Characteristics and Perspectives of Disease at the Wildlife-Livestock Interface in Europe

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Introduction

Europe is the western part of the Eurasian supercontinent. It extends from Iceland in the West to the Ural Mountains in the East and from Arctic Islands in the North to Mediterranean coastal areas in the South. Throughout Europe, habitat change has been significant during the last 3000 years, with deforestation as a historically

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dominating feature (Kaplan et al. 2009). Land-use changes are still going on at a high rate, and it is estimated that annually 0.5% of the whole European territory changes its use between categories such as pasture, agriculture, forest or urban and industrial (EEA 2017). In the last 60 years, however, deforestation has been reverted and forest surface has grown in most if not all European countries (Fuchs et al. 2015). These massive changes in habitat, along with agriculture intensification and human population growth (>742 million inhabitants in 2018, 34/km^2, 74% urban; http://www.worldometers.info/world-population/europe-population/) have had significant effects on the European wildlife communities. Today, Europe is composed of 44 countries, of which 28 (until Brexit) belong to the European Union (EU). In 1970, Europe contributed 27.5% to global agriculture added value. By 2013, this share was only 15.5% (FAO 2015).

Biodiversity loss due to human-mediated habitat change (Fig. 1) has been more intense in Europe than in other less densely or more recently populated regions of the world. However, remaining biodiversity is still significant, particularly around the Mediterranean basin, in the alpine area and in remote regions. In general terms, opportunistic species that benefit from anthropogenic habitat change such as the red fox (*Vulpes vulpes*) or some urban and coastal bird species have seized the opportunity represented by these changes and have greatly increased their numbers(e.g. Rock 2005). Rural abandonment and growing woodland and scrubland habitats, along with agricultural intensification, favour the population growth of the native Eurasian wild boar (*Sus scrofa*) and several wild ruminants (Milner et al. 2006; Massei et al. 2015), often leading to overabundance and conflicts with agriculture including sanitary risks (Gortázar et al. 2006). Large predators are recovering almost Europe-wide due to this population explosion of their prey as well (and mainly) due to protectionist policies (Chapron et al. 2014). By contrast, specialist species and lowland species that are more susceptible to modern agriculture and habitat loss are in general terms declining (Donald et al. 2001). These changes imply that a few actors, including several carnivores, most ungulates and relatively few highly adaptable bird species, become the main wildlife species to consider at the European wildlife-livestock interface and regarding some vector (ticks) overabundance. Driven by the changes in habitat and animal populations, as well as in human behaviour, there is an emergence or re-emergence of infections shared between wildlife and livestock and considering that some of them are zoonotic, an increased impact of wildlife health on human health. Given this context, the goals of this chapter are:

- Describe the main characteristics of the potential interactions between wildlife and domestic animals in the European context.
- Describe the problems related to those interactions that can facilitate disease emergence (management of environment and livestock, sharing of pastoral resources, etc.).
- Discuss the possible impact of climate, environmental or socio-economic change on our capacity to successfully mitigate the sanitary consequences of wildlife-livestock interactions.

Fig. 1 Environmental changes in Europe include new “Naturban” areas (a mix of the urban and natural environment). (**a**) As an example, in this alpine valley, the scattered presence of houses is coupled with abandoned woods and pastures that host abundant populations of wild boars, roe deer, chamois, foxes and wolves. As a consequence, at the end of the rainbow in his backyard one can find, in spite of a jar of coins, (**b**) hundreds of ticks from different genera (*Ixodes*, *Dermacentor Haemaphysalis* and stages) infected by several pathogens

Socio-Economical and Biogeographical Circumstances of the Wildlife-Livestock Interface in Europe

