






Leveraging animal tracking to combat wildlife crime: GPS-tagged vultures and wolves as sentinels of other species' poaching

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Abstract

From satellite imagery to drones or camera traps, remote technologies are increasingly used to enhance wildlife crime detection worldwide. Whereas remotely tracking individuals allows for prompt detection of their illegal persecution, much less attention (concentrated in oceanic ecosystems) has been paid to tagged animals as sentinels to detect other species' poaching through their interspecific interactions. We illustrate this potential in terrestrial ecosystems by showing how GPS-tagged vultures, able to quickly locate dead animals, and GPS-collared wolves enabled the detection of poached wildlife of other species (i.e., illegally shot or snared wild ungulates and carrion-baited illegal snares) in Europe. We further discuss how these interspecific interactions could be systematically monitored to improve detectability of poaching events. Considering the wide variety of tracked wildlife across ecosystems, taking their interactions (e.g., scavenging) into account will enhance the utility of animal-borne technologies in addressing illegal wildlife persecution.

Keywords: biomonitoring, illegal killing, remote technologies, scavengers, species interactions

Wildlife crime, which includes the illegal taking or trading of wild fauna and flora (see United Nations 2019 for a more complete definition), is a significant contributor to environmental crime (Nellemann et al. 2018). Illegal activities harming the environment are acknowledged as one of the most significant threats to biodiversity, but they also jeopardize human well-being, peace, and security (United Nations 2019, INTERPOL 2023). Environmental crime has indeed become one of the world's largest criminal activities next to trafficking in firearms, drugs, and human beings (Nellemann et al. 2018, INTERPOL 2023).

The global dimension of this threat explains the international efforts implemented in the last decades to fight against environmental crimes in general and wildlife crimes in particular. International cooperation within the UN Global Programme on Crimes that Affect the Environment disbursed US\$14 million in 2022 to enhance national authorities' capacity for investigation and prosecution of illegal wildlife persecution (UNODC 2022). Meanwhile, since 2017, the International Criminal Police Organization (INTERPOL) has coordinated actions against the illegal wildlife trade from across more than 100 countries (INTERPOL 2023). International efforts are also coordinated to monitor elephant poaching for ivory through the Convention on International Trade in Endangered Species of Wild Fauna and Flora's program for Monitoring

the Illegal Killing of Elephants across Asia and Africa. Illegal wildlife persecution is also addressed within Europe through its financial instrument for environmental conservation (i.e., the LIFE program, which invested more than €70 million, approximately US\$84 million) in projects to combat this threat between 1992 and 2017 (European Union 2018) and, in 2020–2023, supported the SWiPE (Successful Wildlife Crime Prosecution in Europe) project to face wildlife crime in 11 European countries (Engel 2023).

Wildlife crime detection benefits from new technologies

Effectively monitoring, prosecuting, and preventing poaching requires improved detection, which is instrumental for informing conservation actions and assessing their effectiveness. Improving detection is one of the five critical objectives identified by the International Consortium on Combating Wildlife Crime (IC-CWC 2022). Among the myriad of approaches used to detect cases of illegal wildlife persecution (e.g., DNA analysis of seizures, mapping trade data, enhancing effectiveness of patrolling activities; Wasser et al. 2015, Wich and Piel 2021), remote detection emerges as a useful tool for detecting wildlife crimes

