Wildlife as sentinels of compliance with law: an example with GPS-tagged scavengers and sanitary regulations

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Abstract

1. Monitoring compliance with environmental laws is essential to overcoming possible implementation shortfalls jeopardizing their effectiveness. Besides improving our ecological understanding of wildlife, remote tracking technologies also allow to take advantage of such ecological knowledge to use wildlife as sentinels of compliance with law.
2. We illustrate this sentinel potential of wildlife using GPS-tracking of large scavengers with complementary functional traits (i.e., 21 griffon vultures and 13 wolves) to assess compliance with EU sanitary regulations allowing livestock carcass disposal in the field.
3. Wildlife sentinels allowed the systematic evaluation of 490 livestock carcasses left in the field, which revealed an important mismatch between on-paper and in-reality implementation of these regulations. While <45 % of the carcasses were placed in authorized areas, compliance with all the criteria required by the regulations on livestock carcass disposal (e.g., from carcass characteristics such as species, age, or production system to its location far away from water, buildings, or roads) ranged from 0 to 4.2%, with no major differences between regions with uneven implementation.
4. Major gaps in compliance pointed towards insufficient and over-bureaucratized designation of Scavenger Feeding Zones (SFZs), where livestock carcass disposal is authorized. The indiscriminate nature of distance criteria from carcasses to watercourses, buildings, and infrastructures further affected compliance.
5. *Synthesis and applications*: GPS-tagged scavengers allow the on-ground monitoring of carcasses, the addressing of potential risks for wildlife, livestock and human health, the quantitative assessment of compliance with the law and would improve estimates of carcass availability, substantially contributing to a more effective legislation enforcement. Our results show the huge potential of GPS-tagged wildlife as sentinels for monitoring compliance to enhance the environmental rule of law.

Keywords: biomonitoring, environmental rule of law, law enforcement, livestock carcasses, vulture, wolf

Introduction

Environmental laws are acknowledged as conservation tools whose benefits extend far beyond nature preservation (e.g., Sanderson et al. 2016; Greenwald et al. 2019), from sustainable socioeconomic development to public health and security (UNEP 2019). The integration of environmental concerns into other sectorial policies (i.e., Environmental Policy Integration, EPI; Jordan & Lenschow 2010) contributes to achieving conservation goals by, for example, reducing pollution or slowing down habitat degradation (Biermann & Kim 2020). Despite the global rise of environmentally concerned legal instruments and institutions (UNEP 2019), several shortfalls jeopardize the effectiveness of environmental laws (Trouwborst et al. 2017). Slow transposition, poor coordination, under-resourcing or deprioritizing against economic gain weaken enforcement and compliance (Treib 2014; López-Bao & Margalida 2018; Mateo-Tomás et al. 2019a; UNEP 2019).

Monitoring outstands as an integral part of the law implementation process, to evaluate the degree of enforcement and compliance, identify implementation gaps and adapt accordingly (UNEP 2019; IMPEL 2022). Approaches often used to monitor compliance include official inspections, self-monitoring by affected stakeholders, third-party contributions (e.g., from citizens and NGOs), or tracking environmental parameters susceptible of being affected by regulations. Biomonitoring (i.e., using living organisms) is also a powerful monitoring tool, due to its capacity of synthesizing information from complex systems over whole areas (Markert et al. 2003). om microbes and plants to invertebrates and vertebrates, living organisms can bridge the gap between policy, science, and the public in terms of awareness on the enforced regulations (Markert et al. 2003). For example, while lichens are recommended as a biomonitoring tool for assessing compliance in industrial activities emitting air pollutants (Vitarana 2013), fishes are used to monitoring water quality (Kuklina et al. 2013). Examples also exists with birds, e.g., analyzing the gizzard content of waterfowl to assess compliance with ban on lead ammunition in wetlands (Vallverdú-Coll 2012), and marine mammals, whose bycatch are used as bioindicators to improve compliance with fishing gear regulations (Palka et al. 2008a, b).

The rise of remote monitoring techniques has added a new dimension to the concept of biomonitoring (traditionally linked to disciplines such as chemistry or ecotoxicology; Burger 2006): the use of space-based systems such as satellite imagery or global positioning system (GPS) devices for detailed monitoring of wildlife (Jezt et al. 2022). From tracking pollution in ecosystems (e.g., Biermann et al. 2020) to detecting illegal persecution of wildlife (e.g., Stoynov et al. 2018; Weimerskirch et al. 2020), these applications have a strong potential to inform conservation and management policies. Besides informing on direct threats causing species mortality or habitat degradation (Stoynov et al. 2018; Biermann et al. 2020; Jezt et al. 2022), GPS-tracked animals can provide additional insights on how to effectively assess the level of compliance with law, including regulations on biodiversity conservation, sustainable development, or human wellbeing. Thus, for example, GPS-tagged albatrosses have allowed to detect nondeclared fishing vessels, whose illegal activity jeopardize species conservation and the sustainable use of resources of major importance to humans such as those provided by fisheries (Weimerskirch et al. 2020). Similarly, GPS-tracking of jaguars in Brazil has been reported as a useful tool to detect illegal wildlife poisoning (Csermak et al. 2022) while GPS-tagging of hen harries in the British countryside has helped to identify areas where the species is illegally shot (Murgatroyd et al. 2019).

Here, we offer an illustrative example of the potential of GPS-tagged wildlife for monitoring the level of compliance with law. By using scavengers as wildlife sentinels, we assess compliance with sanitary regulations concerned with, but not strictly focused on, wildlife conservation. We show how GPS-tracked vultures and large carnivores shed light on compliance with European sanitary regulations implemented for aligning biodiversity conservation and public health by allowing the disposal of livestock carcasses in the field for feeding scavengers (i.e., Regulations EU 1069/2009 and 142/2011). According to their uneven implementation in Europe (Mateo-Tomás et al. 2018) and based on previous results pointing towards a lack of compliance with the enforced regulations (Gigante et al. 2021; Mateo-Tomás et al. 2022), here we take advantage of GPS-tracked vertebrate scavengers to quantify the level of compliance with these sanitary regulations across national and sub-national borders in the Iberian Peninsula. We later discuss how the major gaps identified could be addressed to effectively achieve the objectives of these regulations.

Methods

The uneven management of livestock carcasses in the Iberian Peninsula

Our work focused on two countries, i.e., Portugal and Spain, and three Spanish autonomous regions, i.e., Asturias, Castilla y León and Galicia; while the Portuguese central government and its regulatory authorities are the competent bodies for implementing regulations on nature conservation and public health, in Spain this competence is held by the autonomous regions. Two major geographical areas were considered: i) the Cantabrian Mountains in northwestern Spain, and ii) the Douro River at the Portuguese-Spanish border (Fig. 1). Livestock rearing is a major activity in both areas, with an important presence of extensive and semi-extensive farming (Appendix S1).