The early development of agriculture in the Fertile Crescent, including domestication of the main livestock species since around the 12th millennium B.P., spread around the Mediterranean Basin for about 6000 years. From the Mediterranean, the agricultural technologies soon expanded westwards and northwards having a huge impact on European landscapes and wildlife, as well as on the economy of European societies. Neolithic economies changed the original biotic communities and local faunas were progressively replaced by a mixture of domestic animals and adaptable wild fauna (Zeder 2008). Along history, many factors facilitated the growth and expansion of European livestock and the invention of agriculture multiplied human population growth by five (Gignoux et al. 2011), and this, in turn, generated a need for additional animal-derived commodities. In many areas forest reduction was the result of a mix of direct and indirect activities as in many cases deforestation was mainly driven by an increased wood demand for building or heating (not only for fireplace, but also for forge). Anyway, continent-wide deforestation and the development of agriculture created pastures and generated surplus feed for maintaining livestock during the limiting season. More recently, in the last centuries, growth of the mean annual temperature and further land-use change had a positive effect on densities of wild and domestic ungulates, probably through improving food supply (Jędrzejewska et al. 1997). In the last century in many areas rural abandonment has let a recovery of wooded areas with a move from initial scrubland to mature forests of coniferous or, mainly, deciduous threes. These progressive changes in soil coverage drive also the animal communities that in many areas are now represented by species that inhabit forests and benefit also by mast production and the presence of neighbour's cropland. Linked with this spatial change, the human dimension has also greatly changed with a move from the "rural approach" that considers animals as useful or pest, towards a conservationist approach and in the last decades with some fringe that shows an animalist approach. In the vast majority of European countries, the number of hunters is declining, and this can pose a problem in the control of some opportunistic species such as wild boar (Massei et al. 2015).

Because of this early development of agriculture and livestock breeding, several major livestock diseases have their roots in Europe. The change from small hunter-gatherer to large agricultural communities was associated with the emergence of contagious diseases including many food-borne and vector-borne ones, often of animal origin (Jones et al. 2013). Europe has been a historical source of animal diseases, with animal tuberculosis as an example of disease spread worldwide through cattle trade. Other cases of disease emergence were linked to the introduction of domestic animals of European origin into new regions, for instance rabbits and myxomatosis (origin South America) or sheep and bluetongue (origin South Africa). In many cases, alien pathogens have been introduced as is the case of the big liver fluke (*Fascioloides magna*) accidentally introduced from North America in some European countries that has spread in many areas with a negative impact on some populations of deer (Novobilsky et al. 2006). By contrast, Europe is also at the forefront of disease control at the wildlife-livestock interface. For instance, fox rabies and classical swine fever in wild boar are two shared viral diseases which have been largely controlled in western Europe through oral vaccination (Müller et al. 2015), and Foot and Mouth disease has been successfully controlled in several occasions (Alexandrov et al. 2013). Even the use of baits with praziquantel for the control of *Echinococcus multilocularis* in foxes has been successfully adopted (König et al. 2019), but, as the economic crisis has driven resources towards other topics, the sustainability of the cost of such initiative may be at stake, especially true when notifiable diseases are not involved.

The Prevalent Livestock, Farm Typologies in Every Region and Opportunities for Interface

Europe is a major global dairy, beef and pork producer, and maintains also significant poultry, sheep and goat populations. In 2016 (last census), half of the EU-28 livestock units (LU, a reference unit which facilitates the aggregation of livestock from various species and age as per convention, based on nutritional requirements) consisted of cattle, one quarter of pigs and one-sixth of poultry. France, Germany, Spain and the UK had the highest number of livestock units. However, the Netherlands, Belgium and Malta had the highest livestock densities, while Balkanic and Baltic countries had the lowest ones (https://ec.europa.eu/eurostat/statistics-explained/index.php/Agri-environmental_indicator_-_livestock_patterns).
Improved monitoring of livestock and large-scale trends are needed to depict interfaces and evaluate broad-scale risks in Europe, for which high-resolution data discriminating among farming systems would be required. As illustrative of the need for better, harmonised and standardised data in the domestic compartment, Fig. 2 of Chapter ""Host Community Interfaces: The Wildlife-Livestock"" suggests low reliability when predicting the wild boar-pig interface (irrespective of farming type) at European scale (ENETWILD consortium 2020, www.enetwild.com).

Dairy cattle and beef cattle are present all over Europe, with dairy dominating in the more productive and pasture-rich rainy and flat regions and beef cattle more dominant in mountain regions, including the Alpine region and the dry Mediterranean pasturelands. Variability regarding farm size and characteristics is huge, and most cattle farms have a limited biosafety regarding the possible contact with wildlife. Beef cattle sharing communal pastures with other domestic and wild animals are probably at the highest risk, for instance regarding animal tuberculosis, but even most of the dairy cattle herds will have direct or indirect opportunities to contact wildlife such as badgers, wild boar and deer (for contrasting examples, see LaHue et al. 2016; Acevedo et al. 2019)).