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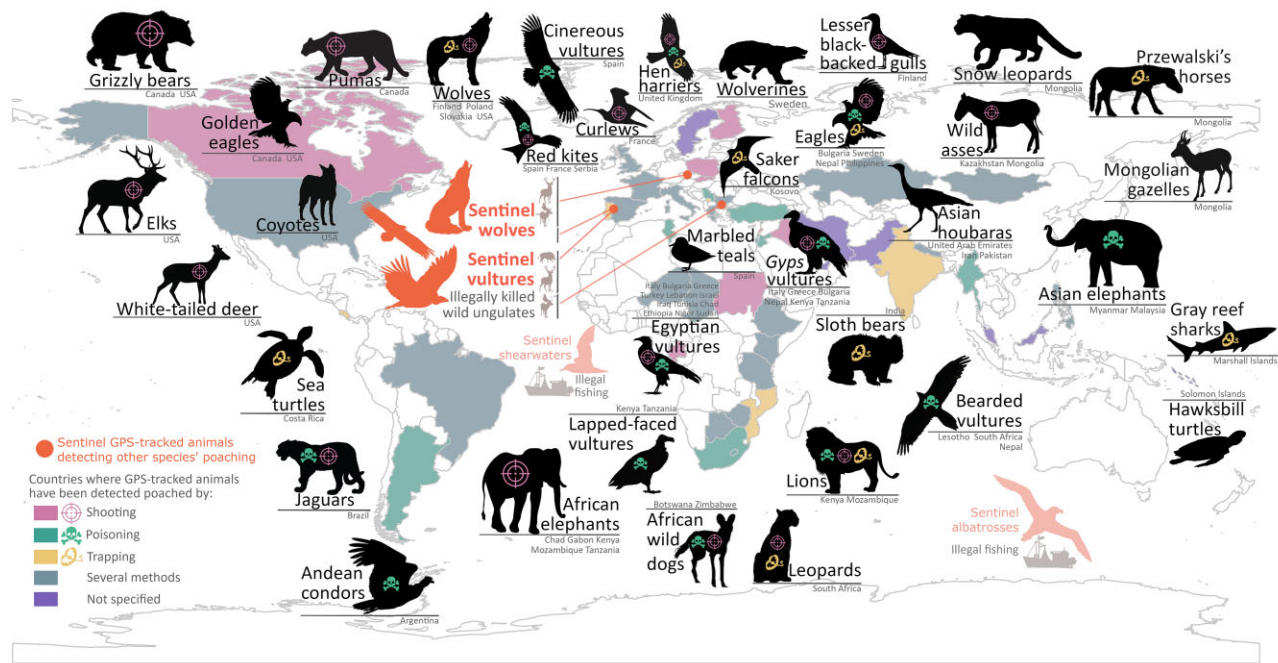


Figure 1. Remotely tracked wildlife (the black silhouettes) is illegally killed or taken worldwide, helping to detect poaching across taxa and ecosystems. Detectability might be increased by monitoring the ecological interactions of tagged species (the sentinels, larger silhouettes for our study cases in terrestrial ecosystems and smaller ones for other works in marine areas) with nontagged species that are targeted by poachers (the small silhouettes next to the sentinels). The black silhouettes without icons inside indicate unspecified poaching methods. [Supplemental appendix S1](#) offers more details on the poaching methods and species reported by our systematic review.

(Lahoz-Monfort and Magrath 2021, Wich and Piel 2021). Satellite imagery to detect illegal logging or fishing, drones supporting on-the-ground antipoaching units, acoustic shotgun detectors, AI-embedded camera traps and wildlife GPS tracking (Lynch et al. 2013, Pheasey et al. 2020, de Knecht et al. 2021, Wich and Piel 2021, Dertien et al. 2023) are examples of remote technologies used to improve detection of wildlife crimes, even in real time (e.g., Dertien et al. 2023).

While allowing major advances to species' ecology (e.g., from individuals' movement, behavior, or fitness to their interactions with natural environments or human activities; for detailed examples, see Nathan et al. 2022), animal tracking provides useful insights into species' threats, including detection of their illegal persecution. Tagged individuals reported as poached can be found across the globe, including turtles and jaguars in Central and South America (Pheasey et al. 2020, Csermak et al. 2023), wolves in Europe and North America (Treves et al. 2017, Nowak et al. 2021), sharks in Oceania (Bradley et al. 2019), elephants in Africa and Asia (Galanti et al. 2006, Sampson et al. 2018), and vultures in Europe, Asia, and Africa (figure 1 and, for details, see [supplemental appendix S1](#); Stoynov et al. 2019, Serratos et al. 2024). In such cases, wildlife crimes are detected because they directly affect the tracked species, which therefore become sentinels of these illegal activities (e.g., Stoynov et al. 2019, Csermak et al. 2023). Moreover, other poached individuals or species can be discovered together with the tracked individuals, especially in the case of poisoning events (see [appendix S1](#); e.g., Csermak et al. 2023).