Livestock carcasses are managed differently across administrative borders according to the uneven implementation of EU Regulations 1069/2009 and 142/2011 (Mateo-Tomás et al. 2018; 2019a; Appendix S2). In Spain, Castilla y León and Asturias implemented these regulations to allow the disposal of livestock carcasses in the countryside in 2013 and 2017, respectively.

Galicia allows the abandonment of carcasses of only free-ranging horses since 2016. Farmers in Castilla y León must apply for an official permit, which limits the number of carcasses to dispose at Scavenger Feeding Zones (SFZs; i.e., officially designated areas where fallen livestock can be left *in situ* for feeding wildlife according to EU Regulations 1069/2009 and 142/2011). Contrastingly, all farmers complying with some sanitary requirements can leave livestock carcasses *in situ* within SFZs in Asturias. Farmers in Galicia, on the contrary, must inform the veterinarian authorities of the exact location where carcasses were abandoned. Although recent changes in Portuguese legislation provide new opportunities for leaving livestock carcasses in the field outside artificial feeding stations (Appendix S2), SFZs are not yet implemented. At the time of this study, livestock carcasses in Portugal should be either collected or buried if located within remote areas declared by the competent authorities.

GPS-tracking of large vertebrates for carcass monitoring

Available livestock carcasses for wildlife to feed on were located in the field by GPS-tracking two scavenging vertebrates: griffon vultures (*Gyps fulvus*) and Iberian wolves (*Canis lupus signatus*). Between 2017 and 2020, 21 adult griffon vultures were captured and equipped with solar powered GPS-GSM trackers by Ornitela® in Spain and Portugal, and GPS-Iridium Followit® collars were deployed on 13 Iberian wolves (11 from 9 different packs and 2 floaters) captured in NW Spain (see Appendix S3 for capture details). From the vertebrate scavenger community inhabiting the Iberian Peninsula (Mateo-Tomás et al. 2015, 2017), these two species are perfectly fitted for purpose since they are tightly related to consumption of large ungulate carcasses in the study area and elsewhere (e.g., Tella 2001; Llaneza & López-Bao 2015; Mateo-Tomás et al. 2015; Mohammadi et al. 2019). Griffon vultures are obligate scavengers adapted to feed mostly on carcasses of large ungulates, because they are highly specialized for the efficient location of dead animals over vast areas from the air (Ruxton & Houston 2004). Contrastingly, large terrestrial carnivores such as wolves retain the flexibility of feeding by either predation or scavenging, being frequently recorded as facultative scavengers (Llaneza & López-Bao 2015; Mateo-Tomás et al. 2015). 92 % of the griffon vultures in Europe inhabit Spain and Portugal, with >3,000 breeding pairs estimated in the study area (Del Moral & Molina 2018; Monteiro et al. 2018; Fig. 1). The Iberian wolf population has its main stronghold in NW Spain (Chapron et al. 2014), with 43 wolf packs detected in Asturias in 2021 (Hernández-Palacios & Quirós 2021), where the GPS-tracked wolves were monitored for carcass location.

During monitoring periods to detect livestock carcasses, GPS locations of each tagged scavenger were collected at fixed intervals of 10 minutes for vultures and 20 minutes for wolves, to detect potential feeding sites (Planella et al. 2016; Rodríguez-Pérez 2020). For vultures, we selected clusters of at least two consecutive locations with a speed ≤15 km/h recorded by the GPS (i.e., indicating possible stops; Spiegel et al. 2013) within a radius of 200 m, ruling out clusters located at breeding colonies and roosting sites (Rodríguez-Pérez 2020). To identify scavenging events in wolves, we used an intensive GPS schedule providing a location every 20 minutes during one week per month. We considered two or more locations with a maximum in-between distance of less than 60 m to identify potential feeding sites (Planella et al. 2016). After identifying GPS clusters for vultures and wolves, we visited them in the field within 1-5 days whenever possible (>90% of clusters were visited within this period). All GPS locations identified in a cluster were visited, and in every location, we explored a 30-m radius (based on GPS error) searching for carcass remains (Planella et al. 2016; Rodríguez-Pérez 2020). In the case of wolves, prey remains were additionally evaluated in order to discriminate between predation and scavenging events (e.g., presence of wounds or subcutaneous hematoma compatible with depredation; López-Bao et al. 2017), and only the latter events were considered for subsequent analyses.

For each located carcass, we evaluated whether it fulfilled the different criteria required by the regulations (Fig. 1; Appendix S4). To allow transboundary comparisons, we considered three hierarchical levels for compliance: i) if the carcass was located within an authorized SFZ, ii) whether carcass characteristics, such as species, age and husbandry practices, complied with the requirements set by the regulations, and iii) if the carcass location met the distance criteria set in the regulations to minimize potential risks for wildlife and public health, i.e., distances to water, buildings, roads, power lines and windfarms. Regarding carcass location within authorized SFZs, in the case of Castilla y León we had access only to the livestock species authorized per municipality, not to the specific farms authorized to leave dead livestock in the field. Therefore, we assumed compliance if the livestock species of the carcass was authorized within the municipality where found, regardless of its farm of origin. In Galicia, we considered that a horse carcass was within an authorized SFZ if the carcass location had been communicated to the competent authorities, a compulsory requirement for authorization. For the second level of compliance, whenever possible, we recorded the species, breed, and age of each carcass (mostly based on dentition; König & Liebich 2001; Dyce et al. 2009). By visual inspection of the surroundings, we also determined if the animal had died *in situ* or if the carcass had been thrown away at the place where located. Based on this information and the breed and livestock farming activity observed in the surroundings (e.g., grazing areas, intensive farms), we determined if the animal was free-grazing or came from intensive farming. Finally, to check if the carcass location met the distance criteria set in the sanitary regulations, besides on-ground verifications, we also used official cartography on the location of these points of interest to calculate distances (CIGeoE 2022; IGN 2022).

Results

Livestock carcasses revealed by sentinel GPS-tagged scavengers

GPS-tagged scavengers helped us to find 490 livestock carcasses in a total of 301 different feeding events in 2017-2021 (mean ± SE: 2 ± 0 carcasses per event; Table 1; Fig. 1). Vultures and wolves provided information on 380 carcasses (320 and 60, respectively) located in Spain, while vultures allowed us to find 110 carcasses in Portugal (Fig. 2). Equine carcasses dominated in Asturias (45.3%, followed by cattle, 35.3%) and, especially, in Galicia (90.0%) (Appendix S5). Contrastingly, most of the carcasses recorded in Castilla y León (62.9%) were of ovine and caprine species, which also dominated the sample recorded in Portugal (70.0%). In Asturias, where vultures and wolves were tracked, bovine and equine species dominated the carcasses found by both scavenging species, agreeing with major livestock practices in the area (see Appendixes S4 and S5).

