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Multi-sensor data loggers identify the location and timing in four poaching cases of the endangered Eurasian Curlew *Numenius arquata*

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ABSTRACT

The Eurasian Curlew is an endangered migratory shorebird benefiting from numerous conservation efforts in Europe, including the remote tracking of individuals to document habitat use and migration strategy. Formerly hunted in France, the species is subject to a hunting ban since 2020. By analysing the data collected by multi-sensor tags deployed on curlews, we were able to document four poaching cases of this endangered migratory bird. Using geolocations, instant acceleration, temperature, battery charge and battery charging current, we determined the place and time where poaching occurred. For comparison, two cases of naturally dropped tags and two cases of naturally predated curlews are also presented. This report is an illustration that the employing of remote multi-sensor tag monitoring has the potential to inform management projects on imperilled or harvestable species affected by illegal or cryptic sources of mortality.

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1. Introduction

The Eurasian Curlew *Numenius arquata* is a large shorebird breeding in temperate Europe and Asia and migrating to spend the non-breeding season (July-March) on a variety of coastal and intertidal habitats. The species has been largely declining during the last decades, and is listed as Near-Threatened to extinction in the regional IUCN Red List [1], with a European population estimated at 212,000–292,000 pairs. The species is therefore subject to numerous conservation efforts to preserve the birds and their habitats [2] and is listed on Annex II of the EU Birds Directive (Directive 79/409/EEC of the European Council of 2 April 1979 on the conservation of wild birds), permitting hunting in few listed Member States, e.g. Denmark, France, Ireland and the United Kingdom. Since the 1979 agreement, because of the continuous declines in breeding populations, hunting bans have been implemented in Denmark, in the UK (1982 for Scotland, England and Wales; 2011 in Northern Ireland) and Ireland (2012). In France, a hunting moratorium was implemented in 2008 but ended in 2012. Since 2012, France was, therefore, the only European country to hunt Eurasian Curlew, with a hunting bag estimated at approx. 7000 individuals (range 4400–9500) in 2013–14 [3]. After engaging in the process of adaptive management for that species, the 2019–2020 hunting season was the last authorising a non-null quota for the harvest of the species. Since summer 2020, annual decrees fixed the hunting quota to zero, so any hunting action leading to the injury or death of a Eurasian Curlew must be considered as illegal.

In a research effort to inform conservation actions, by studying habitat use and migration strategy, several European research teams recently invested in the capture, colour-ringing and GPS-tracking of the species. These teams have collaborated to study the ecology and threats to the species [4–8]. More than a hundred birds have been tagged recently with GPS-tracking devices, providing precise information on 3D locations, but also light intensity, temperature, and accelerometer values of tracked individuals. These data recently proved highly valuable to characterise several poaching cases that occurred in coastal France in August 2022. Here we report how the data collected by multiple sensors of the tags permitted to determine the place and time where poaching occurred in four different cases. For comparison, two cases of naturally dropped tags and two cases of naturally predated curlews are also presented.

2. Material and methods

2.1. Study sites

Curlews breed in grasslands or moorlands then migrate to traditional wintering sites, foraging on large estuaries and mudflats at low tide, flocking in coastal marshes at high tide. Curlews reported here had two origins: wild birds and head-started juveniles. Wild birds have been captured on their breeding territory in agricultural grassland fields, or on high-tide roosts on their wintering grounds. Other birds were head-started juveniles originating from wild nests harvested to increase fledging success and reared in dedicated care centres. Such juveniles are released in the wild during the summer then migrate in late July-early August to southern coastal wintering grounds.

2.2. Capturing and tagging curlews

All curlews reported here were colour-ringed and tagged with a multi-sensor GPS device, the OrniTrack E10 model from the Ornitela company (https://www.ornitela.com/ornitrack). A tag weighs 11 g, and the maximum load equipping a curlew, including metal ring, colour rings, tag and harness, did not exceed 15 g, representing at most 3 % of the body mass of a bird (body mass of the species ranges from 455 to 1180 g, for birds captured and ringed in France; source www.crbpodata.mnhn.fr; 3 % is the standard maximum rule for tagging intervention weight on birds such as waders in Europe). All birds were ringed with an official metal ring from the national ringing scheme, and a combination of colour rings or flags allowing distant visual identification. In France, the harnesses were constructed of leg loops made of silicone tube of 2.1 mm diameter (Reichelt Chemietechnik GmbH, Germany), closed by a double chirurgical knot (no glue). The same silicone leg loop harness was used for head-started juveniles in Germany, while tags were fitted with Teflon wing loop harness on adults. The same tag was fitted to the bird in Belgium but using a Teflon backpack harness (6.5 mm wide tape).

2.3. Multi-sensor recordings

OrniTrack transmitters log GPS positions (latitude, longitude, altitude) and multiple sensor information and upload data via GSM/GPRS or 3G or 4G telecommunication networks. Solar panels allow recharging the internal Lithium-Polymer battery. A full charged battery is sufficient for logging about 800 positions without additional recharge. 2 MB flash memory is capable of storing at least 30,000 records. The tags include high frequency (up to 50 Hz) sensors (accelerometer, magnetometer, temperature, light intensity). Main data record includes: UTC date and time, GPS position, GPS altitude, speed, direction, HDOP (Horizontal Dilution of Precision, a measure of the geometric quality of the GPs satellites configuration), battery voltage, battery charging current, instant acceleration (3 axes), temperature, magnetic field strength (3 axes). Position data collection were usually set up at 5 or 10 min interval recording. For limited periods it is possible to log positions as frequently as every second (a boost programme). Date and time reported here are UTC. Data used in this study are deposited on the online platform www.movebank.org (studies ID 1077731101, 1519345208 and 2157073446). Structures (such as buildings) mentioned in the case histories were first identified from satellite imagery using GPS locations then visited by the investigators on the ground.

3. Results

Dates cited in subtitles are the poaching dates.

3.1. Poached curlew, tag retrieved. Ring DEW 4314024, tag 212469, 6 August 2022

This individual was a head-started juvenile, raised by Tierpark Nordhorn, and released in the wild on 29 June 2022 near Werlte (Emsland), Germany (52.83°N 7.71°E). It started to migrate on 1 August 2022, arrived in the Seine estuary, Seine-Maritime, France, ca. 24 h later, on 2 August 2022 at 15:00 UTC. Detailed data are presented starting on 6 August 2022 at 14:30 UTC (Fig. 1), while data collected during a longer period (4 August 00:00–9 Aug 12:00) are presented in Supplementary Material 1. On 6 August, accelerometer values displayed usual variations in their three dimensions until 19:47, with a recharging battery thanks to regular exposure to sunlight. Before 19:47, the bird was foraging on location 1 at 18:02, then performed a double loop in flight over the mudflat (location 2) before landing on the vegetated area. During that flight, position records were obtained every second according to the 'boost' programme. Thereafter, it commuted several times between the mudflat and the land (locations 3–6). The bird stayed at location 6 from 19:27–19:47. At 19:54, the tag moved to location 7, while the accelerometer values reveal that at this moment, the x and z values have dramatically changed, indicating the tag was upside down. From that time onwards, the battery charge decreased. The solar panel was not exposed to the sun anymore since 18:57, which could also be due to very low light exposure at the end of the day. The tag was immobile from 19:54–20:29, according to the accelerometer values, but the GPS did not function, so we have no available coordinates (from 19:59–20:44). The tag was either in the mud (first) or in a bag, without possibilities to connect to satellites. From 20:35 onwards, the tag was again mobile and moving, and a position is transmitted at 20:49, when it