In addition, tagged animals may also help to detect the illegal persecution of other species with which they interact. In the present article, we compile existing evidence on this matter and expand it with examples of poached wild ungulates and carrion-baited illegal snares detected by GPS-tracked griffon (*Gyps fulvus*),

Egyptian vultures (*Neophron percnopterus*), and wolves (*Canis lupus*). Our main aim is to draw attention to the significant potential that biotic interactions, such as scavenging, could have in improving detection of wildlife crimes that do not affect the tagged individuals but rather other untagged species.

GPS-tagged vultures and wolves as sentinels of other species' poaching

Vultures have the ability to rapidly locate carrion over vast areas (Ruxton and Houston 2004), which makes these species extraordinarily good sentinels of carcass presence (e.g., Mateo-Tomás et al. 2023, Rast et al. 2024). However, this ability also has its downside when, for example, vultures become victims of poachers of African megafauna (e.g., elephants, rhinos, or giraffes). Poachers lace the remains of the illegally killed large herbivores with toxic compounds to prevent vultures from alerting the environmental authorities by conspicuous circling and landing (Ogada et al. 2016). Indeed, this illegal persecution has been referred to as *sentinel poisoning* (Ogada et al. 2016). Therefore, vultures poisoned at poached megafauna offer a clear example of how some species can inform the illegal persecution of other species they interact with.

Beyond major well-known poaching hotspots, such as Africa (e.g., Wasser et al. 2015), wildlife crime is present all over the world. Large wild ungulates, such as red deer (*Cervus elaphus*), wild boar (*Sus scrofa*), fallow deer (*Dama dama*), European roe deer (*Capreolus capreolus*), or ibex (*Capra spp.*), are illegally killed across Europe (Engel 2023). Because vultures and other scavengers such as wolves often feed on carcasses of large wild ungulates, including their hunting remains (e.g., Mateo-Tomás et al. 2015, Arkumarev et al. 2020), GPS-tagged individuals of those species can help detect poaching events, as we show in the present