While most pigs are kept in modern industrial farms where contact to wildlife is limited, millions are kept open-air or semi free-ranging due either to regional

Fig. 2 Examples of potential interactions between pigs and livestock in different habitats and husbandry regimes over Europe. Wild boar is probably one of the most relevant target species for integrated disease surveillance in Europe and, eventually, for targeted disease control interventions at the interface (e.g. Classical swine fever, African swine fever, tuberculosis). The left column represents the animals, and the right one, the habitat they inhabit, respectively. (**a–b**) Domestic pig foraging free on alpine pasture in the French Pyrenees close to the Spanish border. Free-range pig husbandry occurs in many European countries. This is a risk for disease transmission. (**c–d**) Direct contact between wild boar and pigs in South Central Spain, where Iberian pigs typically graze savanna-like habitat conformed by oaks (dehesas) during the mast season. (**e–f**) Indirect interaction between extensively reared pigs and wild boar in Sardinia island (image A. Pintore). (**g–h**) Indirect interaction between wild boar and cattle in Doñana National Park (South West Spain) in pasture-lands associated with the marsh-woodlands ecotone

traditions based on the use of extensive grasslands such as the Mediterranean woodlands or due to the increasing consumer demand for high-quality and more animal-friendly open-air production. This creates challenges for disease control.

Moreover, backyard pigs are still common in some countries or regions such as the Danube delta and this may represent a risk for some pathogen transmission as in the case of *Trichinella spiralis* that is still a problem in the area (Pozio 2019). Even if biosecurity has been greatly increased in most intensive pig farms, some diseases, such as classical swine fever, may enter even into high-biosafety farms. On the contrary others, such as swine brucellosis, are more often linked to open-air production and contact with wild boar (https://thepigsite.com/articles/the-role-of-outdoor-farms-in-the-spread-of-african-swine-fever-in-europe). Recently, the ongoing African swine fever crisis has boosted research about pig farm biosafety in Europe in order to face this notifiable disease, but also to increase preparedness towards this new emerging pathogen.

The same trend observed in pigs holds for poultry: while numerically the industrial farms with generally good biosafety are dominant, open-air production is growing and backyard holdings are still prevalent in many parts of Europe (EFSA 2017). Also, in this case, the move towards more open-range production to warrant better animal welfare or the increase of backyard poultry due to the need of many people of more organic and ethical food creates new challenges. Furthermore, the economic crisis of the last years encourages many people to breed poultry for self-consumption. So, the high farm density and the presence of open-air and backyard production systems, sometimes in close link to habitats that harbour significant waterfowl populations such as for instance in southwestern France, creates ample opportunities for interactions with wildlife. Even if many pathogens may benefit from this situation surely the biggest threat is represented by avian influenza that can easily spread in some contexts (Andronico et al. 2019).

Regarding other livestock, sheep and goats are less uniformly distributed, as these species are able to use less productive habitats and are therefore more typical of extreme climates in the northwest and in the south, around the Mediterranean. The proportion of intensive sheep and goat farming has grown in recent decades, but most of the herds still have access to pasturelands and are therefore in contact with wildlife and eventually, with other livestock, particularly cattle and free-range pigs.

Minor livestock species, which can locally be abundant, include equids, gamebirds, farmed deer, South-American camelids and a diversity of other recently domesticated species even if their contribution to the wildlife-livestock interface and to infection maintenance can be locally significant. Fish-farming is also a relevant activity in some of Europe's coastal regions, but it is not addressed in this chapter.

The livestock sector contributes €168 billion annually to the European economy (45% of the total agricultural activity), helps in levelling the trade balance and creates employment for almost 30 million people, often in rural areas that are at risk of depopulation (http://www.animaltaskforce.eu/Portals/0/ATF/Downloads/Facts%20and%20figures%20sustainable%20and%20competitive%20livestock%20sector%20in%20EU_Final.pdf). While the relative contribution of Europe to the global agricultural GDP is declining, the European livestock sector is still significant and one of the most modern ones in terms of animal health and welfare. The EU has an animal health law (AHL; https://ec.europa.eu/food/animals/health/regulation_en) and modern veterinary services with common disease control strategies. The AHL considers aspects such as climate change, disease emergence at the interface including vectors, and wildlife.