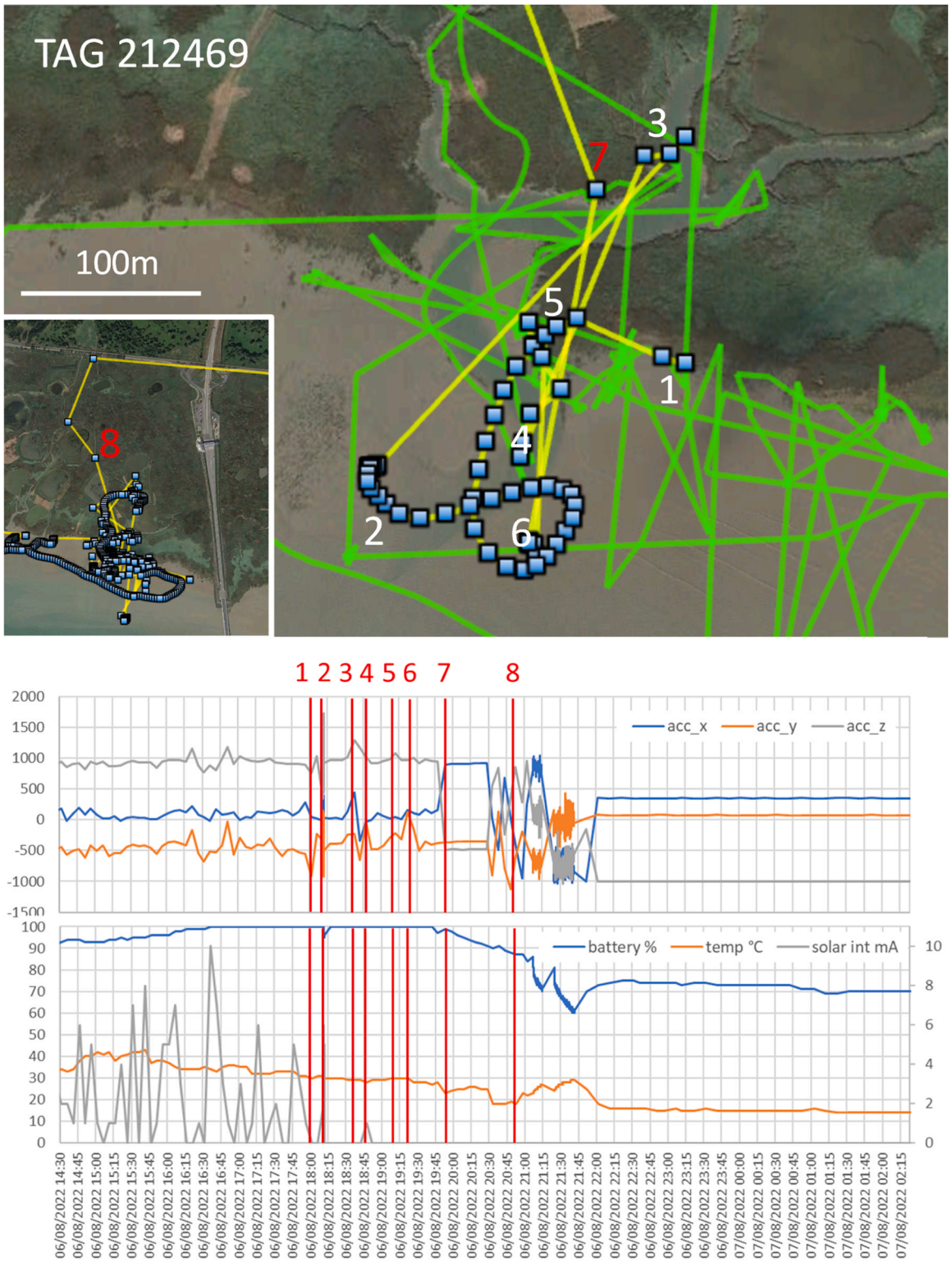

Fig. 1. Tag 212469, data recorded during the afternoon of 6 August 2022. General map until 20:00 UTC, insert map starts at noon and includes the next hour. The curlew was alive at location 6, and dead at location 7. Mapped locations 1–8 are reported on the data graphics, upper graph for instant accelerometer (3 dimensions), lower graph for temperature (in °C), charging current (solar intensity in mA) and battery charge (%), from 6 August 2022 14:30–7 August 02:20 UTC. Satellite images ©Google Earth.

was located at location 8. After this, the tag was moving to a car park, and ended up in a house north of the Seine estuary. The dense data acquisition, including accelerometer values after location 8 corresponds to part of the car drive to a house, when the tag recorded high frequency data as if the tagged bird was flying. The tag stayed in that house, at temperatures just above 20 °C and without exposure to the light. On 8 August noon it started moving again until the evening (see Supplementary Material 1), GPS fixes revealing that it moved in a vehicle along the A6 motorway, ending near Marseille city, southern France (Bouches-du-Rhône department).

3.2. Poached curlew, tag and bird retrieved. Ring DEW 4314114, tag 212484, 7 August 2022

This individual was a head-started juvenile, released on 21 June 2022 near Auen (Cloppenburg), Germany. It started to migrate at noon on 29 July 2022, arrived in Bay of Canches, Pas-de-Calais, France, on 31 July at 22:00 UTC. Detailed data are presented for the morning of the 7 August 2022, from 03:13–10:44 UTC (Fig. 2). Data collected during a longer period (4 August 06:00–11 Aug 18:00) are presented in Supplementary Material 2. On 7 August, the sunrise occurred at 04:25 UTC, and the bird started a flight at 05:10:49, so that the tag started high frequency recording, including accelerometer and 3D coordinates collected every second. This flight track is annotated as 1 on Fig. 2. The flight entered the pond of a hunting hut at exactly 05:13:27, at an altitude of 20 m a.s.l. and a regular speed of 42 km.h^{-1}. When in front of the hunting hut, the bird started to descend to reach location 2, where speed was 34 km.h^{-1} at 05:13:39, 9 km.h^{-1} at 05:13:40 and 0 at 05:13:41, with constant altitude of 9 m. The tag recorded again 9 positions at this fix location, with null speed, then the flight boost recording stopped, and the tag recorded one position every ten minutes. At 05:33, the tag was located in the hut, where it was still immobile at 08:03. At 08:13, it left the hut and moved towards a car park at a speed of 6 km.h^{-1}. Then the tag followed roads and ended in a house, where the tag and the bird were later retrieved by police investigators. X-ray imagery revealed the presence of a spherical radio-dense object in the right flank, with an appearance typical of a shotgun pellet (1 mm diameter), and a broken ulna of the right wing. The bone fracture was associated with an internal haemorrhage, with no external bleeding. We interpret the data as a bird shot while flying above the pond at 05:13, then stored in the hunting hut, before leaving the hunting site at 08:13 UTC.

3.3. Poached curlew, tag retrieved. Ring Brussels L178314, tag 216762, 8 August 2022

This individual was a head-started juvenile female, hand-raised by the wildlife rescue centre in Oudsbergen, Belgium, and released on July 11 in a nature reserve near Glabbeek [9]. It remained on site in the nature reserve until 6 August. It started to migrate on 6 August 2022 at 18:10, stopped just south of Le Touquet, Pas-de-Calais, France, from 02:55–11:30 on 7 August, then moved to the Bay of Somme, Somme, France, where it arrived at 13:16. It spent only one day at this site before being dying. Detailed data are presented for the 8 August 2022, from 07:12–13:12 UTC (Fig. 3). Data collected during a longer period (5 August 00:00–8 Aug 18:00) are presented in Supplementary Material 3. The bird spent the night from 7 to 8 August on the sand bank at location 1. The bird was moving from location 1 to location 2 between 08:51 and 09:16, partly in flight as some locations are associated with speed of 16 km.h^{-1} and 38 km.h^{-1}. There were three recorded positions at location 2, at 09:11, 09:16 and 09:21, with normal accelerometer values (no boost programme set up in this case). The next positions were recorded at location 3 from 09:31–10:01. Although accelerometer values looked also normal at this location, there were intermediate data obtained at 09:26 with a switched negative z-accelerometer value, indicating that the tag was upside down; there was no position associated with this data transmission, suggesting that the tag was not able to connect to the GPS satellites – probably below the bird, against the mud. After that, the tag provided again normal accelerometer values (normal position with solar panel upwards) but no light reaches the solar panel, except shortly at 10:01 when the tag was leaving location 3 to reach location 4, a car park, 20 min later, so at an average speed of 4.6 km.h^{-1}, in accordance with a human walk. From the car park, the tag followed roads and ended in a house. We interpret these data as a kill occurring between locations 2 and 3 between 09:21 and 09:26, the bird being then stored in a bag, tag upwards; the poacher left their hunting post at 10:01 to go back to his car, then back home.