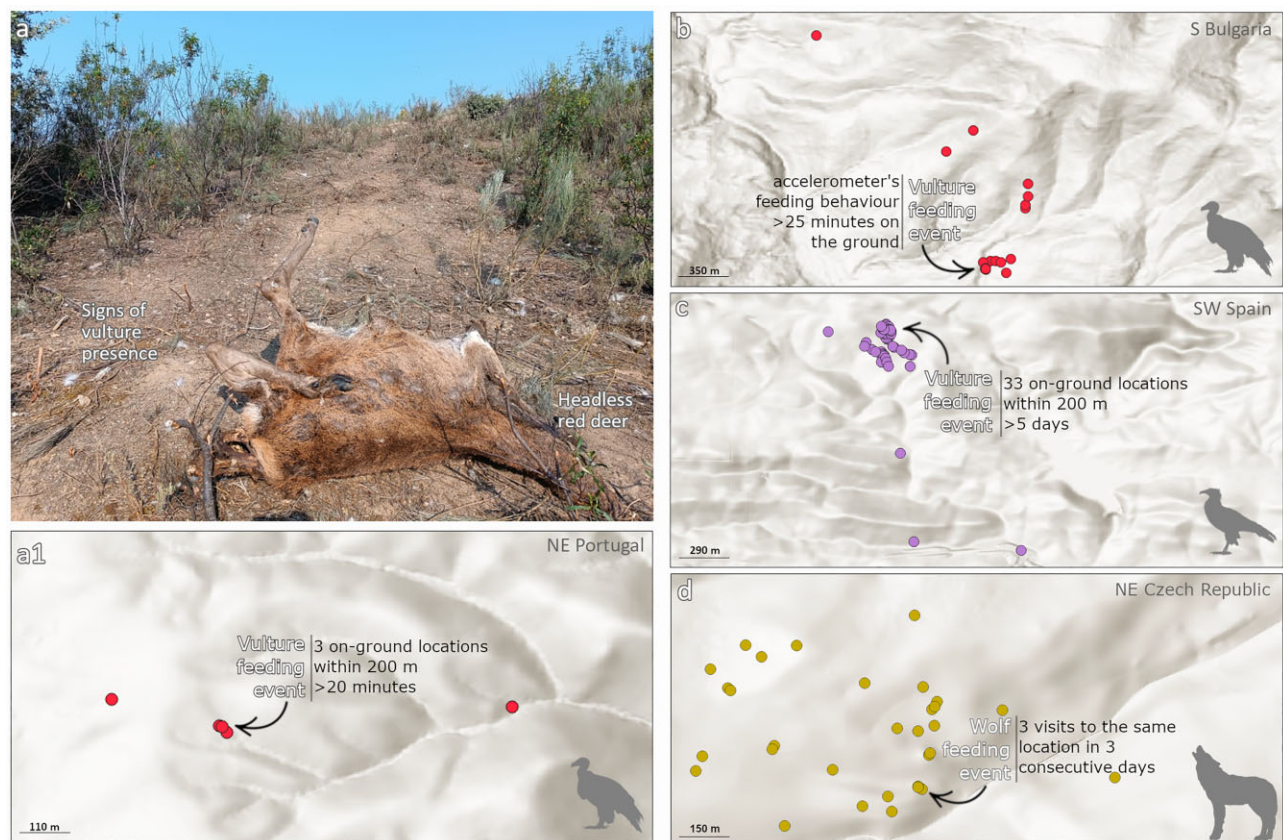


Figure 2. Illustrative examples of wild ungulates suspected to be illegally shot and found by ground-truthing of the feeding sites identified from GPS locations (dots) of tagged vultures and collared wolves in Portugal (a, a1), Bulgaria (b), Spain (c) and the Czech Republic (d). Males of red and fallow deer were often found at these places without their heads (a), appreciated as a trophy. The specific characteristics that allowed the identification of the sentinel species' feeding events at each location are also shown (see box 1 for more details). The background maps show the relief in the areas. Photograph: Iván Gutiérrez.

article with nine illustrative cases of wildlife shooting (figure 2) and snaring (figure 3) that took place in Portugal, Spain, Bulgaria, and the Czech Republic (figures 2 and 3, appendix S1).

On-the-ground monitoring to confirm vultures' feeding allowed us to locate three shot red deer males without their heads at two different locations in northwestern Spain and northeastern Portugal in September 2019 and June 2023, respectively (figure 2a). The carcasses were at sites previously identified as possible feeding spots of GPS-tracked griffon vultures (see box 1 for the criteria used; Rodríguez-Pérez 2020). On-the-ground visits revealed the missing heads (figure 2a), which are highly valued as trophies. Because the three animals were in areas or periods where hunting of the species was not officially authorized, the findings were reported to the authorities. Noteworthy, the authorities confirmed one of the cases as a poaching event by illegal shooting, and, because of this vultures' discovery of the carcass, the suspected poacher was arrested. Ground-truthing of a potential feeding spot of GPS-tagged griffon vultures (Arkumarev et al. 2020) resulted in the discovery of a fallow deer suspected to be shot by poachers in Bulgaria in November 2018 (figure 2b). The animal was missing its legs and rumps, probably taken for consumption. In southern Spain, the remains of a red deer were also discovered after visiting the feeding site of a young Egyptian vulture GPS tagged as a chick in the north of the country. In September 2018, during its migration, the vulture stopped to feed on the deer remains for several days (figure 2c). We reported this finding to the environmental authorities, who considered it as a poaching event. Two

red deer and one fallow deer suspected to be poached were also found in the northeast Czech Republic while ground-truthing the potential feeding spots of one collared wolf at three different locations in February 2024 and January 2025 (figure 2d). The three deer were males suspected of having been illegally shot, and two of them were found headless. These findings were reported to the authorities at the hunting grounds where they were found, and they considered them as poaching incidents.