Compliance with EU sanitary regulations

The proportion of carcasses that simultaneously complied with all the legally-required criteria was negligible in both countries (2.1 *vs.* 0% in Spain and Portugal, respectively). The total level of compliance across autonomous regions in Spain ranged from 0 to 4.2% (Fig. 3). The highest compliance level was observed in Asturias, but barely 4 out of 100 livestock carcasses found fulfilled all the criteria required by the law. None of the carcasses found in Castilla y León and Galicia met all the criteria simultaneously (Fig. 3; Appendix S4).

Overall, the main reason for non-compliance was livestock carcasses found outside authorized SFZs (Fig. 3). Focusing on this criterion only, we observed similar levels of compliance in Asturias and Castilla y León, with ~45% of the carcasses found within SFZs (Table 1; Figs. 2a, 2b and 3). Contrastingly, all carcasses found in Galicia and Portugal were outside authorized SFZs. Although 95.2% of the carcasses in Galicia were located within areas of free-grazing horses where carcasses abandonment could be authorized (Fig. 2a), none of the carcasses were communicated to the competent authorities, and therefore they were not considered within authorized SFZs (Xunta de Galicia, pers. comm.; Fig. 2a and 3). Contrasting with the SFZ criterion, most livestock carcasses (>75.0%) corresponded to species, ages and husbandry practices authorized by the enforced regulations in Spain (Table 1). This resulted in a high level of compliance with all the carcass characteristic criteria simultaneously in all regions but

Asturias (Figs. 2c and d), where almost 50% of the carcasses did not comply the criteria of being abandoned *in situ* (Table 1). When overlapping authorized SFZs with carcass characteristics, compliance decreased below 45% in Asturias and Castilla y León, with a sharper decrease in Asturias (up to 14.6%; Fig. 3). Finally, adding the distance criteria further reduced the overall compliance levels well below 5%, reaching zero in Castilla y León. Although the 28.6% of the carcasses found in Galicia simultaneously fulfilled most of the required criteria regarding carcass characteristics and distances to water and buildings (Appendixes S4 and S6), no communication to the competent authorities reduced total compliance to zero (Fig. 3). Similarly, the level of total compliance in Portugal could slightly increase up to 16.4% if SFZs would be officially designated according to recommendations in Despacho 7148/2019, i.e., in remote areas where the burial of fallen livestock is already allowed and in areas prioritized for the conservation and supplementary feeding of necrophagous birds (Fig. 2b; Appendix S6).

Discussion

Our study shows the utility of GPS-tagged wildlife as sentinels to monitor compliance with the law. Our approach was useful to locate livestock carcasses (Planella et al. 2016, Rodríguez-Pérez 2020), and thus GPS-tracking of large scavengers, such as griffon vultures and wolves, enabled us to illustrate a remarkably low level of compliance with the enforced EU sanitary regulations, regardless of the region and the contrasting implementation (Mateo-Tomás et al. 2018, 2019a). Poor compliance with laws intended for environmental conservation has been detected also in other contexts through, for example, biomonitoring porpoise bycatch in the Atlantic coast of North America (Orphanides & Palka 2013), or by GPS-tracking albatrosses in the south Indian Ocean between Africa and New Zealand (Weimerskirch et al. 2020). All these results support previous concerns about the lack of correspondence between on-paper and in-reality implementations, and reinforce the need of improving data collection to identify major gaps in enforcement and compliance with environmental law (UNEP 2019). GPS-tagged sentinel wildlife emerges therefore as a good ally to monitor compliance with laws, and to identify major gaps that can otherwise remain unnoticed or give rise to misleading interpretations. For example, in line with their uneven implementation across Europe (Mateo-Tomás et al. 2018), EU Regulations 1069/2009 and 142/2011 have been considered a major conservation success for scavengers in countries like Spain, with officially designated SFZs (Morales-Reyes et al. 2018). On the contrary, the lack of SFZs has been depicted as a cause of food shortages in countries like Portugal (Arrondo et al. 2018). However, previous evidence from both countries already pointed towards a lack of correspondence between the methods authorized for livestock carcass management and those actually used by farmers (e.g., Gigante et al. 2021; Mateo-Tomás et al. 2022). Our results confirm these mismatches and provide additional insights into their magnitude and characteristics to better inform law enforcement.

A key factor limiting compliance in our case concerned the designation of SFZs. Designating as much surface as possible and reducing the bureaucracy burden for inclusion in SFZs have been recommended to increase the effectiveness of EU sanitary regulations regarding livestock carcass availability across scavengers' foraging areas (Mateo-Tomás et al. 2019a, 2022). GPS-tagged scavengers revealed how these two drawbacks truly reduce the level of compliance. In Asturias, with a low bureaucracy burden (i.e., farmers do not need to apply for inclusion in designated SFZs; Appendix S2), insufficient land designated as SFZs substantially reduced compliance (44.3 %) as many livestock carcasses were found outside SFZs. Designating new SFZs in the northwestern part of this autonomous region would increase the level of compliance, as vultures, wolves and other species often scavenge on livestock carcasses there (Fig. 2a). Contrastingly, in Castilla y León, bureaucracy would limit compliance. Indeed, farmers interviewed in this region complained about the complex process of application for SFZs (Mateo-Tomás et al. 2022). This level of compliance could be even lower than the one here provided, as we assumed compliance if the livestock species found was authorized for disposal at municipality level (see Methods). Other bureaucratic requirements, i.e., farmers' communication to the authorities of carcass location, sharply decreased compliance in Galicia (from 28.6 to 0 %; Fig. 3). Worth mentioning, all the carcasses found in Portugal were within areas that may be potentially designated as SFZs in the future (Figs. 2b; Appendix S4). Our results from Spanish autonomous regions provide useful guidance for enhancing the effectiveness of this designation through, for example, cutting red tape.

Compliance and traceability may benefit from closer collaboration between environmental and animal health authorities (Mateo-Tomás et al. 2019b). Similarly, fluent communication with insurance carriers could increase the information retrieved by the authorities in charge of monitoring carcass disposal. Collaboration among stakeholders has, for example, allowed the Cameroon government to improve compliance and enforcement of wildlife laws, achieving up to 87 % success rates in prosecuting violators (UNEP 2006; Clynes 2010). As most farmers are not aware of the sanitary regulations implemented for handling livestock carcasses (Gigante et al. 2021; authors, unpubl. data), improving communication with stakeholders to increase their knowledge of the enforced regulations would impact on compliance. Indeed, outreach on existing regulations was considered to increase by >20 % compliance of fishermen with using gear modifications required by law to reduce porpoise bycatch (Palka et al. 2008b).

Most livestock carcasses found in each area corresponded to authorized livestock species and husbandry practices. GPS-tracked scavengers revealed however some carcasses from intensive farms, with special concern in the case of pigs consumed regularly by vultures at the collection points of at least four different intensive farms located in Castilla y León, up to >110 km away from the vultures' breeding colonies. Vultures feeding at these farms indicate an additional lack of compliance with regulations that obliges the collection of carcasses from intensive farms by authorized operators to prevent carcass consumption by wildlife. Meanwhile, EU regulations require the maintenance of appropriate containers that prevent wildlife access to carcasses of intensive farmed animals, which are expected to contain toxic substances not authorized for animal consumption (Shore et al. 2014).