3.4. Poached curlew, tag and bird retrieved. Ring DEW 4314007, tag 212422, 28 August 2022

This individual was captured and ringed as an incubating adult on 9 May 2021 at Polder Hollerdeich, NSG Borgfelder-Wümmewiesen, Bremen, Germany. In 2022, it left its breeding grounds on 8 July, and arrived in Baie du Mont-Saint-Michel on 15 July. Detailed data are presented for the day when the bird died, 28 August 2022, from 12:00–23:59 UTC (Fig. 4). Data collected during a longer period (26 August 00:00–31 Aug 12:00) are presented in Supplementary Material 4 (no boost programme set up in this case). During July and August, the bird foraged in the western part of the Mont-Saint-Michel Bay, as illustrated in the small map inserted in Fig. 4. During the afternoon of the 28 August, the bird was in the Bay and last recorded at location 1 at 17:31, with usual accelerometer values. At 17:47, the tag was on the beach (location 2), with negative values of x- and z-accelerometer: the tag was upside down. Accelerometer values were varying until 18:45, with the tag moving slightly to locations 3 and 4. The tag moved from location 4 to location 5, up the beach, during the night on 30 August, between 00:46 and 01:46. The tag and the carcass of the bird were retrieved by a volunteer at this place the next day. An X-ray imagery followed by a necropsy of the curlew carcass revealed the presence of two pellets, one in the left pectoral muscle and one in one lodged in the coelomic cavity in the caudal region (caudal to the kidneys). We interpret the data as a poaching act killing the bird on 28 August probably between location 1 / 17:31 and location 2 / 17:47, with the carcass being left on the beach, being later balanced by the rising tide, until it was moved to the upper beach by a meso-predator or scavenger at night on 30 August. The injuries on the legs were supposedly caused after the death, by a scavenger (a fox or a dog) which cut the legs, as the bones were not clear broken but rather chewed; this probably occurred when the carcass moved to the upper beach (from location 4 to location 5 on Fig. 4).

3.5. Natural tag drop. Ring MNHN Paris EA581508, tag 215424, 10–13 August 2022

This individual was an adult bird which was captured by nocturnal mist-netting on 1st March 2022 on a high tide roost, at its wintering grounds at Reserve Naturelle de Moëze-Oléron, Charente-Maritime, western France. This bird migrated northwards in spring 2022 to breed in European Russia, near Sharya in the Kostroma Oblast. It was back on its French wintering grounds on 2 July 2022. Detailed data are presented from 9 August 2022 00:00 UTC to 13 August 09:00 (Fig. 5). During the presented period, the bird was regularly commuting between mudflats at low tides, and upper shore or coastal marshes at high tides. Attendances of locations 1–5 are illustrated on Fig. 6, with regular alternances between high tide roosts, e.g., locations 1 and 2. During the nocturnal high tides of 12 August, the bird visited location 4, while the tag stopped transmitting data abruptly at location 5 on 13 August at 07:17, while the battery was still charged at 62 %. On 10 August at 19:17, the accelerometer values suddenly changed, with x- and z-values switching from null to negative and from positive to null, respectively, indicating that the tag toggled. We interpret the data as a partial rupture of the silicone harness on 10 August, with the bird continuing to move as usual until the harness finally broke on 13 August, with the tag falling in the water / mud and got lost. The tag felt from the bird 60 h after the harness started to break up.

3.6. Natural tag drop. Ring MNHN Paris EA581509, tag 215408, 22–26 August 2022

This individual was an adult bird which was captured by nocturnal mist-netting on 1st March 2022 at a high tide roost on its wintering grounds at Reserve Naturelle de Moëze-Oléron, Charente-Maritime, western France. This bird migrated northwards in spring 2022 to breed in Belarus, between Pinsk and Salihorsk. It was back on its French

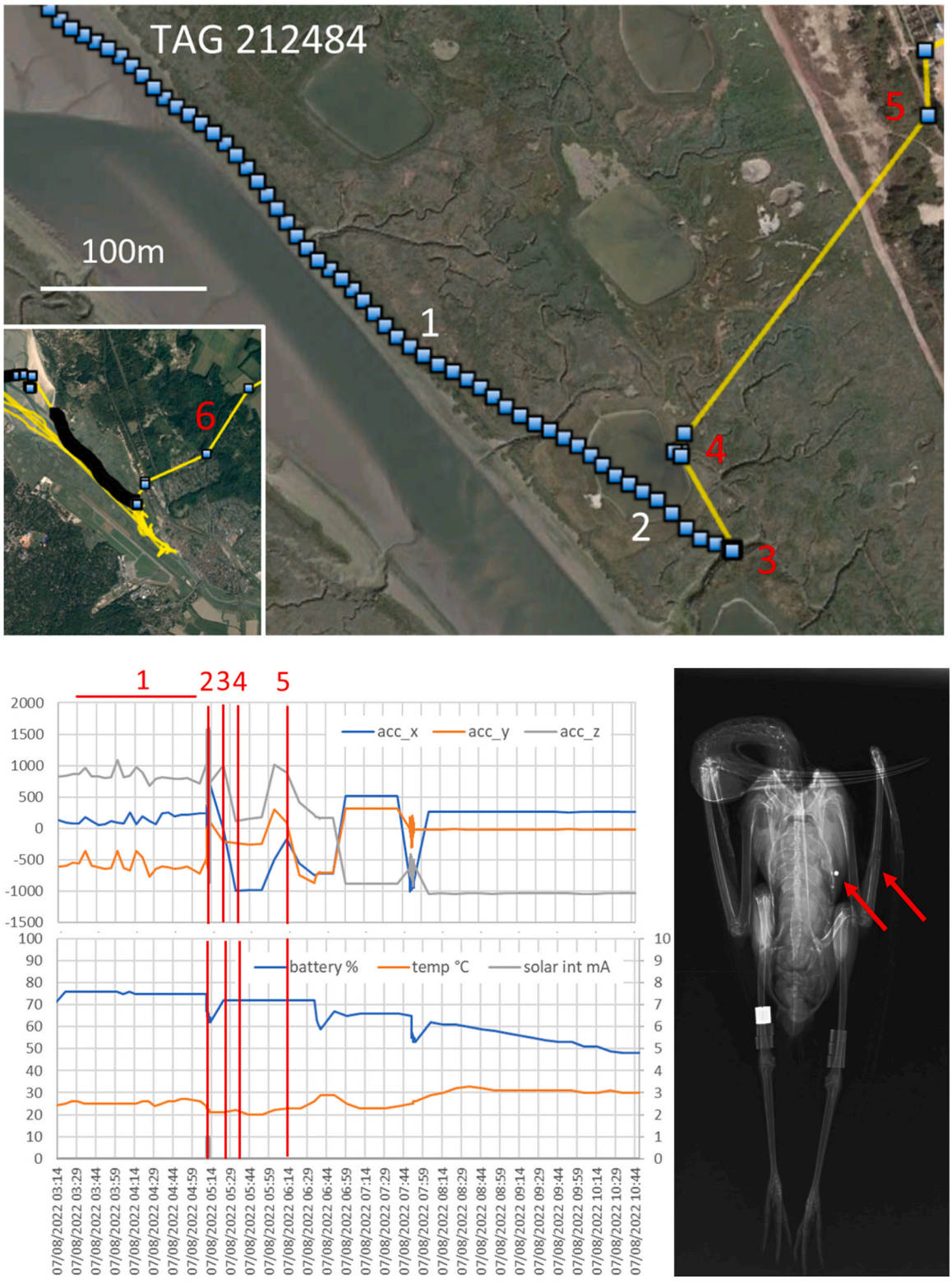

Fig. 2. Tag 212484, data recorded during the morning of 7 August 2022, from 03:14–10:44 UTC (insert map). The large map focuses on data collected from 05:00–06:14 UTC. The curlew was flying and alive at location 2, and dead at location 3 before moving to the hut at location 4. Mapped locations 1–5 are reported on the data graphics, upper graph for instant accelerometer (3 dimensions), lower graph for temperature (in °C), charging current (solar intensity in mA) and battery charge (%). An x-ray image of the retrieved corpse of that bird reveals an ammunition (lower red arrow) and a broken wing bone (ulna, see upper red arrow). Satellite images ©Google Earth.