GPS-tracked griffon vultures also helped to discover the remains of a wild boar trapped in a snare made of braided steel wire in northern Portugal in May 2021 (figure 3a). Similarly to the deer cases, we found the poached animal while visiting a place previously identified as a possible feeding spot of griffon vultures. Snaring and other nonselective means are not allowed for hunting wildlife across the European Union (e.g., Council Directive 92/43/EEC, Portuguese Law 173/99, Portuguese Decree-Law 202/2004 with its subsequent amendments, Portuguese Decree-Law 38/2021, Spanish Law 42/2007), so the finding was communicated to the authorities. In May 2020, GPS-tracked wolves in northwestern Spain helped to detect another illegal snare during ground-truthing of a place previously identified as a possible feeding spot of a GPS-collared individual (figure 3b). The wolf was not captured by the snare, and the authorities were immediately notified to dismantle the illegal trap. The snare was baited with carrion, likely from a wild ungulate, which was in an advanced state of decomposition when found.



Figure 3. Illegal metal snares were found during ground truthing of feeding sites previously identified from GPS locations (dots) of tagged griffon vultures (a) and collared wolves (b) in northern Portugal and northwest Spain, respectively. Vultures scavenged a wild boar trapped in the snare while wolves fed on carrion used as bait. The specific characteristics that allowed the identification of the feeding events at these locations are also shown (see box 1 for more details). The background map shows the relief in the areas. Photographs: Jorge Rodríguez-Pérez and Emilio J. García.

Remote monitoring of species' interactions to detect poached wildlife

A systematic search on biologging and illegal wildlife persecution was launched in Scopus on 16 April 2024 with (*gps* OR *satellite* OR *biologging* OR *biologged* OR *animal-borne*) AND ("*cryptic kill*" OR "*human-caused mortality*" OR "*wildlife crime*" OR "*environmental crime*" OR *poison** OR *poach** OR "*illegal kill*" OR "*illegal trad*" OR "*illegal fish*" OR "*illegal trap*" OR "*illegal shot*" OR "*illegal shoot*" OR *snar*") in the "Article title, abstract, keywords" field (for details, see appendix S1). This search showed that most poaching cases detected by remotely tracked species directly affected the tagged individuals, which were poisoned, shot, or illegally trapped (figure 1). Contrastingly, only two studies reported the detection of poached species different from the ones equipped with GPS devices without the latter being killed or injured by poachers (see appendix S1; e.g., Weimerskirch et al. 2020, Navarro-Herrero et al. 2024). These works, carried out in oceanic ecosystems, used GPS tracking of wild species (i.e., albatrosses *Diomedea* spp. and shearwaters *Calonectris* spp.) to detect illegal wildlife persecution (i.e., fishing in the Indian and Atlantic Oceans), highlighting the species' potential as ocean sentinels (Weimerskirch et al. 2020, Navarro-Herrero et al. 2024).

The poaching events detected by GPS-tagged vultures and wolves that we describe in the present article considerably expand the evidence available in terms of the sentinel species, the type of poaching, and ecosystems where illegal wildlife persecution might be detected by paying attention to the tagged species' interactions (figure 1). These cases underline how GPS-tracked

species can provide additional information on wildlife crimes by further considering their interspecific interactions. Scavengers can therefore act as sentinels of other poached species killed by a variety of different means (e.g., illegal shooting and snaring). Vultures' ability to quickly find dead animals over large areas (Ruxton and Houston 2004) makes them good sentinels of the illegal persecution of a wide range of species. Through their feeding interactions, vultures might also become sentinels of compliance with regulations combating illegal wildlife persecution (e.g., poisoning; Stoyanov et al. 2019, Vaadia et al. 2025). In fact, by feeding on the carcasses of domestic large animals, vultures and other scavengers, such as wolves, have already been highlighted as sentinels of compliance with other legislation related to nature conservation—that is, the sanitary regulations allowing the feeding of wildlife with livestock carcasses in Europe (Mateo-Tomás et al. 2023).