The Wildlife

European bioregions are defined by official delineations used in the Habitats Directive (92/43/EEC) and for the EMERALD Network set up under the Convention on the Conservation of European Wildlife and Natural Habitats (Bern Convention). GIS data can be accessed in https://www.eea.europa.eu/data-and-maps/data/biogeographical-regions-europe-3. Of the 11 bioregions defined by the European Environmental Agency, the largest ones are the Continental (large parts of central and eastern Europe) and the Boreal (Baltic and northern Russia), followed by the Mediterranean (the Iberian, Italic and Balkanic peninsulas) and the Atlantic (northern Iberia and central and northern European west coasts) ones. The Alpine bioregion is split into several spots following the main mountain chains (Maiorano et al. 2013).

There are about 700 bird species in Europe, and they represent an enormous biodiversity and recreational value (http://ec.europa.eu/environment/nature/conservation/wildbirds/eu_species/index_en.htm). Most species can potentially be involved in the epidemiology of shared infections. Some species however are scarce and only locally distributed, while a few others are widespread, at least regionally abundant, and hence more commonly present at the wildlife-livestock interface (Figs. 2, 3 and 4). The following Table presents a simplistic overview of some key groups and their possible roles at the interface (Table 1).

Regarding mammals, all groups include potentially relevant species for the wildlife-livestock interface. However, a handful of more successful and widely distributed ones are at the top of the list. The following paragraphs address this by taxonomic groups.

Among the rodents, two groups are of particular relevance. Peridomestic mice and rats, for instance, are important bridge hosts regarding zoonotic bacterial pathogens such as *Salmonella* or *Leptospira*, among others, or good intermediate hosts for *Toxoplasma gondii* or *Neospora caninum* with important effects on human health in the first case and on livestock abortion storms in the second. Voles and other rodents sometimes are important in the cycle of *Mycobacterium microti*, an emerging member of the *Mycobacterium tuberculosis* complex increasingly reported from wild boar, deer and cattle, mainly in Atlantic and Alpine bioclimates. Small rodents are also the reservoir for some emerging tick-borne pathogen such as Borrelia burgdorferi, tick-borne encephalitis or zoonotic *Babesia microti* and *Babesia venatorum*.

Lagomorphs (hares and the European wild rabbit) has been recently demonstrated to be a maintenance host for *Leishmania infantum*. Leishmaniosis is, due to climatic changes that now let the vector to survive also in continental and climate areas (Ferroglio et al. 2005), an expanding zoonotic vector-borne disease that is also important for wild canids and domestic dogs.

Fig. 3 Examples of indirect interactions in Mediterranean livestock extensive systems (**a**) in a waterer and (**b**) a seasonal stream, involving wild boar and red deer, the most widely distributed wild ungulates over the continent (together with roe deer). Pigs, cattle and goats are observed. The need to identify interactions with the potential for pathogen transmission among the community of hosts at the wildlife-livestock interface has led to the use of multiple methodologies, such as camera trapping. The study of both direct (i.e. the simultaneous presence of two individuals at a certain point) and indirect (i.e. the sequential presence of two individuals at a certain point) interactions are addressed in Chapter "Collecting Data to Assess the Interactions Between Livestock and Wildlife"

Fig. 4 Wildlife reservoirs harbour microbial organisms or parasites that are mostly commensals or non-pathogenic in the wild reservoir but became pathogenic for domestic species and eventually humans and vice versa. Some pathogens adapted to the human, the wildlife or the domestic compartment, respectively, may be transmitted between these compartments thanks to bridge hosts species, such as domesticated animals or peridomestic wildlife. The white stork (*Ciconia ciconia*) is a traditional trans-Saharan migrant in Europe. Recently, storks have adapted to rubbish dumps (**a–b**) as a reliable food source and have reduced migratory distance or become sedentary. (**b**) White stork interacting with cattle at a water source (pond) in central Spain. (**c**) The cattle egret (*Bubulcus ibis)* is a cosmopolitan species of heron, originally native to parts of Asia, Africa and Europe which has undergone a rapid expansion in its distribution. The image illustrates some individuals scavenging on discarded eggs (normally broken) in the periphery of a hen farm. (**d**) House sparrows (*Passer domesticus*) may bring health hazards to poultry facilities. The image was taken in backyard hen holding (note the unusual presence of a semi-domesticated roe deer). Images: courtesy of U. Höfle

Generally, rabbits are locally abundant, while hare population trends are generally declining, however, wild Lagomorphs have a domestic counterpart in the domestic rabbit that is important for meat production in the Mediterranean basin so the interface risk could be high in these areas.