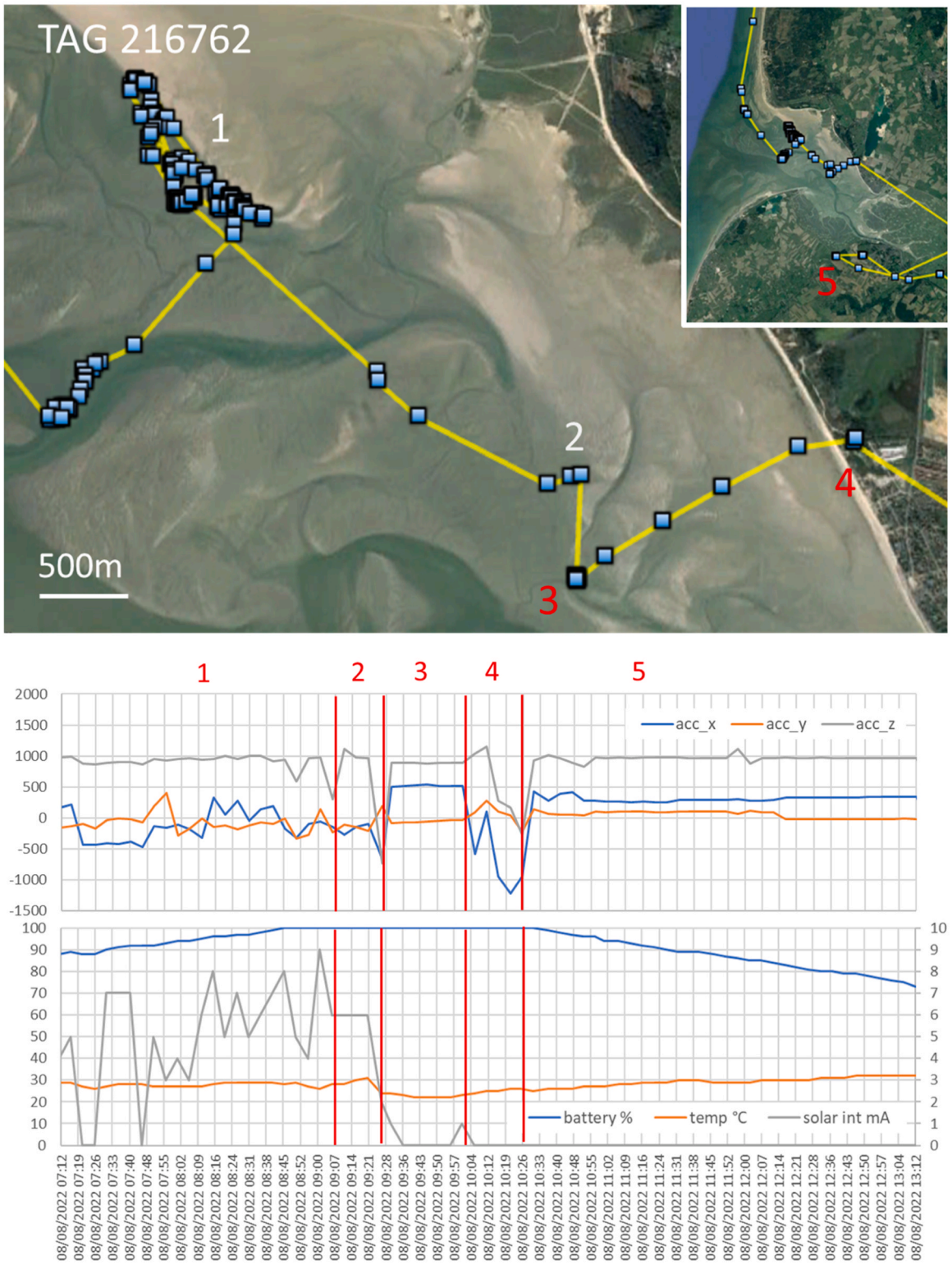

Fig. 3. Tag 216762, data recorded during the morning of 8 August 2022. General map from 07:12–13:15 UTC, insert map includes the arrival of the bird in the bay the previous evening. The curlew was alive at location 2, and dead at location 3. Mapped locations 1–5 are reported on the data graphics, upper graph for instant accelerometer (3 dimensions), lower graph for temperature (in °C), charging current (solar intensity in mA) and battery charge (%). Satellite images ©Google Earth.

wintering grounds on 6 June 2022. Detailed data are presented from 21 August 2022 00:00 UTC to 26 August 08:00 (Fig. 6). On 22 August at 12:35, the z-accelerometer switched from positive to negative values, indicating that the tag moved, being now upside down. From this moment onwards, the solar panel was rarely exposed to the light, and the battery was not recharging, but the temperature was not dropping, and the temporal variations in accelerometer values (all three dimensions) attested of regular movements of a live bird. The GPS positions also confirmed that the bird was alive and moving, commuting between different sites inside in the bay of Marennes-Oléron (locations 1–4). Data transmission ended abruptly on 26 August at 07:25, the tag being located at location 3. At this time, the collected data were similar

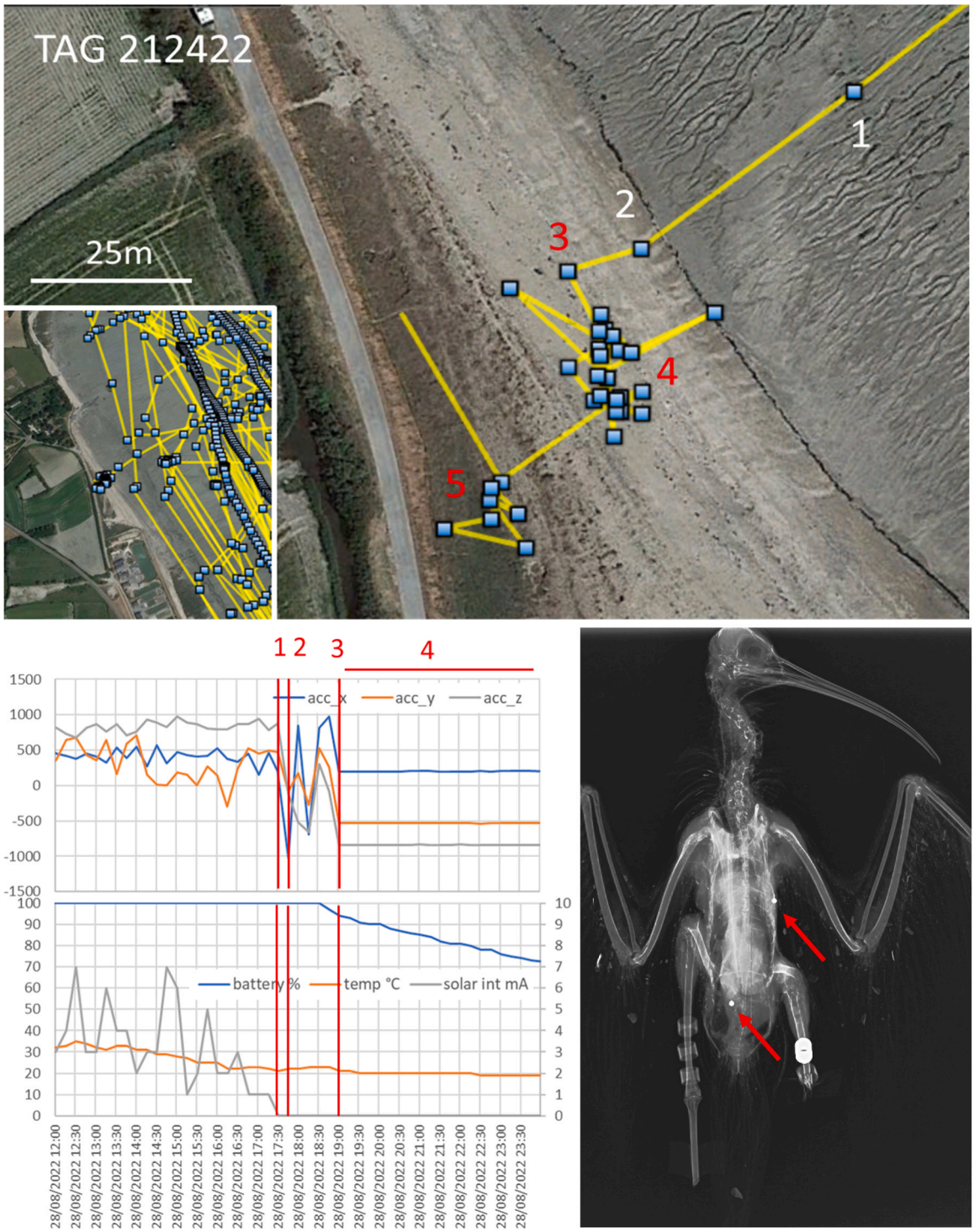

Fig. 4. Tag 212422, data recorded during the afternoon of 28 August 2022 from noon to midnight (general map and graphics). The insert map reports the movements of the bird in the nearby bay during the previous month. The curlew was alive at location 2, and dead at location 3, while the tag and the corpse were found at location 5. Mapped locations 1–4 are reported on the data graphics, upper graph for instant accelerometer (3 dimensions), lower graph for temperature (in °C), charging current (solar intensity in mA) and battery charge (%). An x-ray image of the retrieved corpse of that bird reveals two ammunitions (red arrows) in the body. Satellite images ©Google Earth.

to that of the previous four days, while the battery was still charged at 36 %. We interpret the data as a partial rupture of the silicone harness on 22 Nov, with the bird continuing to move as usual until the harness finally broke on 26 August, with the tag falling in the water / mud and got lost. The tag felt from the bird almost 91 h after the harness started to break up.

