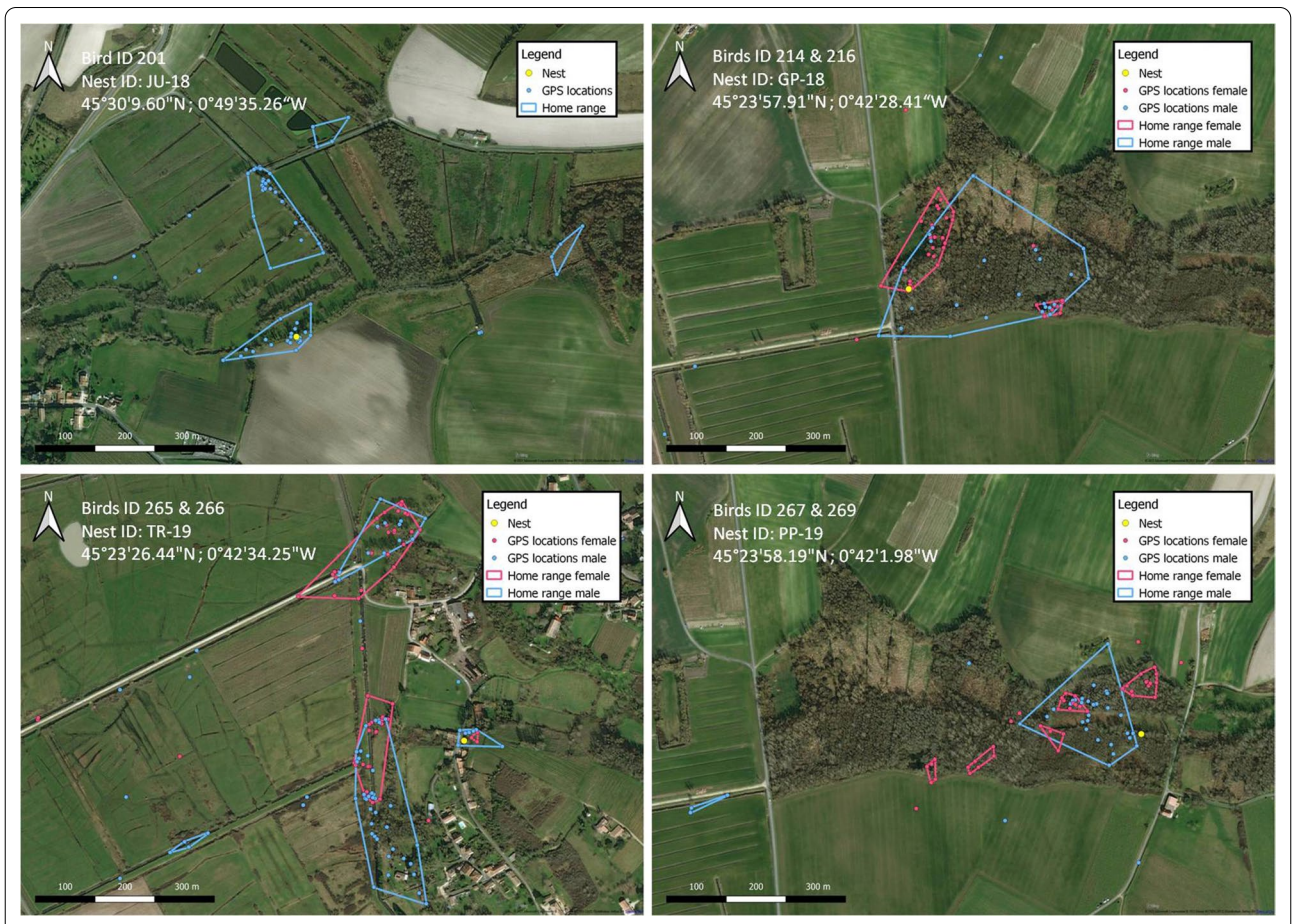

Fig. 3 Examples of home ranges of seven European Kingfishers (*Alcedo atthis*) breeding within the marshes distributed along the right bank of the Gironde estuary (one male and three pairs). Bird ID 208: nest located in the bank of a small river; birds ID 214 & 216: nest located in the roots of a fallen tree within an alluvial forest; birds ID 265 & 268: nest located in a limestone cliff overhanging a small water basin; birds ID 267 & 269: nest located in located in the roots of a fallen tree within an alluvial forest

3 pairs monitored, we observed more or less overlapping clusters. Thus, the pattern of the clusters highlights that mates of the same pair, breeding within habitats where small wetlands may be homogenously distributed, such as alluvial woodlands, tend to exploit the habitats around their nest in a markedly different manner than birds breeding within heterogeneous habitats where trophic resources are probably less equally distributed (Fig. 3).