Many infections of dogs and cats, such as rabies, distemper or feline leukaemia, can also infect wild carnivores generating conservation concerns. Even if the risk is usually linked to uncontrolled stray dog and free-roaming cat populations, the increase of outdoor activities of urban dogs when follow their owner or suburban areas, from one side and the increase of urbanisation of wild carnivore such as the red fox from the other increase the risk of the healthy interface. At the same time, European badgers have been shown to act as relevant maintenance hosts for *Mycobacterium bovis*, the main causative agent of animal tuberculosis, complicating the

Table 1 key groups of European bird species and their possible roles at the wildlife-livestock interface in Europe

Group	Examples	Relevant links with the interface
Urban and peri-urban birds, and birds that are common on farm premises	Rock pigeons, wood pigeons, collared doves, corvids, blackbird, starlings, sparrows	Close contact with human beings and livestock. Some are migratory. Some can act as bridge hosts, crossing farm fences and other barriers (sparrow, magpie). Others are frequent hosts for mosquitoes.
Ducks, gulls and waders	Mallard, diving ducks, black-headed gull, herring gull, lapwing	Many are migratory and most are gregarious. Their adaptation to aquatic habitats makes them relevant regarding infections linked to wetlands
Gamebirds: Pheasants, quail and partridges	Ring-necked pheasant, grey partridge, red-legged and chukar partridge, common and Japanese quail	Gamebirds belong to the same order as poultry (Galliformes) and share most infections. Many gamebird species are farmed and millions (probably >100) are released yearly to re-stock for hunting. Gamebird farming and releasing create many opportunities for infection sharing at the interface.
Carrion consumers: Vultures, corvids; and waste consumers: Gulls, storks, corvids	Gulls, griffon vulture, raven, carrion crow, magpie, white stork, starlings	On the one hand, necrophagous birds are important allies for the destruction of carcasses, contributing to a lower environmental persistence of infected remains; on the other hand, frequent rubbish-dump visitors such as gulls or corvids can act as bridges between these sites and urban or farm sites.

eradication of this zoonotic and communicable disease in livestock. Canids such as the abundant and widespread red fox and the expanding wolf participate in the cycles of many viral, bacterial and parasitic infections as the before mentioned *Leishmania infantum* (Oleaga et al. 2018) or hydatidosis (*Echinococcus granulosus*—wolf *E. multilocularis*—fox, e.g. Sobrino et al. 2006). Hence, carnivores and their diseases at the interface are often triggers of human-wildlife conflicts in Europe.

European wild ruminants belong to two main families, cervids and bovids, and both share several infections with domestic animals, mainly ruminants (Putman and Apollonio 2010). Regarding the cervids, the most abundant one at the European scale is probably the roe deer. For several reasons, this widespread selective browser is not a very relevant host for shared infections. Instead, deer belonging to the subfamily Cervinae, such as red deer and fallow deer, do participate in the epidemiology of many relevant shared infections including bluetongue, tuberculosis and a large list of tick-borne diseases (Gortázar et al. 2016) Regarding bovids, their distribution is patchier, but they are locally relevant for infections at the interface, sometimes as a source of infection (e.g. *Brucella melitensis* spill-over from Alpine ibex to cattle, Mick et al. 2014) and sometimes as victims of spill-over from livestock (e.g. sarcoptic mange in Iberian ibex and Cantabrian chamois). Among the wild ruminants, the locally abundant and generally widespread red deer is possibly the single most relevant species at the interface in Europe.

However, another artiodactyl, the Eurasian wild boar, is possibly the most important wild host at the interface. This is because, being the ancestor of the domestic pig, wild boar share potentially all relevant infections with their domestic counterpart, but are also implicated in other shared zoonotic infections such as hepatitis E and tuberculosis. Wild boar are expanding both in geographical range and in number throughout Europe, generating concern regarding disease maintenance and disease emergence (see boxes).