More of the livestock carcasses found would comply with the age limits set by the regulations, with the lowest values corresponding to those regions with a higher presence of bovine species (i.e., Asturias), since animals older than 48 months are not authorized to be left in the field. The high compliance with age found in Castilla y León and Portugal was due to assuming that all carcasses of ovine and caprine species over 18 months complied with the mandatory testing procedures (4% of the animals), otherwise compliance with this criterion would drop to 50.9% and 35.2%, respectively. While in Galicia most of the carcasses were abandoned *in situ*, almost half of the carcasses found in Asturias were thrown away from the place where the animal died. Moreover, 54 illegal dumps were found across the study areas, some of them in dangerous places for wildlife and/or people, such as at road borders, windfarms, and power lines. The largest proportion of carcass dumps (29.0% of carcass locations) was recorded in Portugal, where the absence of SFZs could facilitate carcasses to be thrown away at dumpsites instead of being left *in situ*.

Remarkably, non-compliance with distance criteria sharply decreased the total level of compliance across regions. Nonetheless, depending on the distances considered, compliance greatly varied, indicating the indiscriminate nature of many of these criteria. For example, varying the minimum distance from carcasses to windfarms from 200 m (as required in Asturias) to the 4,000 m recommended by the Spanish Government (2011), would decrease compliance from 96.9 to 71.9% in Asturias, 100 to 71.3% in Castilla y León and 52.4 to 4.8% in Galicia. In fact, despite not including distance to windfarms in the regulations for authorizing the abandonment of horse carcasses, Galicia was the study region with the largest proportion of carcasses near wind turbines. Instead of setting fixed distances, on-ground monitoring could help to better adapt these criteria regionally, while gathering useful information for better assessment of the actual effectiveness of the EU sanitary regulations in reconciling scavenger conservation and public health (Mateo-Tomás et al. 2019b).

Although out of the scope of this study, the functional complementarity of vultures and wolves would provide information on carrion availability across habitats and for other scavenging vertebrates (Mateo-Tomás et al. 2015, 2019a; Gigante et al. 2021; Olea et al. 2022). No major differences were found between vultures and wolves in terms of the carcass species found (>78% cows and horses in both cases; Appendix S5) or compliance with SFZs (44.4 and 44.1%, respectively), but to what extent the combination of several sentinel species with different functional traits could improve carcass monitoring deserves further investigation.

We show here how GPS-tagged large vertebrates can act as sentinels of compliance with law, but also of other risks for biodiversity. Not in vain, GPS-tagging has frequently revealed illegal persecution of wildlife (e.g., poisoning; Surkes 2021), *de facto* indicating a lack of compliance with regulations for species conservation (e.g., Weimerskirch et al. 2020). Although the high cost of GPS devices may limit their usefulness, for example, in having enough marked individuals (Fisher et al. 2018), low-cost GPS technologies are increasingly available for tracking more and more species across the globe (Jetz et al. 2022). Meanwhile, advances in movement ecology through, for example, remote identification of species behaviors from GPS sensors (Nathan et al. 2012; Resheff et al. 2014) can significantly reduce the costs of on-ground monitoring GPS-tagged individuals, even allowing data collection from remote areas of difficult access. The on-ground monitoring of carcasses used here can therefore be coupled with remote identification of feeding behaviors of the tracked animals (e.g., griffon vultures; Nathan et al. 2012; Resheff et al. 2014; Rodríguez-Pérez 2020; Arkumarev et al. 2021) to reduce the costs of fieldwork while increasing the precision of the estimates of carcass availability in space and time. This would enhance in turn the usefulness of GPS-tracking of wildlife as sentinels for monitoring compliance with EU regulations for wildlife conservation and public health, thus contributing to a more effective adaptive management. Likewise, given the increasing availability of information from GPS-tagged animals (Jetz et al. 2022), this approach could be used to monitor compliance with different regulations affecting biodiversity conservation almost elsewhere on the planet.

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Table 1. Level of compliance (%) with the different criteria set by the existing regulations allowing livestock carcasses to be left in the field in different autonomous regions in Spain, and in Portugal. *Compliance was evaluated separately for all criteria but age, which was only evaluated for those species specifically authorized for disposal in the field under the enforced regulations. Within brackets the number of carcasses used to assess compliance with the criteria, as some carcasses could not be checked for some criteria during on-ground visits; no number in brackets indicates that the total number of carcasses found in each area were considered for calculations.

Country/Region		Number of livestock carcasses found by GPS-tracking scavengers			Level of compliance with each criterion separately (%)									
						Carcass characteristics				Distances for public health and wildlife conservation				
		Vultures	**Wolves**	**Total**	**Designated SFZ**	**Species**	**Age***	**Non-Intensive**	***In situ***	**Water**	**Buildings**	**Roads**	**Power lines**	**Windfarms**
Spain	Asturias	133	59	192	44.3	90.6	76.4 (161)	84.1 (189)	54.6 (185)	69.8	24.0	20.8	81.8	96.9
	Castilla y León	167	--	167	44.9	100	92.8[a] (166)	86.8 (151)	--	53.3[b]	70.7[b]	21.0[b]	65.3[b]	71.3[b]
	Galicia	20	1	21	0	90.0 (20)	100 (18)	95.2	80.0 (20)	76.2/81.0[c]	85.7	--	--	--
	Total	**320**	**60**	**380**	42.1	94.7 (379)	85.5 (345)	85.9 (361)	--	62.9	47.9	21.1	70.0	80.3
Portugal		**110**	**--**	**110**	0	91.8	100[a] (101)	91.5 (71)	--	59.1[b]	85.5[b]	68.2[b,d]	65.5[b]	100.0[b]

[a]Considering that all the ovine and caprine carcasses older than 18 months were tested in compliance with the existing regulations (i.e., Royal Decree 3454/2000) and guidelines from competent authorities (DGAV 2019). [b]Distances are not specified in the regional legislation so we used those recommended in the guidelines of the Spanish Government for implementing EU regulations for feeding scavengers with livestock carcasses and the distances recommended for supplementary feeding stations in the LIFE Rupis project in Portugal (see Appendix S4). [c]Distance to sources of drinking water after the slash. [d]Only paved roads considered.

Figure 1. Griffon vultures and wolves tracked with GPS devices provided information on livestock carcasses (black dots) disposed over a large area of ~70,000 km^2 in NW Iberian Peninsula. The area encompassed territories in Portugal and in three autonomous regions in Spain, all of them with different implementation of EU Regulation 142/2011 regarding the designation of Scavenger Feeding Zones (SFZs), which are still not officially designated (but discussed in Despacho 7148/2019) in Portugal (dotted area).