3.7. Natural predation. Ring MNHN Paris EC111344, tag 211000, 6 August 2022

This individual was an adult female, captured with a passive trap on its nest the day of egg hatching, and tagged on 11 May 2021 at Carentan marshes, Normandy, France. It left the breeding ground on 9 June 2022 late afternoon, arriving on its wintering site in the Sado estuary, south of

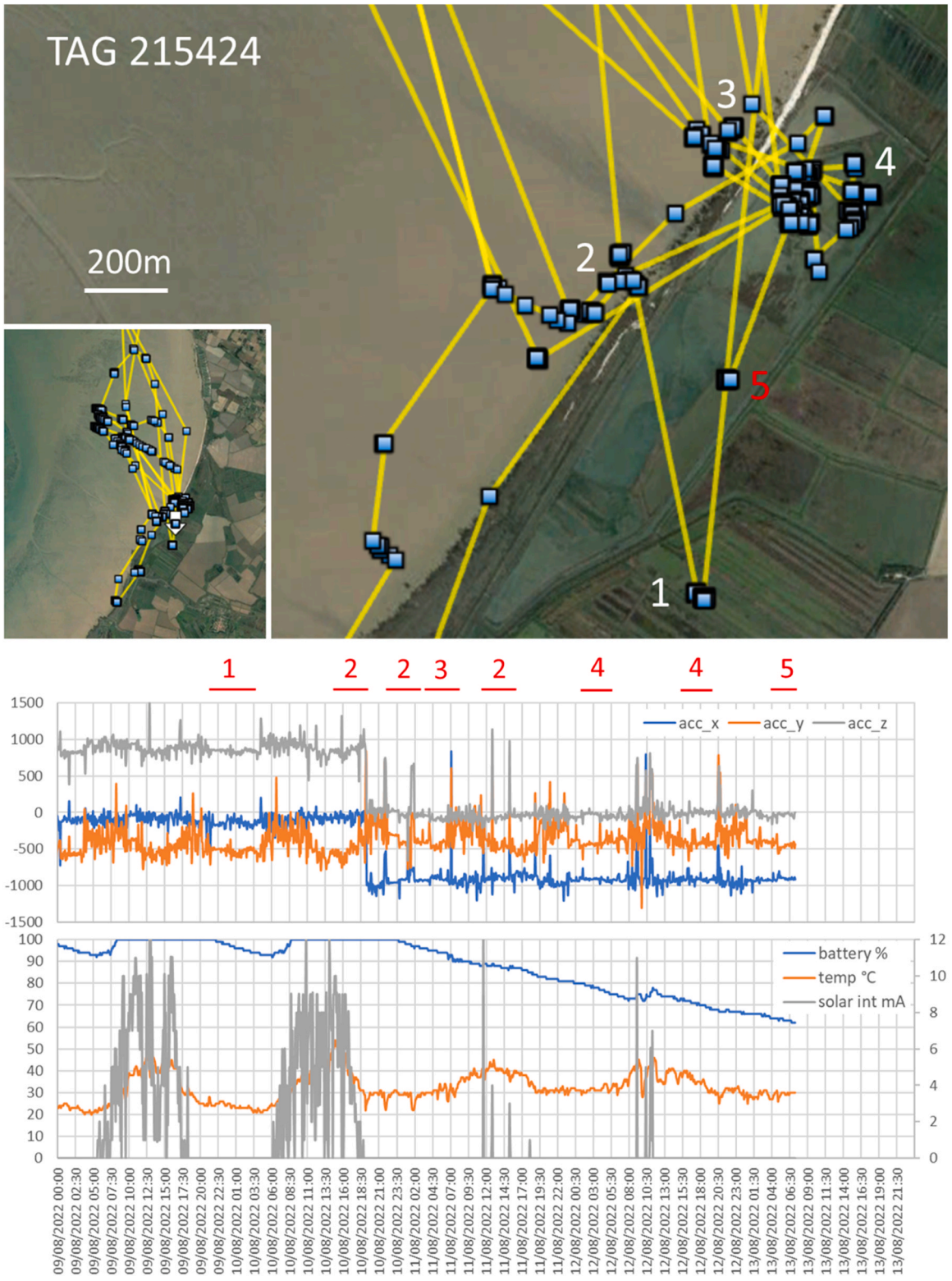

Fig. 5. Tag 215424, data recorded from 9 August to 13 August 2022 22:00 UTC. The general map focuses on the inland visited locations, the insert map includes foraging locations on the mudflats. Location 5 is where the tag was finally lost by the bird on 13 August. Mapped locations are reported on the data graphics, upper graph for instant accelerometer (3 dimensions), lower graph for temperature (in °C), charging current (solar intensity in mA) and battery charge (%).Satellite images ©Google Earth.

Lisboa, Portugal, at 04:00 on 11 June. Detailed data are presented from 3 August 2022 00:00 UTC to 12 August 00:00 (Fig. 7). From 3–6 August, the bird is staging within the bay (location 1), with a few movements away from the large muddy island where it stayed. At 11:32, accelerometer values indicate that the tag went upside down at location 2 (z values switching abruptly from positive to negative values). The battery recharge also stopped from this time onwards, while the tag was immobile during a few hours before being balanced from 19:32 to the 7