Bats, insectivores and other mammals are occasionally relevant for diseases at the interface, but in Europe generally this occurs at a local scale and so they are less relevant than the above-described groups. Of all the species mentioned in this section, rabbit, badger, fox, red deer and wild boar are probably the most relevant targets for integrated disease surveillance and, eventually, for targeted disease control interventions at the interface. A general overview of the status of transmissible diseases in European wildlife has been recently updated (Yon et al. 2019).

The Disease at the Interface: One Heath Perspective

Till now wildlife diseases have gathered authority's attention mainly when a communicable disease is involved. So, a few shared diseases have a strong impact on the European economy, with implications beyond the wildlife and livestock sectors. Tuberculosis is currently regarded in many parts of Europe as the main sanitary problem in cattle and the factor making the difference between profit and loss, especially in beef herds from TB-endemic countries (see Box 1). But beyond that, the badger TB-debate also confronts the urban and rural society, especially in the UK. A second example is wild boar population control, either for TB control in Iberia or for ASF control and prevention elsewhere in Europe (see Box 2). Among other actions, reverting the current wild boar population trends requires feeding bans, which are not popular among hunters, and increased culling, which is opposed by animalist-oriented public. In fact, Europe is the historical source of animalism, and the so-called Bambi-syndrome generates strong debate wherever wildlife is harvested for hunting purposes or culled as an intervention for disease control. Progressively, this debate is expanding to question the very existence of livestock production. More and more, interventions at the wildlife-livestock interface will require prior negotiations and involvement of stakeholders from the livestock and the hunting sectors, and the more open-minded conservation NGOs as the animalist fringe is unlikely to enter any agreement.

However, many reports clearly highlight the new challenge played by wildlife diseases for the One Health perspective in Europe. As stated above Europe is a highly populated continent with a huge number of livestock and pet animals, but also, in the last decades, a significant increase in many wild species abundance and distribution. This is the heritage of century of human activities (practical and cultural) that is still in progress and we are facing a new era where the rewilding of many lands, with the consequent increase in many wild species, will coexist with a more fragmented landscape with an increment of suburban areas that will boost the overlapping of wild and domestic animals and of animals and humans also for pathogen transmission. Land-use and climatic changes are reshaping also vector distributions and abundance and, except for the case of sandflies and leishmaniasis, mosquito driven infections, such as West Nile Virus, has also increased in the last decades due to the introduction of new mosquito species. Ticks and tick-borne diseases are a health issue of greater concern as it has been shown that up to 75% of pathogens found in ticks collected from dogs are of sylvatic origin (Zanet et al. 2020) and that a high prevalence of zoonotic *Babesia* species, with wildlife as reservoir, has been found in ticks collected from humans (Battisti et al. 2020). The spread of *E. multilocularis* towards many new countries all across Europe up to the Scandinavian peninsula represents another example of the new scenario, to which contributed the introduction of a competent alien reservoir, the raccoon dog, the natural movement and increasing densities of red foxes, and the movement of domestic dogs that can act as the competent definitive host.

To face the challenge represented by this complex network between local and global chances, wild and domestic animals, vector and pathogen and human activities, wildlife medicine will move from the small circle of adept and embrace clearly the One Health approach, but moreover that wildlife diseases issue must be fully embedded in policymaker decisions. Europe is a crossroad and the movement of animals and goods can easily introduce new pathogens in the continent, and the fact that 24% of European wildlife EID have been introduced (Yon et al. 2019) clearly demonstrates this risk. Table 2 summarises examples of disease transmission from livestock to wildlife and vice versa.

Management Practices at the Interface (from Traditional Grazing Systems to Modern Techniques)

The European livestock sector is extremely varied regarding the management systems, ranging from backyard holdings and traditional pastureland use to ultramodern high-biosafety pig or poultry farming. However, all farming systems and all habitats are prone to the emergence of relevant shared infections. Avian influenza outbreaks have taken place in modern aviculture facilities, and both CSF and ASF eventually

Table 2 examples of disease transmission from livestock to wildlife and vice versa in Europe