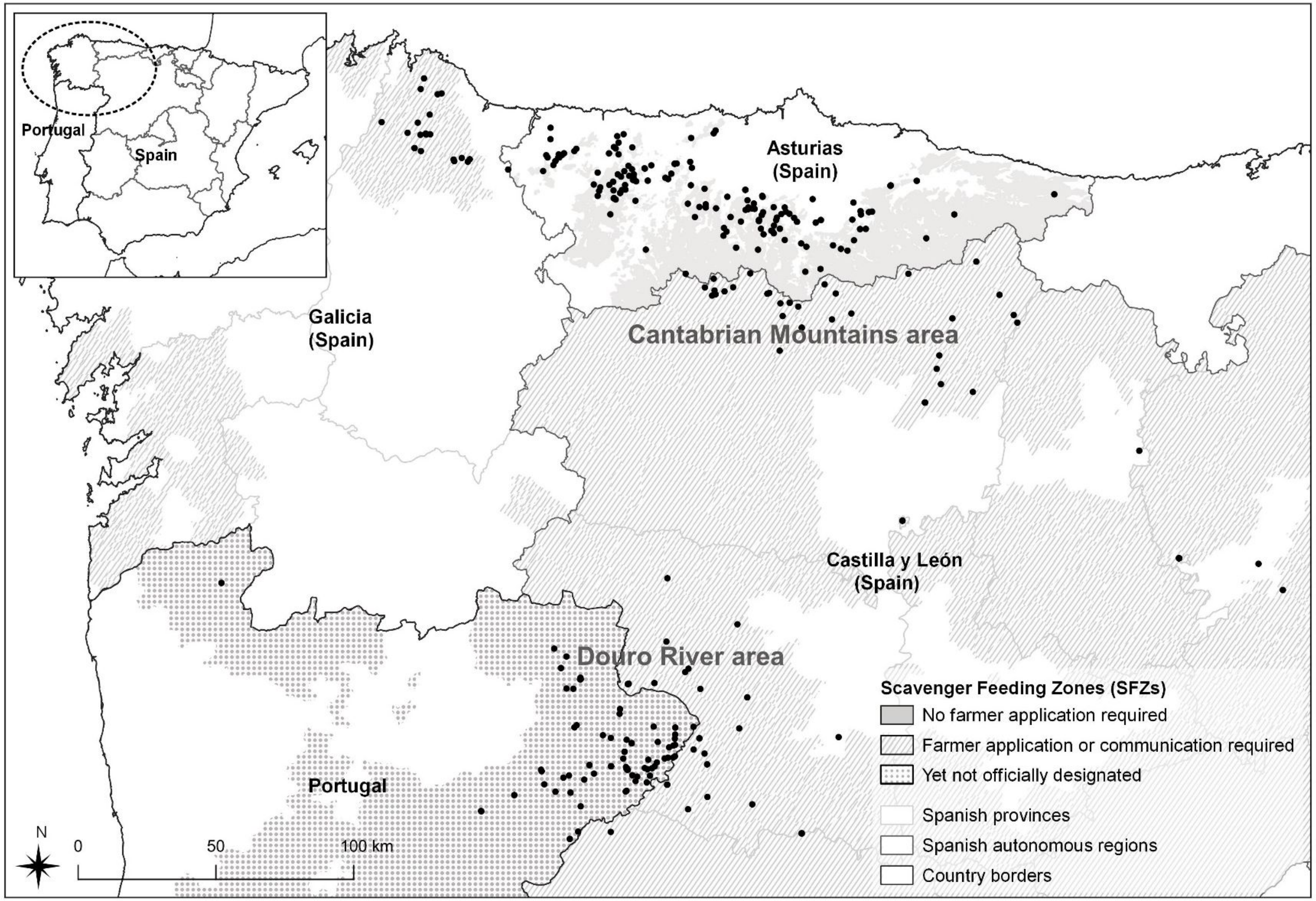


Figure 2. Spatial variation in compliance with the three groups of criteria required by the legislation for carcass disposal enforced across the study areas, i.e., three Spanish autonomous regions in the Cantabrian Mountains (left column) and Portugal and Spain in the Douro River area (right column). Panels **a** and **b**) show compliance with criteria for disposal within Scavenger Feeding Zones (SFZs), panels **c** and **d**) display compliance with all the carcass characteristics criteria, and panels **e** and **f**) exhibit compliance with all the distances established to reduce potential risks for human and animal health.