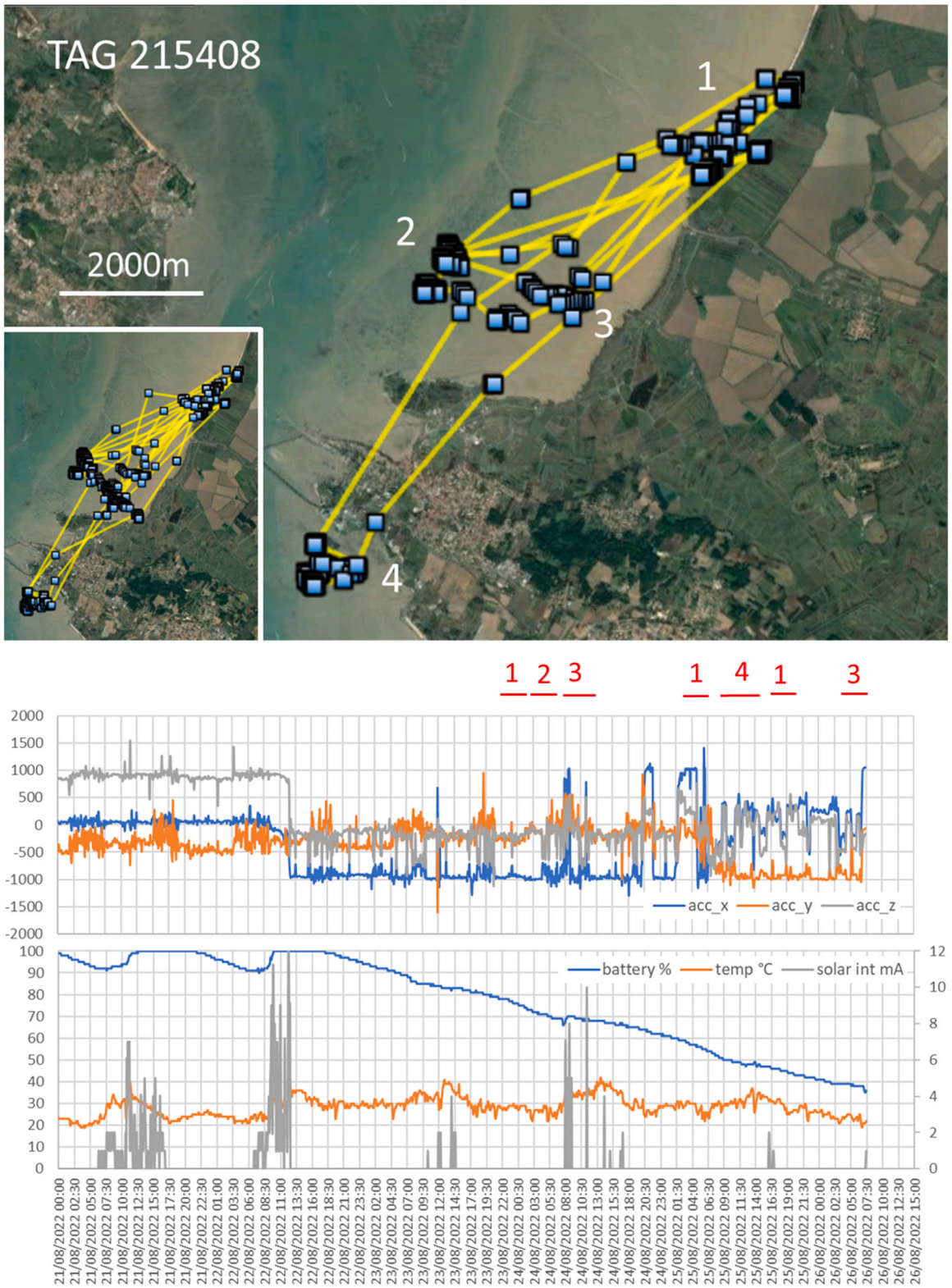

Fig. 6. Tag 215408, data recorded from 21 August to 26 August 2022 15:00 UTC. The general map focuses on locations visited on 24–26 August, the insert map includes the full period. Location 3 is where the tag was finally lost by the bird on 26 August. Mapped locations are reported on the data graphics, upper graph for instant accelerometer (3 dimensions), lower graph for temperature (in °C), charging current (solar intensity in mA) and battery charge (%).Satellite images ©Google Earth.

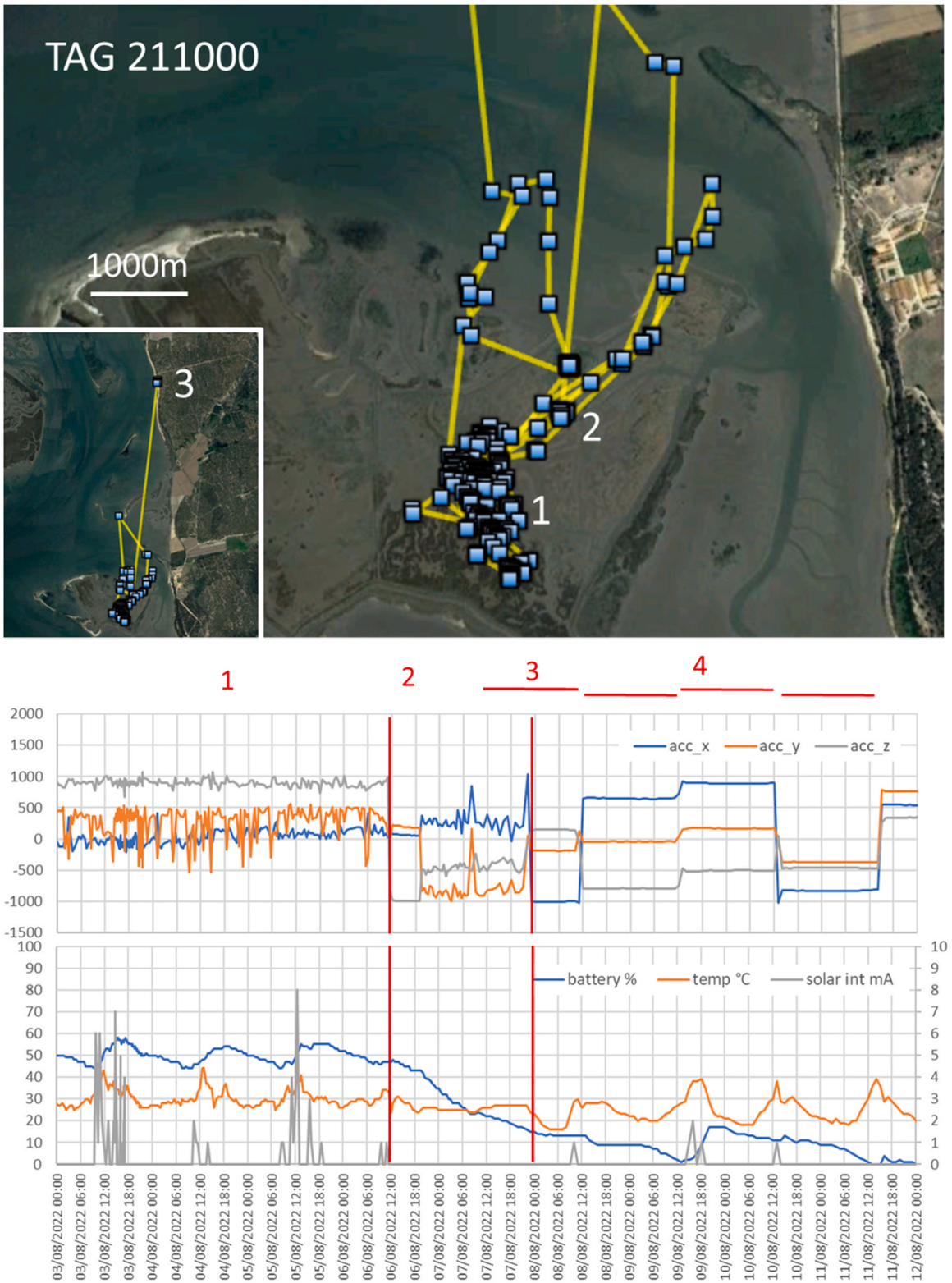

Fig. 7. Tag 211000, data recorded from 3 August to 11 August 2022. The general map focuses on the locations visited within the bay, the insert map includes location 2 where the bird was predated and location 3 (same as 4) where the tag finally stopped moving. Mapped locations are reported on the data graphics, upper graph for instant accelerometer (3 dimensions), lower graph for temperature (in °C), charging current (solar intensity in mA) and battery charge (%).Satellite images ©Google Earth.

August at 23:20. Between these two dates, there were no recorded GPS positions, but on 8 August at 00:02 the tag was located at location 3, where it stayed until the battery was completely discharged and data transmission stopped (last data transmission on 12 August 23:51). While the tag was on location 3, the accelerometer values indicate that its position changed substantively every 24 h. We interpret these data as a probable predation of the bird on 6 August evening, the carcass and/or tag being thereafter moved by the cyclic tides to location 3, where the

battery completely discharged with the last data acquisition and transmission.

3.8. Natural predation. Ring MNHN Paris EA688898, tag 215344, 3 November 2022

This individual was a juvenile born in Carentan marshes, Normandy, France. It was initially ringed as a few-day old chick on 23 May 2022,