Remote tracking of wildlife is widely acknowledged as a powerful tool for studying species ecology, with recent advances allowing the remote identification of animals' behaviors and interactions (e.g., vulture feeding events; Resheff et al. 2014, Rast et al. 2024, Vaadia et al. 2025) and, therefore, increasing the usefulness of animal tagging in conservation and management (Nathan et al. 2022). For example, changes in animal movement (e.g., speed, acceleration, directional persistence) of GPS-tracked African elephants and ungulates have been related to real or simulated poachers' presence, respectively (Ihwagi et al. 2018, de Knecht et al. 2021). In the particular case of vultures and wolves equipped with GPS devices, feeding events can be remotely identified

Box 1. Systematic detection of scavenging events by GPS-tagged vultures and wolves

Potential feeding sites of GPS-tagged griffon vultures in Spain and Portugal (figures 2a and 3a) were identified with an accuracy of more than 70% by selecting clusters of locations with a speed of at least 4 meters per second recorded by the GPS (i.e., indicating possible stops; Spiegel et al. 2013) within 20 minutes or more in a radius of 200 meters (Rodríguez-Pérez 2020). In Bulgaria, griffon vulture feeding events were identified through accelerometer-based classification in the web application AccelaRater (Resheff et al. 2014) and visual inspection of the GPS data (figure 2b). A potential feeding site was therefore considered if one or more of the following criteria were met: The accelerometer data indicated feeding behavior, two or more tagged vultures visited a same location considered unsuitable for roosting or perching, or the individual spent less than 15 minutes on the ground in a deep valley, forest, bushy area, or another place unusual for roosting or perching (Arkumarev et al. 2020). A visual inspection of the GPS data allowed us to identify the feeding event in the present article described for one tagged Egyptian vulture, which visited a place unsuitable for roosting during several days (figure 2c).

For wolves, we took advantage of intensive GPS schedules adopted in order to maintain an acceptable balance between battery life and monitoring period. In the Czech Republic, every 6 months, GPS positions were fixed every 30 minutes between 6:00 p.m. and 9:00 a.m. (GMT time) for 1 month to study wolf feeding ecology. At least two GPS locations clustered with a maximum distance of 50 meters between them were selected for on-the-ground visits, as well as places visited on several consecutive days (figure 2d). In Spain, a location was taken every 20 minutes during 1 week per month; this was previously identified as the best fix rate to extend battery life and detect feeding events (see Planella et al. 2016 and Mateo-Tomás et al. 2023 for more details). The criteria to identify potential feeding events were two or more locations within 40 minutes or more with a maximum distance between them of 60 meters (i.e., the double of GPS error; figure 3b). We did not visit clusters related to long periods of inactivity during daylight hours, considering those as resting sites (Planella et al. 2016), as well as recurrent clusters in the same location where we previously found prey remains (Planella et al. 2016).

(for details, see box 1; Resheff et al. 2014, Planella et al. 2016, Arkumarev et al. 2020, Rodríguez-Pérez 2020, Mateo-Tomás et al. 2023, Rast et al. 2024), therefore facilitating the systematic selection of locations of interest for ground-truthing. We provide a methodological workflow to show how GPS-tracking of wildlife could be scaled up for poaching detection (figure 4). Although this could initially lead to a high number of locations to visit, the behaviors of interest of GPS-tracked sentinels (i.e., potential feeding events in our examples) could be reduced by cross-referencing the information provided by the sentinels with other relevant data in each case. For instance, in our study areas, where both vultures and wolves often feed on livestock carcasses (Arkumarev et al. 2020, Mateo-Tomás et al. 2023), the number of feeding events to visit might be considerably reduced by excluding livestock carcasses reported by owners to the livestock insurance or the animal health authorities, as well as those claimed as wildlife damages to the environmental authorities. In addition, overlapping the feeding sites of the sentinel species with data on authorized hunting locations (e.g., dates and coordinates where hunting remains are abandoned) would further reduce the number of sites for ground-truthing, helping to identify potential poaching spots where enhancing surveillance, as was recommended, for instance, in the case of illegal fishing (Weimerskirch et al. 2020). The number of feeding events to visit might be further reduced by focusing on areas of interest such as previously identified poaching hotspots (Sooñi et al. 2022), protected areas, or suitable habitats for the poached species. For instance, after applying all the criteria described in box 1 to the GPS locations sent during 1 week by 18 griffon vultures tagged in northwest Spain and northeast Portugal, we obtained 35 potential feeding sites for ground truthing (mean = 3, standard deviation = 2, range = 0–6 feeding sites per vulture). This number of locations could be further reduced depending, for example, on the objectives of wildlife managers. If the priority was to detect red deer poaching (figure 2a), the effort would be reduced to 10 sites to visit within the species distribution (Carranza 2007, Carvalho et al. 2023). Similarly, seven sites should be checked if the surveillance is focused on protected areas only.