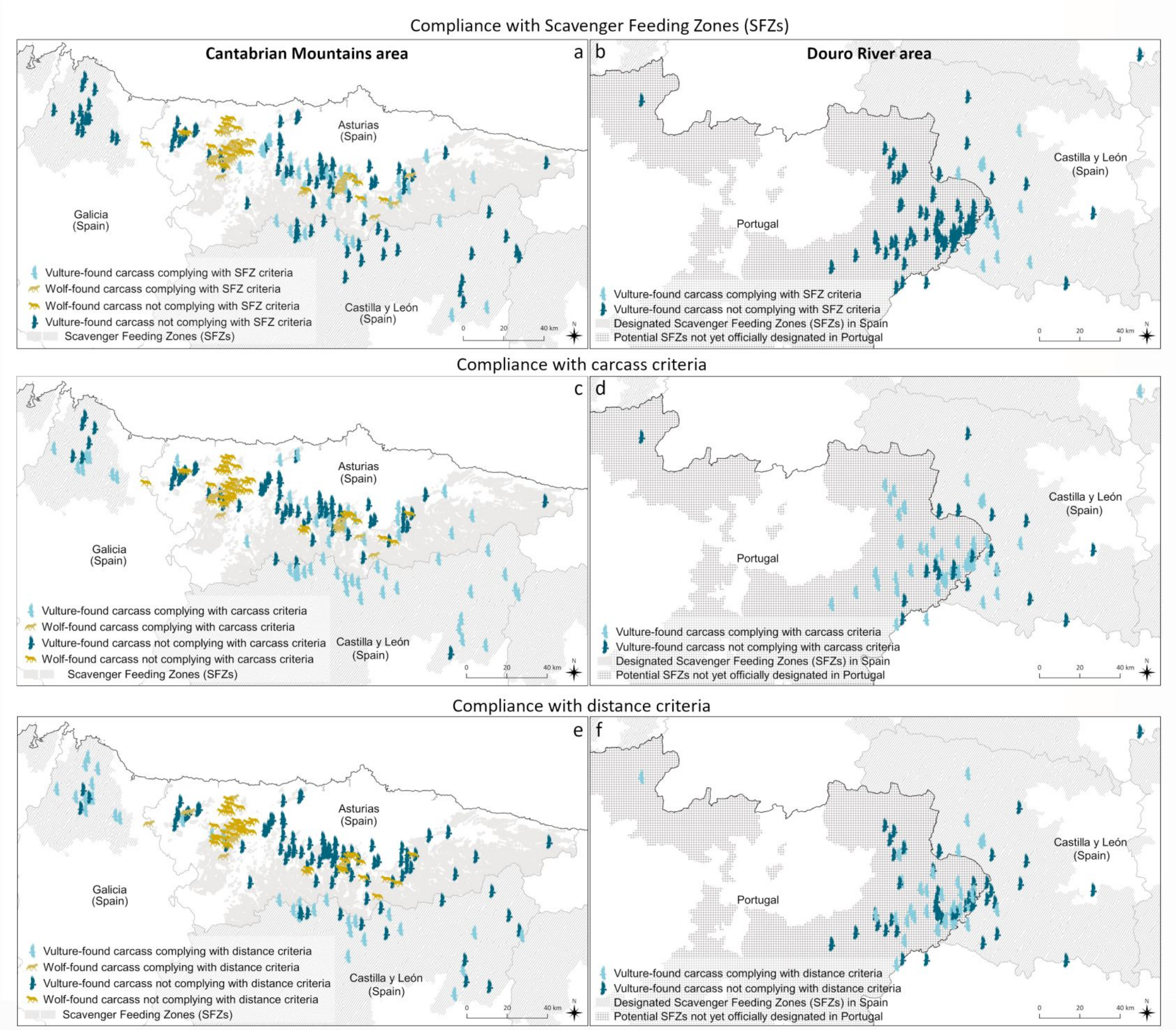
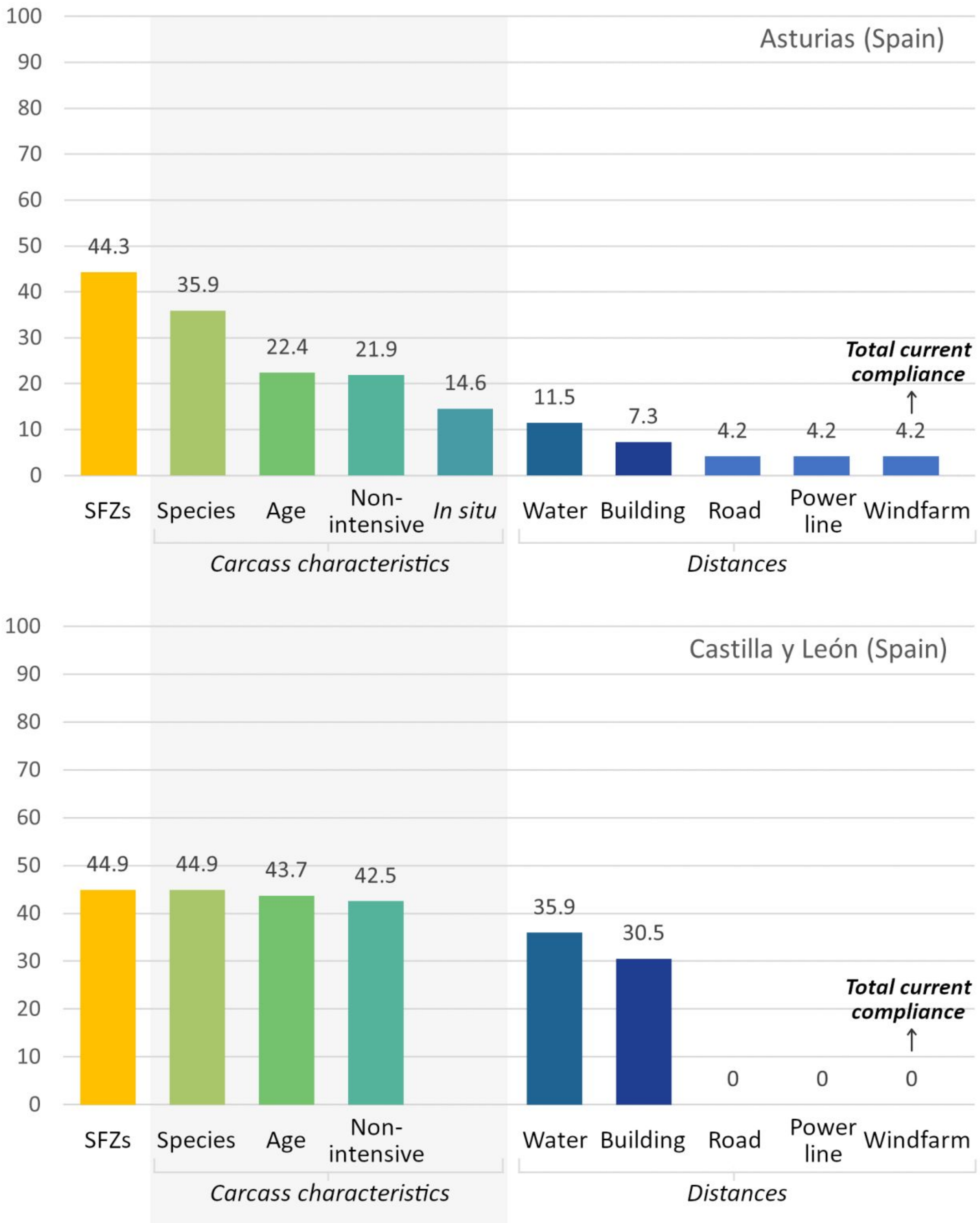


Figure 3. The level of compliance with the legislation for carcass disposal enforced at each study area at the time of this study progressively reduced as overlapping the different criteria, until reaching a total compliance varying from 4 out of 100 livestock carcasses simultaneously fulfilling all the legal requirements in Asturias (Spain) to none in the other three regions analyzed, including Galicia and Portugal. Graphs for these two last regions are not shown because initial compliance was zero, since no carcasses were located within officially declared Scavenger Feeding Zones (SFZs).



Supplementary Material for:

Wildlife as sentinels of compliance with law: an example with GPS-tagged scavengers and sanitary regulations

Appendix S1. Livestock farming in the Cantabrian Mountains (NW Spain) and the Douro River at the Portuguese-Spanish border.