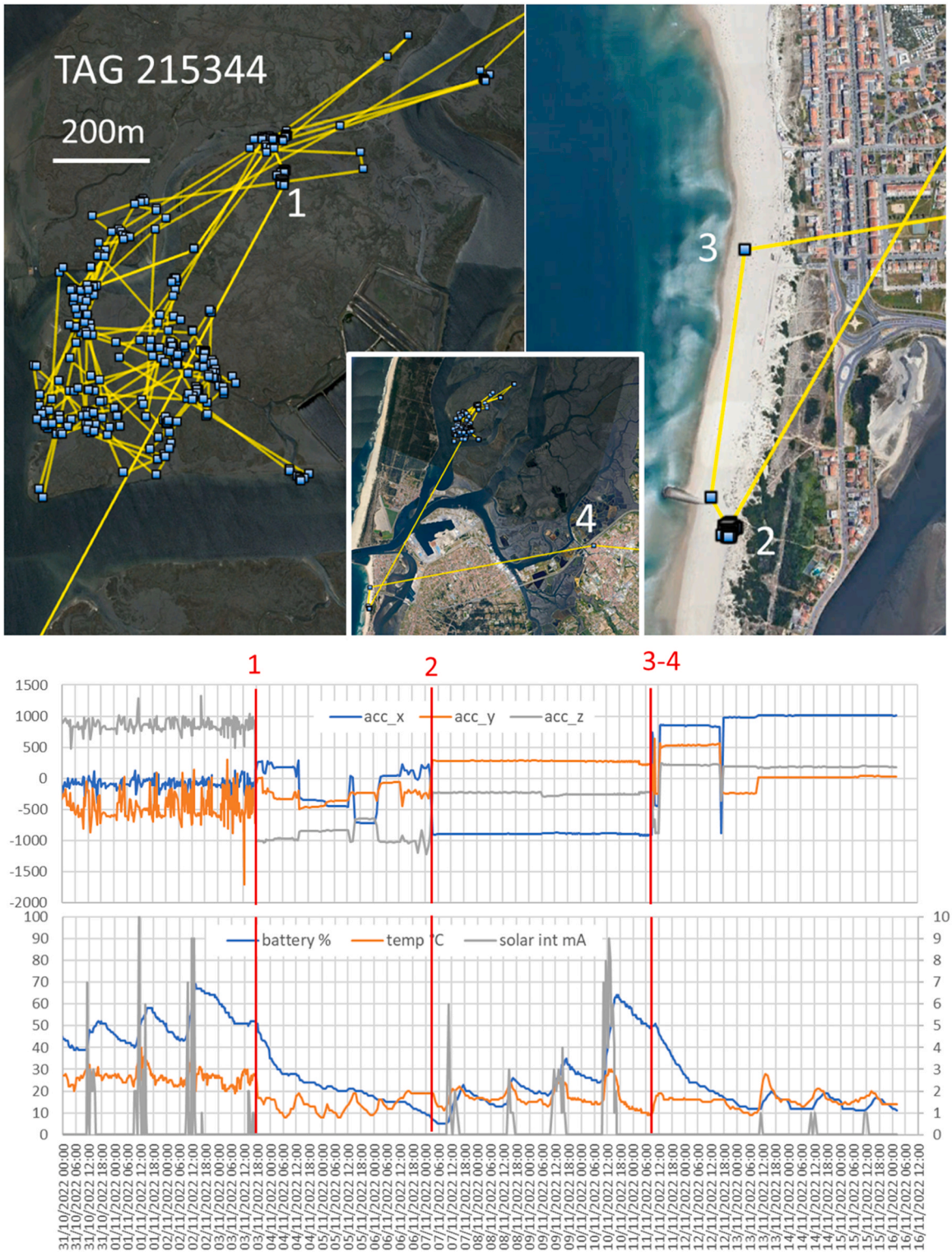

Fig. 8. Tag 215344, data recorded from 31 October to 16 November 2022 12:00 UTC. The general left map focuses on the visited locations on the inland mudflat, the right map the locations on the beach, while the insert map gives an enlarged view of these former sites and the initial travel to a human settlement. Location 1 is where the bird was predated on 3 November. Mapped locations are reported on the data graphics, upper graph for instant accelerometer (3 dimensions), lower graph for temperature (in °C), charging current (solar intensity in mA) and battery charge (%).Satellite images ©Google Earth.

recaptured at night by hand and tagged on 15 June. It left the breeding grounds on 26 July late afternoon, and arrived on its wintering grounds at Aveiro, Portugal, on 28 July early afternoon. Detailed data collected by the multi-sensor tag are presented from 31 October 2022 00:00–16 November 12:00 (Fig. 8). From 31 November onwards, the bird was foraging in the Aveiro estuary, with obvious recharge-discharge of the battery according to light exposure and data recording, with accelerometer values witnessing a classical activity pattern. The last record of normal alive data was obtained at 17:27 on 3 November 2022, while at 17:43 accelerometer values indicate that the tag was upside-down (inversion of the z-value), while there were no associated coordinates (fail to connect to GPS satellites). The tag was then immobile at the same location (location 1) until 6 November 12:27. The next coordinates were transmitted on 7 November 03:28 when the tag moved to location 2. This second site is far from the death site, on a beach, where the tag was immobile but the solar panel was partly exposed to the light, so the battery was recharging during the day. On 11 November 09:42, the tag left the beach, moved along the beach to location 3, then across the city to location 4 and then to a house where it arrived at 12:43. We interpret the data as a death on 3 November in the estuary, probably by predation, then transportation of the carcass and tag by a flying scavenger to the beach (maybe a gull) on the 6 Nov, where a walker found the tag on 11 Nov and took it back to a house.

4. Discussion

4.1. The use of multiple sensors to document animal behaviour and death

Many GPS tags used to track animal movements include multiple sensors that record a variety of parameters, most commonly an accelerometer, but also a thermometer, sometimes a magnetometer, and records of battery charge, light intensity (reaching the solar panel, if present), speed, directions (xyz) of movement. Such multiple sensor data have been widely used to study animal behaviour, generally combining data from two sensors, e.g., GPS and accelerometer [10], geolocations associated with speed and direction of movement [11], GPS and magnetometer [12]. However, a complete combination of multiple sensor data is seldom considered. Most studies using GPS tags to document animal death are based on geolocation data. Kendall and Virani [13] used GPS-GSM tags to estimate annual mortality for vulture species in East Africa, using geolocations only. Poisoning was confirmed as the cause of death in four cases and was suspected in the majority of deaths recorded. Sergio et al. [14] provided a review of studies using telemetry to identify animal death, and proposed a framework to reliable use of GPS-tracking data, though the reported studies concerned mainly geolocation data (with Doppler or GPS-GPRS tags), do consider accelerometer values but their framework relies mainly on geolocation frequency and quality. Peshev et al. [15] recently reported how tracking was implemented to monitor vulture poisoning in the Balkan region, and display data collected by the accelerometer as well as speed and temperature recorded by the tag, as indicative of animal movements or immobility. Here we explain how the data collected by the different sensors can be combined to detail the spatial and temporal occurrence of illegal and cryptic sources of mortality, linked to illegal hunting activities.

4.2. Data contribution of multiple sensors

GPS positions. The examination of coordinates provided by the GPS are often the first indication of an abnormal behaviour of the tag/bird. Fixed coordinates during successive hours are rarely related to a roosting live bird in shorebirds, unlike in some large soaring birds, e.g. migrating raptors and storks, which remain inactive at night. Tracks following roads and ending up in human buildings can help identify a person who retrieved the tag and potentially shot the tagged bird (cases 1,2,3), though can also occur when someone finds an already dead bird or a fallen tag, and takes the tag back home (case 8). It is hardly understandable that poachers take a tag home without realising that the device is able to inform on their location, though they probably consider that hiding the solar panel should stop the functioning of the geolocation system or data transmission. In the maps presented here, the final destinations of the tags ending in a house have been hidden, for privacy reasons.

Instant acceleration (3 axes). When the tag is placed on a live bird, the x-acceleration has typically values oscillating around 0 (the tag is centred on the bird's back), while the y-values are negative (the fore part of the tag is slightly higher than rear part, as the bird's back is higher near the neck and lower near the rump); the z-values are positive (around 1000, the solar panel is directed towards the sky). Systematic variations above and below averages are typical in live birds, independent of their behaviour (flying, foraging). Even when resting, high-frequency data acquisition can reveal small movements of a tag, only related to the breathing of the bird [5]. A dead bird handled and travelling in a bag or a car will also provide oscillating values of the three acceleration axes, but often around average values differing from the normal 'live' ones: see the case 1 (Fig. 1 and Supplementary Material 1). The detection of death, either natural or poaching-induced, is often associated with an abrupt change in values of the z acceleration. This change is very useful to identify the first location where a bird was just after it died: case 1 (site 7 on Fig. 1), case 2 (site 4 on Fig. 2), case 3 (site 3 in Fig. 3), case 4 (site 2 in Fig. 4). The same is true for birds that are probably killed by an animal predator, like in case 8 (at site 1 in Fig. 8). There is also a typical pattern of accelerometer values when the harness is starting to dislocate and the tag topples sideway: the average values of the three axes can change, generally the x-values becoming the lowest values (the tag toppled to the bird's flank), but the variations / oscillations above and below these averages are typical of a live and moving bird (cases 5 and 6, Figs. 5 and 6). In the case 5, the harness probably dislocated completely and the tag fell off at site 5 (Fig. 5), while in the case 6, the tag adopted two different abnormal positions before falling: first from 22 to 24 August when the tag was probably on one flank of the bird, then on 25–26 August when it was on the other flank (change in x- and y-accelerometer values; Fig. 6).