Identified interface	Area/Region	Specific /Major diseases at the interface	Main characteristics and relevance
Birds	Widespread	Avian influenza[a]; West Nile[a] and other Flavivirus; Pathogenic *E. coli*[a] and other zoonotic bacteria; ticks	Many species are migratory, others can act as bridge e.g. between contaminated and clean areas
Carnivores	Widespread	Distemper	Endemic with sporadic outbreaks impacting conservation of local populations
Carnivores	Eastern Europe	Rabies[a]	Zoonosis. Largely controlled by fox oral vaccination
Carnivores	Widespread except UK, Ireland, Finland and Malta	*Echinococcus multilocularis*	Transmissible also to dogs and cats, zoonosis.
Lagomorphs	Southern/East/Central Africa	Myxomatosis and Calicivirus infections	Some have huge impacts on wildlife and cascading ecosystem effects; farmed rabbits are vaccinated but may contribute to infection spread, as do wildlife translocations
Rodents	Widespread	Tularemia	Multiple hosts, including invertebrates, and spill-over to human beings
Wild boar	Sardinia and 13 countries of mainland Europe	African swine fever[a]	Severe impact on pig industry and on wild boar
Wild boar	Not reported in EU in 2018	Classical swine fever[a]	Severe impact on pig industry. Largely controlled by oral vaccination
Wild boar	Widespread in continental Europe	Aujeszky's Disease (pseudorabies)[a]	Almost under control in pigs but endemic in wild boar with occasional spill-over to carnivores
Wild boar	Widespread in continental Europe	Swine brucellosis	Epidemiological links between pig and wild boar
Alpine ibex	Northeastern France—Alps	Brucellosis (*B. melitensis*)[a]	Locally endemic with spill-over to cattle and sporadic human cases
Multi-species	Widespread	Sarcoptic mange	Variable effects, mainly on local wild ungulate populations
Multi-species	Widespread except Scandinavian countries	Animal tuberculosis[a]	Badger, wild boar, red deer and others

(continued)

Table 2 (continued)

Identified interface	Area/Region	Specific /Major diseases at the interface	Main characteristics and relevance
Multi-species	Widespread, depending on the distribution of the tick species linked to the specific disease, e.g. Atlantic habitats for *Ixodes ricinus* or Mediterranean ones for *Hyalomma* species.	Ticks and tick-borne diseases such as Anaplasmosis, Babesiosis, Lyme disease and Crimean-Congo haemorrhagic disease	Many mammals play a role in tick maintenance or tick-borne pathogen epidemiology

[a]Indicates for each disease the existence of Governmental Programs

manage to enter high-biosafety pig farms. However, farming systems where one or several domestic species are in contact with wildlife (and farmed game) represent fertile ground for the maintenance of multi-host infections. Such settings include communal pastures, free-range and open-air production systems, and backyard or small-scale farm holdings.

All across the continent the transhumance of livestock (cattle, sheep and goat) from the low lands towards mountains in summer is common practice and this exposes livestock to contact with wild ruminants and increase the risk of transmission of pathogens, such as the case of brucellosis in chamois and Alpine ibex, Schmallenberg virus, vector-borne pathogens and a lot of other transmissible agents that represent a treat also for wildlife conservation such as Infectious keratoconjunctivitis (e.g. Giacometti et al. 2002). In contrast to the past when livestock ranging in the mountains in summer was largely represented by dairy ruminants, in the last decades, there has been a shift towards beef cattle that require less human labour. This however increases the risk of overlapping between wild and domestic ruminants. Social changes and EU agricultural policy will deeply affect this trend so wildlife and mutual transmission of diseases must be considered in every future EU plans.

Means of risk mitigation are available for all situations but will depend on the means of transmission of the target pathogens, on the local livestock and wildlife situation, and on the willingness and capacity of veterinary authorities, farmers and eventually hunters to take action on specific risks. Some settings are particularly challenging, for instance the open-air duck production in southwestern France, where contact with waterfowl and gulls is almost unavoidable and hence influenza virus will often circulate at the interface. A similar risk setting is given by those regions were free- or semi-free range pigs share woodlands or pastures with wild boar. ASF virus and other pathogens will, if entering the system, become very difficult to control due to the limited possible actions on the wild reservoir. Such settings occur on the Mediterranean islands of Corsica, Sardinia and Sicily (with ASF and CSF circulating on Sardinia, Fig. 3e), but also in southwestern Spain (where tuberculosis is a major concern) and in parts of Eastern Europe (for instance Mangalitsa pigs in Romania and Hungary).