Livestock rearing is a major activity in both study areas, with important presence of extensive (i.e., livestock grazing in the countryside most of the year) and semi-extensive (i.e., livestock grazing outside part of the day or of the year) farming. In the Cantabrian Mountains, livestock practices are dominated by cattle (*Bos taurus*) breeding, with an official census of ~412,000 heads in 2019 only in Asturias (SADEI 2022), of which 70% (~290,000 heads) are reared extensively. Although a traditional and marginal practice in NW Spain (López-Bao et al. 2013), the census of horses (*Equus caballus*) has increased in some areas in the last years (e.g., from 33,314 heads in 2013 to 37,320 in 2019 in Asturias; SADEI 2022). On the contrary, sheep (*Ovies aries*) and goats (*Capra aegragus hircus*) show a clear decrease, e.g., from ~100,000 sheep and ~45,000 goats in Asturias in 2000 to ~59,000 and ~39,000 in 2019, respectively (SADEI 2022). Transhumant sheep and goats, previously abundant in the alpine summer pastures of the Cantabrian Mountains, show an even sharper negative trend (i.e., from ~90,000 heads in 1990 to ~35,000 in 2007; Olea & Mateo-Tomás, 2009). Contrastingly, sheep farming dominates at both sides of the Douro River (i.e., the border between Spain and Portugal), with 106,626 and 33,790 heads according to 2018-2019 livestock official censuses, respectively (Gigante et al. 2020). Cattle is also present, with more animals registered in the Spanish than in the Portuguese side (i.e., 21,184 vs. 9,635). Contrastingly, the presence of goats is higher in Portugal (3,688 vs. 1,316; Gigante et al. 2020). Intensive pig farms are scattered in the area, especially in Spain, with >467,000 pigs censused in the province of Zamora (Castilla y León) in 2019 (Datos Abiertos de Castilla y León 2021) *vs.* only 12,900 in the nearby Portuguese district of Bragança (Instituto Nacional de Estatística 2021). Pigs have increased by 14,4 % in Castilla y León in 2006-2019 (Datos Abiertos de Castilla y León 2021).

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Appendix S2. International, national and subnational regulations enforced for the management of livestock carcasses in the study area.

Scope	Legislation	Territory	Main measures
International	Commission Regulation (EC) 1069/2009	European Union	Recognizes the need of integrating biodiversity conservation into sanitary policies, considering *"the natural consumption patterns of the species concerned"* as well as *"community objectives for the promotion of biodiversity, as referred to in the communication entitled 'Halting the loss of biodiversity by 2010 – and beyond' from the Commission of 22 May 2006"*.
	Commission Regulation (EU) 142/2011		Provides guidance for implementing Commission Regulation (EC) 1069/2009. Accordingly, carcasses of extensive livestock can be left uncollected in concrete areas designated by the competent authorities, i.e., Scavenger Feeding Zones (SFZs). Food supply from livestock to up to 51 vertebrate species (including facultative and obligate scavengers) is guaranteed (Mateo-Tomás *et al.,* 2019a). It also includes a list of priority countries for implementation, including Spain and Portugal.
National	Decree-Law 33/2017	Portugal	Ensures enforcement and compliance with Commission Regulations (EC) 1069/2009 and (EU) 142/2011. It establishes the rules of funding and functioning of the Portuguese livestock carcass collection system, i.e., *Sistema de Recolha de Cadáveres de Animais Mortos na Exploração* (SIRCA). It also refers to the possibility of establishing 'remote areas' where the burial or burning of animal by-products (including livestock carcasses) can be allowed, as well as other forms of carcass disposal upon approval of a plan by the competent authorities and in accordance with the rules laid down in EU regulations.
	Despacho 3844/2017		Establishes and lists 'remote areas' where the burial of livestock carcasses and other forms of carcass disposal are allowed under supervision. It also states that *"[...] the feeding of avian scavengers using animal by-products is allowed if the rules and procedures established regarding the feeding of necrophagous birds and other species living in their natural habitat are followed [...]"*, thus opening a window for designating Scavenger Feeding Zones (SFZs). The conditions and procedures for feeding avian scavengers inside and outside feeding stations were subsequently published in official guidelines in 2018 and updated in 2019 (DGAV, 2019).
	Despacho 7148/2019		Approves the Portuguese Action Plan for the Conservation of Necrophagous Birds. Based on the changes made in the Despacho No 3844/2017 regarding the non-removal of extensive livestock carcasses in 'remote areas', which can be used in benefit of the conservation of avian scavengers, it contemplates the implementation of SFZs.
National	Royal Decree 1632/2011	Spain	Transposes Commission Regulation (EU) 142/2011 into national legislation, acknowledging the importance of Spain for the conservation of scavengers at European level and promoting the designation of SFZs with special attention to Natura 2000 sites. It tries to homogenize the implementation criteria across Spanish autonomous regions.
Sub-national (in Spain)	Decree 17/2013	Castilla y León	Enhances the application of the Royal Decree 1632/2011 and therefore also the application of the Commission Regulation (EU) 142/2011 in the autonomous region of Castilla y León. It establishes the assumptions, conditions and SFZs where farmers can apply for authorization to leave extensive livestock carcasses for the feeding of scavengers.
	Order 25th May 2017 (modified by Order 3rd July 2018)	Asturias	Enhances the application of the Royal Decree 1632/2011 and therefore also the application of the Commission Regulation (EU) 142/2011 in the autonomous region of Asturias. It establishes the assumptions, conditions, and areas for the potential use of extensive livestock carcasses for feeding scavengers. Farmers can apply for authorization but SFZs are already designated where fallen grazing livestock can be left *in situ*.
	Decree 72/2016	Galicia	Based on Commission Regulations (EC) 1069/2009 and (EU) 142/2011, it establishes the assumptions, conditions, and areas where the *in-situ* degradation of extensive livestock carcasses of equines can be allowed in the autonomous region of Galicia. For the disposal to comply with the decree, farmers must inform about the location of each horse carcass left in the field.

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Appendix S3. GPS-tagging of large vertebrates for carcass location.

Griffon vultures were live-trapped using leg-hold snares (Utility model No. 201930577, Spain) and physically immobilized and hooded to prevent them from injuring and minimize stress during tagging. Wolves were live-trapped with Belisle® leg-hold snares (Edouard Belisle, Saint Veronique, PQ, Canada) and chemically immobilized by intramuscular injection of medetomidine (Domitor®, Merial, Lyon, France). Immobilization was reversed with an intramuscular injection of atipamezole (Revertor®, Merial, Lyon, France).

All traps were monitored with alert activation systems. All captured animals were evaluated as clinically healthy both when captured and at their posterior release. All procedures that included the capture, handling and GPS-tagging of vultures and wolves were specifically approved by the competent authorities (permits Res. 17-02-2017, Res. 19-07-2017, Res. 01-03-2018, 2019/007875, 886-891/2019/CAPT, 623-628/2020/CAPT, AUES/LE/92/2020, 2020277030). Field procedures and animal handling were carried out following animal welfare regulations.

Appendix S4. Main criteria considered to assess the level of compliance of the livestock carcasses found in the field according to the regulations enforced at each considered region. "--" indicates that the criteria is not demanded by the considered regional or national law.