Battery charging current. When exposed to the sunlight, the solar panel is recharging the tag battery, and the charging current is recorded by the device. During daylight, this current can be null when the sun is hidden, for example by clouds, or when the tag is not exposed to the sunlight. This can occur when the solar panel is facing the ground, on an upside-down bird, or when the tag is placed in a bag, a car, a house. A charging current stopping abruptly, almost definitely, during the first half of the day is a strong indication of a dead bird or a fallen tag (cases 2 and 3; see Supplementary Materials 2 and 3), while if it occurs near the end of the afternoon, it can hardly be interpreted in this way (cases 1 and 4, Supplementary Materials 1 and 4), because it can also correspond to low light intensity when the sun is close to the horizon, until sunset. In some cases, the battery is recharging punctually after the retrieval of the tag, the latter being certainly shortly exposed to the direct sunlight. This can be due to the displacement of the tag, by the tide or an animal (case 8, Fig. 8). This is however not systematic, and some displacement of a carcass can fail to re-expose the solar panel to the sunlight (case 4, Supplementary Material 4). When the harness is starting to dislocate and the tag topples sideway, the solar panel is often hidden or not directed towards the sunlight, resulting in sporadic and chaotic recharging current, as illustrated by cases 5 and 6 (Figs. 5–6).

Battery charge. When the battery is not recharging and the tag is still recording and sending data, we observe a regular almost linear decrease in battery charge, which can be used to predict the total battery discharge and anticipate the final loss of connexion to the tag. This is important to organise the retrieval of the device before it gets off the radar. This happened for case 1, as the tag was relocated in three successive houses, the latter approx. 800 kilometres away from the poaching site.

Temperature. All tags recorded cyclic changes in temperature, with diurnal peaks and nocturnal lows. These wavy variations reflect those in ambient temperatures, so that temperatures recorded by the devices are somehow a mix between the air temperature and the bird body temperature. When the tag falls or the bird dies, the animal body is getting cold, so that the temperatures recorded by the tag decrease globally, but still display cyclic changes linked to nychthemeral periods. The recorded temperatures then depend on air temperature, or on water temperature if the tag or the tagged corpse is located in an intertidal environment. Case 8 from 3 to 6 November (Fig. 8) is a nice illustration of this: temperatures oscillated between 10 °c and 20 °c, instead of between 20 °c and 30 °c when the bird was alive.

4.3. Poaching evidence

Within the four tagged individuals reported here as poached (cases 1–4), all occurred during days of authorised hunting on the public maritime domain, where the opening of the hunting season occurred on 6th August 2022. So, three cases occurred during the first three days of the hunting season. Three tags provided tracks that ended in a house (cases 1,2,3). One carcass was also retrieved, the further x-ray imagery performed on that corpse revealing the presence of an ammunition and a broken wing bone (ulna) (Fig. 2) - the latter could have occurred when the bird was forced to land after being shot while flying, but it should also be mentioned that many recovered carcasses of legally shot birds do not contain any shotgun pellets because they all pass through the body, especially likely for birds shot in the wing [16]. Finally, case 4 is also confirmed as the corpse was retrieved, and x-ray imagery revealed the presence of ammunitions in the body (Fig. 4). The environmental police started investigations on three of these four cases, and the data collected by the multiple sensors of the tags enabled to determine the precise time and location where the birds died. The collected information will be very useful when confronting the narratives of the persons who hold the tags in their houses, to challenge putative evidence of poaching.

4.4. Harness dislocation

The overall recorded data are clearly different for birds that dropped their tag naturally. Accelerometer and solar intensity data indicate that the tag switched from a top to a side position, with the solar panel hidden from the sunlight. This corresponds to a move from the back of the bird, probably to the flank, hidden under a wing. Then the tag continues to deliver data, potentially until the battery is empty, but in the two illustrated cases data transmission stopped before the complete discharge of the battery, suggesting that the harness completely dislocated and the tag felt in the mud or the water, without being able to connect further and send data anymore. In the cases 5 and 6 illustrated here, the delay between the first damage to the harness and the end of data transmission is approximately 60 and 92 h. As data transmission occurs every 24 h, the definite loss of the data from the bird occurred within the following 24 h of the last data transmission, so between 2 and 5 days after an initial deterioration of the silicone harness. We don't know if such a deterioration could be due to the aging of the silicone or action from the bird.

4.5. Natural predation

The last two cases reported here (7 and 8) are considered to relate to natural predation and later displacement of the tag. The immobilisation of the tag is sudden and occurs on mudflats, at usual foraging sites. The tag is probably removed from the prey by the predator (supposedly an avian predator, such as a Marsh Harrier *Circus aeruginosus* or a Peregrine *Falco peregrinus*), and can thereafter move depending on tidal intensity and calendar. In case 7, the tag was initially balanced by the tide, but was then taken by the water and floated until it reached again a shore in the bay, where it was again submitted to regular tidal movements. The tidal movements is also obvious in case 8 at mapped location 1 (Fig. 8; see the cyclic changes in accelerometer values, every approx. 6 h), while the tag (and carcass remnants) was then obviously moved to a distant location (to the beach), supposedly by an avian scavenger (a gull *Larus sp.*) given the long distance and numerous obstacles (mudflat, river, city). At this second location (site 2 in Fig. 8) the tag is immobile, so in the upper part of the beach, outside the intertidal zone. Someone found the tag there and took it back home. By the time of writing these lines, we have not been contacted by this person so are not able to report on the state of the tag and harness at retrieval.

4.6. Poaching threat to the species

The Eurasian Curlew first breeds when two years old, and the oldest known bird is at least 34 years old. According to available estimates from European populations, the annual rates of mortality are 66 % in the first year [17], while the overall annual survival rate of adults is estimated at 92 % ± 3 % in the absence of hunting [18]. As a consequence, any additional adult mortality can have a noticeable impact on population dynamics, increasing extinction risk. The poaching of one adult bird here is potentially highly damageable for the species conservation. This is not the first case of a poached adult Eurasian Curlew in France. A similar case for one out of 10 tagged adults had been reported [5]. An increase in adult mortality must be compensated by a higher reproductive success to maintain a stable population size. In long-lived species, hunting mortality of young individuals might be less impacting the species fate, but in the Eurasian Curlew, low breeding success has been identified as a key factor driving current declines and challenging population recovery [19,20]. Any additional juvenile mortality impact future recruitments, and the multiple yearlings poached in summer 2022 in France reduce the chances of head-starting measures to be successful in restoring a favourable conservation status for the target Belgian and German populations. Young birds might be particularly sensitive to hunting mortality, because of their inexperience. If juveniles migrate in flocks, like adults [21], they perform their migration later in the summer than adults, on their own. They will later integrate curlew flocks and benefit from the experience of older local winterers, which survived previous winters. Juveniles recently arrived on non-breeding sites are not yet integrated in flocks of experienced individuals so less inclined to identify and escape dangerous areas and situations. The three juveniles reported here as poached in France in August 2022 had arrived on the wintering site 1, 4 and 7 days before being shot, respectively, and were shot within the first three days of the hunting season. It is also noteworthy that within the concerned regions (Hauts-de-France and Normandy), there were only three tagged juveniles from our research and conservation projects, and all were shot. Considering that thousands of curlews do winter there, with probably hundreds of recently arrived juveniles, we can expect that the real numbers of curlews shot in France in 2022, despite being subject to a zero quota, has been far higher than the cases reported here.

Obviously, the high frequency of curlew shooting in summer 2022 illustrate the non-appropriation of the ongoing adaptive management process by French hunters. It certainly questions the way adaptive management was introduced in the country. The absence of initial dialogue and common objectives is certainly responsible for that. There are several examples of successful adaptive management processes (see e.g., [22]) that French authorities and hunters should learn from to better insure the sustainability of curlew and other gamebird population across the European continent. Finally, we must recommend to improve education and awareness towards hunters concerning hunting bans and the potential deleterious effects of such an illegal shooting, intentional or not, on population dynamics of an endangered species. As reported in [14], improved employing of remote multi-sensor tag monitoring will advance the efficiency, planning, and implementation of management projects on imperilled or harvestable species affected by illegal, conflictual, or cryptic sources of mortality.

Ethical statement

We hereby declare and testify that all bird captures and tagging reported in our manuscript have been realised in compliance with national regulations and with official permissions to capture, ring and tag these wild animals.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fsiae.2023.100069.

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