As animal-borne technologies become increasingly capable of collecting high-quality data on the species' ecology, they enable better identification of biotic and abiotic interactions, allowing us to improve our understanding of environmental impacts such as habitat loss or climate change (Lahoz-Monfort and Magrath 2021, Jetz et al. 2022, Nathan et al. 2022). By paying more attention to the ecological interactions of GPS-tracked species, remote monitoring will become an even more powerful tool to detect other major threats to biodiversity such as illegal wildlife persecution. This approach will therefore contribute to making the most out of the data provided by wildlife tracking, in line with animal welfare recommendations to reduce the number of tagged individuals to limit potential negative impacts (e.g., on survival or reproduction; Bodey et al. 2018). Moreover, considering the highly sensitive nature of the fight against environmental crimes, other ethical implications posed by wildlife tagging (e.g., locate and kill or disturb tagged animals; Cooke et al. 2017) should also be taken into account to guarantee a meaningful contribution of GPS-tracked sentinels to combat wildlife poaching. Although GPS-tagged individuals may have lower poaching-related mortality compared with their untagged conspecifics (Milleret et al. 2021), additional measures should be taken to prevent deliberate persecution of GPS-tracked sentinel individuals. Following recommendations such as ensuring data security, encouraging the telemetry industry to prevent sabotage or illegal exploitation or clearly articulating (e.g., through data-sharing policies) who can access and use data and for what purpose should be a priority when implementing GPS tracking of wildlife as sentinels.

Besides wildlife poaching, GPS-tracked sentinels could also help to combat other environmental crimes. For example, GPS-tracked yellow-legged gulls (*Larus michahellis*) feeding on urban waste allowed the detection of illegal dumping sites (Navarro et al. 2016). As occurring with scavenging, which is widespread across taxa (e.g., Mateo-Tomás et al. 2015), many different species visit dumping sites worldwide to feed on garbage but also as hunting grounds for prey or to collect nesting material (e.g., white storks *Ciconia ciconia* and carrion crows *Corvus corone* in Europe, spotted