SPAIN					
Criteria	**Description**	**Compliance threshold**	**Law articles**		
			Castilla y León (Decree17/2013)	**Asturias** (Order 25th May 2017)	**Galicia** (Decree 72/2016)
Scavenger Feeding Zones (SFZs)	The livestock carcass is in an authorized SFZs	Located within an authorized SFZs	Articles 8.1, 8.2, 9 and Annex II	Third.1.b)	Articles 1.1.d and 16.3
Carcass characteristics					
Species	The livestock species is authorized by the existing regulation	Equine, bovine, ovine, caprine and pig	Article 10 and Annex VI	--	--
		Equine, bovine, ovine and caprine	--	Third.1.a)	
		Equine		--	Article 1.2.b
Age	The age of the carcass is authorized by the enforced regulation	Equine: all	Annex VI	Third.2.a)	Article 1.2.b
		Bovine <48 months			--
		Ovine and caprine <18 months	--		
Non-intensive	The animal does not come from an intensive farm	Non-intensive breed or farm nearby	Article 8.3.c)	Third.1.b) and c)	Article 1.2.b
Carcass *in situ*	The carcass was left *in situ* where the animal died, not thrown where found after dying in another unauthorized place	No signs of thrown carcass (i.e., dumpsites, wheel tracks, old bones)	--	Third.1.c)	Article 1.2.b
Inaccessible	The carcass is in a place of difficult and/or dangerous access with the means necessary for removal or burying	Carcass location cannot be reached by motor vehicles (e.g., tractor, truck) able to remove the dead animal	--	--	Articles 12.1 and 16.2
Other criteria for species conservation and public health					
Distance to buildings	Distance (in meters) from the carcass to the nearest house or farm	>100 m	--	--	Article 12.2 and Annex I
		>500 m	Article 9.6[1]	Third.3	--
Distance to water	Distance (in meters) from the carcass to the nearest water course	>50 m	--	--	Annex I
	Distance (in meters) from the carcass to the nearest source of drinkable water	>250 m			
	Distance (in meters) from the carcass to the nearest body of surface water, i.e., river, lake, spring, channel, reservoir, and uncovered water tank	>200 m	Article 9.6[1]	Third.3	--
Distance to roads	Distance (in meters) from the carcass to the nearest paved or unpaved road	>200 m	Article 9.6[1]	Third.3	--[2]
Distance to power lines	Distance (in meters) from the carcass to the nearest power line (i.e., power line, tower, or substation)	>200 m	--	Third.3	--[2]
		>1000 m	Article 9.6[1]	--	
Distance to windfarms	Distance (in meters) from the carcass to the nearest wind turbine	>200 m	--	Third.3	--[2]
		>4000 m	Article 9.6[1]	--	

PORTUGAL				
Criteria	**Description**	**Compliance threshold**	**Law articles**	**Other documents**
			Despacho 7148/2019	Manual of procedures for the use of animal by-products to feed avian scavengers (DGAV 2019)
Scavenger Feeding Zones (SFZs)	The livestock carcass is in an authorized SFZs	Located within officially designated SFZs	--	--
		Located within SFZs to be designated[3]	Annex I. Specific objective B-6	4.2.1 a)
Carcass characteristics				
Species	The livestock species is authorized by the existing regulation	Ovine, caprine and pig		4.2.2 b)
Age	The age of the carcass is authorized by the enforced regulation depending on the performance of a TSE test	Ovine and caprine < 18 months without Transmissible Spongiform Encephalopathies (TSE) test		
		Ovine and caprine >18 months when 4% of carcasses test negative for TSE		
		Pig: all		
Grazing regime	The animal was under extensive grazing when died	The animal comes from extensive farming	Annex I. Specific objective B-6	4.2.2 a)
Other criteria for species conservation and public health				
Distance to water	Distance (in meters) from the carcass to the nearest body of surface water, i.e., river, lake, spring, channel, reservoir, and uncovered water tank	>500 m	Annex I. Specific objective B-6	4.2.2 c)[4]
Distance to buildings	Distance (in meters) from the carcass to the nearest inhabited house			
Distance to roads	Distance (in meters) from the carcass to the nearest paved road			
Distance to power lines	Distance (in meters) from the carcass to the nearest power line (i.e., power line, tower, or substation)			
Distance to windfarms	Distance (in meters) from the carcass to the nearest wind turbine	>1,000 m		

[1]It does not set any specific distance, only obliges carcasses to be "far from" these elements, so the distances recommended in the technical guidelines of the Spanish Government (2011) have been used.
[2]Annex I sets an option for other environmental, social, landscape, hunting or similar concerns that could require carcass collection but neither distances nor other details are provided.
[3]These areas are not clearly defined but Despacho 7148/2019 refers to remote areas listed in Despacho 3844/2017 and to areas with regular presence of vultures, so we have considered as potential SFZs for future designation in Portugal the remote areas listed in the Annex of Despacho 3844/2017 and the important areas for conservation and feeding of necrophagous birds listed in Annexes 2 and 3 in Despacho 7148/2019.
[4]It does not set any specific distance, only refers to "suitable distances" between these elements and the carcass which should be previously endorsed by the authorities. Accordingly, the distance criteria used to maintain the safety of avian scavengers when creating new feeding stations in the "LIFE Rupis Cross-border artificial feeding strategy for Egyptian vulture (*Neophron percnopterus*)" (LIFE Rupis, 2017) have been used as they have been already implemented in the Portuguese side.

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Appendix S5. Livestock carcasses revealed by sentinel GPS-tagged scavengers.

By monitoring GPS-tagged scavengers between 2017 and 2021, we found 490 livestock carcasses in 301 different feeding events. Equine carcasses dominated the samples located by vultures and wolves in Asturias (45.3 %) and, especially, in Galicia (90.0 %). The 35.4 % of the carcasses found in Asturias were of bovine, followed by similar proportions of ovine/caprine and pig (i.e., 9.4 % each). Contrastingly, most of the carcasses recorded in Castilla y León were of ovine and caprine (62.9 %), with 31 carcasses corresponding to pig (18.6 %), 19 to bovine (11.4 %), and 12 to equine (7.2 %). Ovine and caprine carcasses also dominated the sample recorded in Portugal (70.0 %), where GPS-tracking vultures also allowed us to locate pig (21.8 %), bovine (7.3 %) and equine (0.9 %) carcasses.

From the total sample, 380 carcasses were found by GPS-tracked vultures and wolves in Spain and 110 by vultures in Portugal. GPS-tracking of vultures allowed us to locate 430 carcasses, and 60 carcasses were located with the help of tracked wolves.

In Asturias, where vultures and wolves were tracked, bovine and equine dominated the carcasses found by both species, agreeing with major livestock practices in the area (see Appendix S4). The 46.6 % of the carcasses found by vultures and the 39.0 % of those found by wolves were horses, while bovine represented the 32.3 % of the carcasses found by vultures and the 42.4 % of those located by tracking wolves.

Appendix S6. If all the carcasses abandoned in the field in Galicia (Spain) would be notified to the competent authorities, compliance in this region would increase from 0 up to 28.6 %. Similarly, the official designation of remote areas and important areas for necrophagous birds as SFZs in Portugal would increase compliance from 0 up to 16.4 % if at least 4 % of the sheep and goats older than 18 months were tested negative for Transmissible Spongiform Encephalopathies (TSE) (*), and up to 1.8 % otherwise.