Discussion

The deployment of telemetry tags for diving birds constitutes a real challenge for biologists given the necessity to be able to find a meaningful trade-off between possible impacts on animal behavior and tag retention (Spiegel et al. 2017). Whatever the attachment method used to attach loggers to diving birds, the literature has often revealed that the devices may impact their behavior or health conditions (Spiegel et al. 2017). For pursuit-diving birds, several negative effects of device attachments were highlighted. For instance, for the Common Murre (*Uria aalge*), Hamel et al. (2004) revealed that birds tagged with subcutaneous anchor radio transmitters made fewer but longer trips away from their nest and provisioned their chicks significantly less than their untagged mates. For the Sooty Shearwaters (*Puffinus griseus*), Adams et al. (2009) demonstrated that for birds equipped with multi-sensors glued on plastic "Darvic PVC" rings (only 1.4% body-mass equivalent), chick mass was negatively related to the tracking interval. For birds equipped with tags fitted using harnesses, Spiegel et al. (2017) reported a notable impact on behavior or mortality of different diving species such as the Red-throated Loon (*Gavia stellata*) or the Surf Scoter (*Melanitta perspicillata*). The European Kingfisher is a plunge-diving bird which uses a plunge technique that can be accelerated by a few wing beats when entering water (Brooks et al. 1985). Nevertheless, unlike other diving birds, the species does not pursue its prey for long periods into water. The results we obtained related to the body mass variations of tagged birds compared to untagged birds do not highlight any tangible effects of miniaturized GPS tags fitted with leg-loop harnesses on bird health conditions. This suggests that the use of this technique on the European Kingfisher probably does not significantly impact its feeding behavior, at least in the short term (i.e. over a few days). Future studies dedicated to home range features of this species of conservation concern, using tags deployed with leg-loop harnesses, is thus possible, but closer examination should be considered if birds would have to be monitored over a period exceeding three weeks (maximal period of tag attachment as part of our study). Unfortunately, we were unable to collect data to compare the behavior and bird fishing efforts between tagged and untagged birds. Further studies dedicated to these questions may thus be relevant in order to analyse if tagged birds are not handicapped by the devices themselves or their attachments, and if they would subsequently need to increase their foraging efforts to maintain their body condition or to feed their chicks.

Despite a capture-recapture scheme with mist-nets deployed as close as possible to the nests, our results in terms of recapture rate of tagged birds (81%) reveal a significant probability of not recapturing untagged birds. The inability to recapture three females during our study is explained by the fact that two females did not occupy the targeted nests, and by a third female, equipped with a GPS tag, that we were unable to recapture before ending the occupation of its nest. The risks in capturing birds that do not occupy targeted nests appear relatively significant for the European Kingfisher, even if the capture efforts are deployed very close to the burrows of the selected nests. Hürner and Libois (2005) noticed some movements of European Kingfishers a few meters from nests occupied by other birds when the latter were temporarily absent. During our study, an adult male ringed in front of its nest within an alluvial forest was recaptured a few days later, about 1 km away from its nest and in front of another occupied nest (dug in a limestone cliff overhanging a small water basin). Such movements of birds close to nests occupied by other individuals highlight the risk of capturing birds that do not occupy the targeted nest and the risk of being unable to recapture some individuals. This imperfect recapture probability of birds that we document for the European Kingfisher emphasizes the ethical importance to use harnesses designed with breaking points for tags deployed for short term studies, as underlined by Kesler (2011). Such technical arrangements may eliminate the risk of birds keeping tags unnecessarily, which otherwise could impact their behavior and their survival probability.