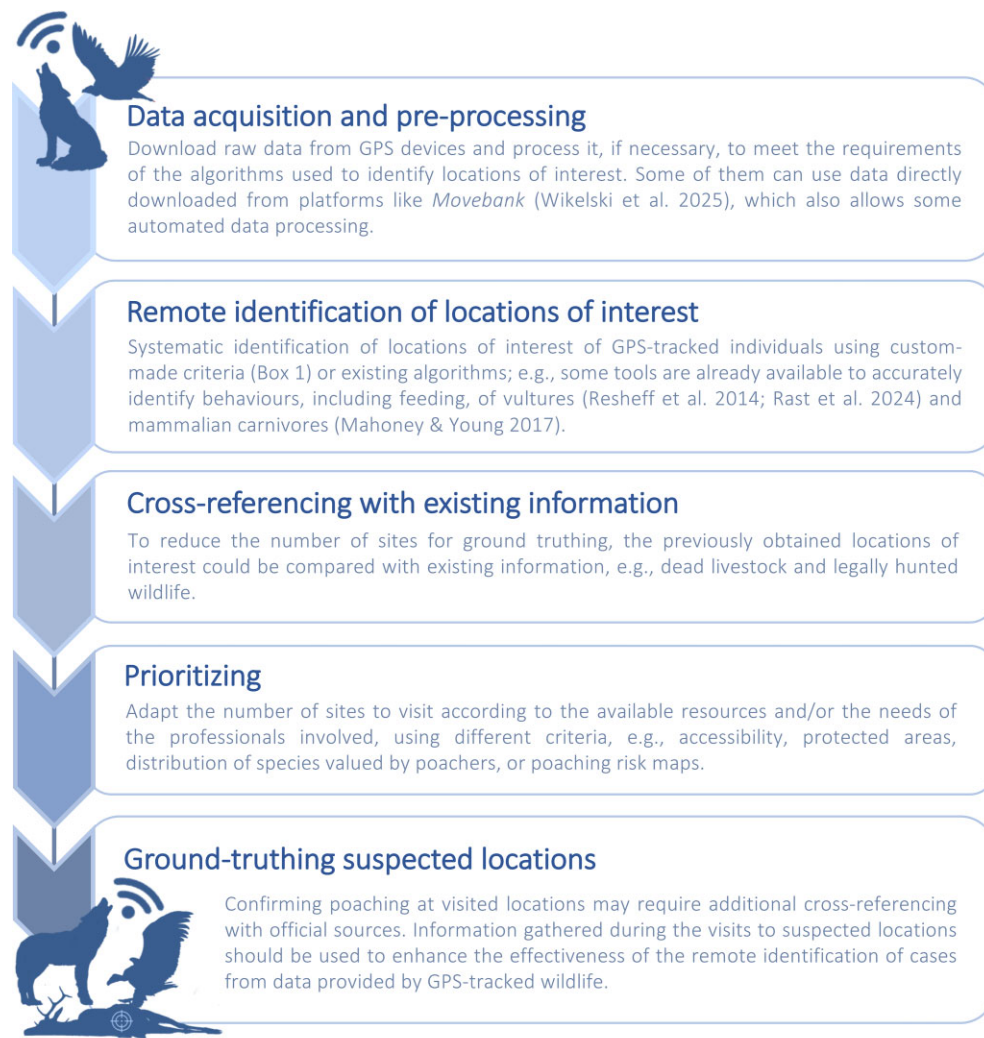


Figure 4. Proposed workflow for systematically scaling up GPS tracking of wildlife for poaching detection.

hyenas *Crocuta crocuta* and black kites *Milvus migrans* in Africa, golden jackals *Canis aureus* and Egyptian vultures in Asia, black vultures *Coragyps atratus* and brown bears *Ursus arctos* in America; Sangkachai et al. 2024). Both scavenging and wildlife visits to dumping sites illustrate the many different species that could act as potential sentinels of environmental crimes. Such species diversity may also help overcome limitations arising from higher tagging rates of species with certain functional traits, allowing for the consideration of sentinel species with complementary traits and interactions. For example, although some species can migrate away from an area of interest (e.g., Egyptian vultures), others spend the entire year in the same areas (e.g., griffon vultures, especially adults, and wolves). In addition, although vultures are more skilled at locating carcasses in open lands, wolves can more easily access carrion in areas with denser vegetation (Mateo-Tomás et al. 2023). This complementarity will boost the effectiveness of using GPS-tracked sentinels to detect wildlife crimes.

Satellite tracking of wildlife increasingly allows for deeper insights into species ecology (Jetz et al. 2022), facilitating, for example, the remote identification of their behaviors and interactions and thereby expanding the applications of animal tagging in biodiversity conservation and management (Lahoz-Monfort and

Magrath 2021, Nathan et al. 2022). In the present article, we draw attention to the underused potential of considering the ecological interactions of GPS-tracked species to help detect environmental crimes such as illegal wildlife persecution. Several examples, in the present article and elsewhere, illustrate how GPS data alone (e.g., clustered locations) can be used to remotely identify sites of interest in this regard (e.g., feeding sites; Navarro et al. 2016, Planella et al. 2016, Rodríguez-Pérez 2020, Mateo-Tomás et al. 2023). The increasing availability of different sensors incorporated into GPS devices (e.g., accelerometers, radar detectors; Resheff et al. 2014, Arkumarev et al. 2020, Weimerskirch et al. 2020, Rast et al. 2024, Vaadia et al. 2025) is expected to improve the accuracy of such identifications, facilitating their systematic implementation and reducing associated costs (e.g., due to ground-truthing false positives). The ongoing advances in both wildlife tracking technologies, which allow the collection of increasingly more data from a growing number of species and in the processing and analyzing of big data (Nathan et al. 2022) open a promising avenue to explore ways to facilitate the implementation of this approach in ecological studies using GPS-tagged fauna and therefore enhance the usefulness of animal-borne technologies in combating wildlife crime.

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Supplemental data

Supplemental data are available at [BIOSCI](#) online.

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