Our study is, to our knowledge, the first work to document home range features of the European Kingfisher using GPS devices. Since the limited study performed by Hürner and Libois (2005) using VHF radio tags with the aim to examine the possible overlap of territories exploited by two males, no work has characterized home range features of the species. The home range structure of birds that we highlight as part of our study, with a rather high habitat fragmentation and different nuclei composed by different habitat typologies, is symptomatic of a population for which access to trophic resources are unevenly distributed around the nests. Indeed, most of the population we monitored breeds within areas where feeding habitats are unequally distributed. Although being rather fragmented, the home ranges exploited by birds remain relatively small (2.50 ± 0.55 ha), with

a limited diversity of use of the nuclei (DivLocs) and of their corresponding area (DivArea). Despite the limited number of birds monitored during this pilot study, our results reveal that within the same pair, birds may have different habitat use strategies, depending on the distribution of trophic resources they can exploit in the vicinity of their nests. Thus, the mates of breeding pairs exploiting rather homogenous habitats, such as alluvial woodlands, tend to differently exploit the habitats distributed around their nest, benefiting probably from a rather large distribution of small water bodies. This appears less true for pairs breeding within small wetlands—where feeding habitats are less equally distributed around their nest, and whose mates tend to more significantly overlap their home ranges. In our study, birds were sampled between April and June of two different years. In view of the habitats exploited by birds (for instance within alluvial woodlands with varied water levels or along small rivers) seasonal or annual effects on home range features are possible given potential spatial redistribution of trophic resources that may occur with water level fluctuations or given the biological cycle of prey. Nevertheless, for our study, this possibility could not be tested given that birds were sampled on a rather large spatial scale, in various locations with different habitat features, and without intra- or inter-annual resampling of birds.

Since our study is the first to document home range features of the European Kingfisher, we cannot compare our results with those of other studies dedicated to this species. However, the results collected as part of our work revealed that small wetlands exploited by birds (wet ditches, small ponds or waterholes located within alluvial forests) can provide important trophic resources that are highly predictable for individuals. The European Kingfisher is a species capable of exploiting a large diversity of habitats and prey (Brooks et al. 1985), and our results demonstrate the importance of small wetlands in maintaining trophic resources exploitable by birds, particularly for populations with few possibilities of exploiting large water bodies (i.e. large rivers or large ponds) in the vicinity of their nests.

Conclusions

From a conservation perspective relating to the European Kingfisher, today considered as a species of conservation concern in Europe, our results highlight the importance of restoring wetland ecological networks and developing conservation policies that integrate small wetlands particularly sensitive to global change (draining, anthropogenic transformations or pollution by peripheral agricultural activities). Throughout the world, the contribution to biodiversity offered by small wetlands is regularly overlooked or ignored, and often neglected in habitat conservation plans which tend to give priority to large wetlands (Semlitsch and Bodie 1998; Melly et al. 2018). Despite these unfit conservation strategies, small wetlands play important ecological functions at local and regional scales (Hefting et al. 2013). For instance, using a spatially-structured demographic model, Gibbs (1993) revealed that local populations of turtles, small birds and mammals, which remained stable under conditions of no wetland losses, faced a significant risk of extinction after disappearance of small wetland areas. Thus, the development of research schemes including the use of miniaturized GPS tags, such as the devices used during our study dedicated to the European Kingfisher, could help better characterize the home ranges of small animals exploiting limited wetland areas, habitats often insufficiently taken into account when defining the issues and challenges faced by avian species dwelling in a particular territory.

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Authors' contributions

RM managed the design of the research, the analysis of the data, and wrote the manuscript. MB, CB and CR contributed to the collection data in the field and to data analysis. OD contributed in designing the field protocol. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used for the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

Our study was carried out in agreement with the laws of the French Republic dedicated to the protection of wildlife. Ringing sessions and the GPS-tracking scheme implemented for this study, and which involved the capture of wild birds, have been conducted with the authorization of the Centre de Recherches sur la Biologie des Populations d'Oiseaux (CRBPO – Muséum National d'Histoire Naturelle, Paris; personal research program registered under number 988).

Consent for publication

Not applicable.

Competing interests
The authors declare that they have no conflict of interests.

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