Research on Diseases at the Wildlife/Livestock Interface

A few diseases at the interface, such as fox rabies, badger TB or CSF in wild boar, have traditionally received the most attention. In the last few decades, this selected group has grown to include avian diseases such as influenza and West Nile, emerging diseases in wild ruminants such as bluetongue, TB in other wildlife, brucellosis or mange, and several others. The key maintenance host species are well characterised although many aspects of transmission mechanisms and disease dynamics still deserve additional research. Also, in the last decades, European research on wildlife diseases has broadened its spectrum from the initial case reports and prevalence surveys to risk factor analyses using quantitative epidemiology tools and to intervention-oriented research aiming at improving disease surveillance and at assessing disease control options (Gortazar et al. 2015a, b, 2016).

However, long-term studies are still extremely scarce and only a few monitoring schemes do yield accurate time trends considering both host populations and disease prevalence (Vicente et al. 2013). One important gap is the generalised lack of the so-called "denominator data," i.e. data on the susceptible (wild) host populations. Only for birds (and not for all) are there reasonable data available on numbers or at least relative abundances. For mammals in the best of cases, there are hunting back records, which can indicate large-scale trends but are generally not suitable for comparisons in space or at local scales. Therefore, in the context of the ongoing ASF crisis, the European Food Safety Authority promoted the ENETWILD consortium (www.enetwild.com, see Box 3). This consortium is combining abundance and distribution data with innovative spatial modelling techniques to generate valuable information on wildlife population size and trends, in collaboration with all EU member states.

Once a sound, integrated, disease and population monitoring scheme has been set up, options for intervention are relatively few. Direct intervention options include (1) prevention and biosafety; (2) vector control; (3) host population control; and (4) vaccination. Alternatively, indirect intervention may include zonification or compartmentalisation (Gortazar et al. 2015b). Some diseases, notably rabies and CSF, even imply obligatory wildlife vaccination if EU funding is requested for control programs. In other cases, such as animal tuberculosis, the role of wildlife is increasingly acknowledged, but significant steps are still required to really address TB as a multi-host system (see Box 2). Steps towards a more holistic approach to the control of multi-host diseases are often limited to certain countries.

Box 1 Animal Tuberculosis: A Multi-Host Infection

Animal tuberculosis (zoonotic TB) is caused by *Mycobacterium bovis* and other closely related members of the *M. tuberculosis* complex (MTC). This disease, often named "bovine TB," is far from being limited to bovines: in Europe, at least seven other domestic and wild animal species can contribute to

(continued)

Box 1 (continued)
MTC maintenance depending on the local epidemiological circumstances: goat, sheep, pig, badger, wild boar and red and fallow deer (Gortazar et al. 2012, 2015a). Moreover, MTC can survive for a certain time in the environment, for instance in water or mud, on feed or even on saltlicks. Therefore, TB control is unlikely to be achieved if interventions only target one or two maintenance hosts (cattle and badger in the British Isles; cattle and goat in Iberia), instead of targeting the whole reservoir community (Santos et al. 2020, (see Fig. 5 top)).

In 2018, 18 EU member states (MS) were officially TB-free (OTF) and the overall EU proportion of cattle herds infected with, or positive for, bovine tuberculosis (herd prevalence), considering all OTF and non-OTF regions, remained low (0.9%). However, the EU herd prevalence was 0.4% in 2005, indicating a slow but steady recent increase. While TB prevalence is declining in the OTF regions, it is increasing in the non-OTF ones, with some regions still recording cattle TB herd prevalence>10%. Moreover, nothing is reported on the time trends of TB prevalence in other domestic or wild maintenance hosts in Europe (EFSA and ECDC 2018).

The way out is not easy and might prove unrealistic in some settings. In most cases, a One Health approach consisting of integrated TB control using all available tools in all relevant domestic and wild hosts will at least reduce the impact of TB (and TB control) on farmers. This process is represented in the Fig. 5 bottom. First, an honest epidemiological diagnosis is required. This implies identifying all hosts that are relevant for MTC maintenance in this setting, as well as their likely interactions. Second, decide whether to intervene or not, but in any case, set up an integrated disease and population monitoring scheme: if you do not have indicators, you will not be able to assess any effects of future intervention. Third, once proper monitoring has been set up, decide on the tool or tools to be employed for intervention. These tools range from biosafety, through population control, to vaccination. Most probably, suitable tools will vary between species, for instance combining test and cull in domestic animals with population control, biosafety or even vaccination in wildlife. In any case, a periodic re-assessment of the strategy is advised.

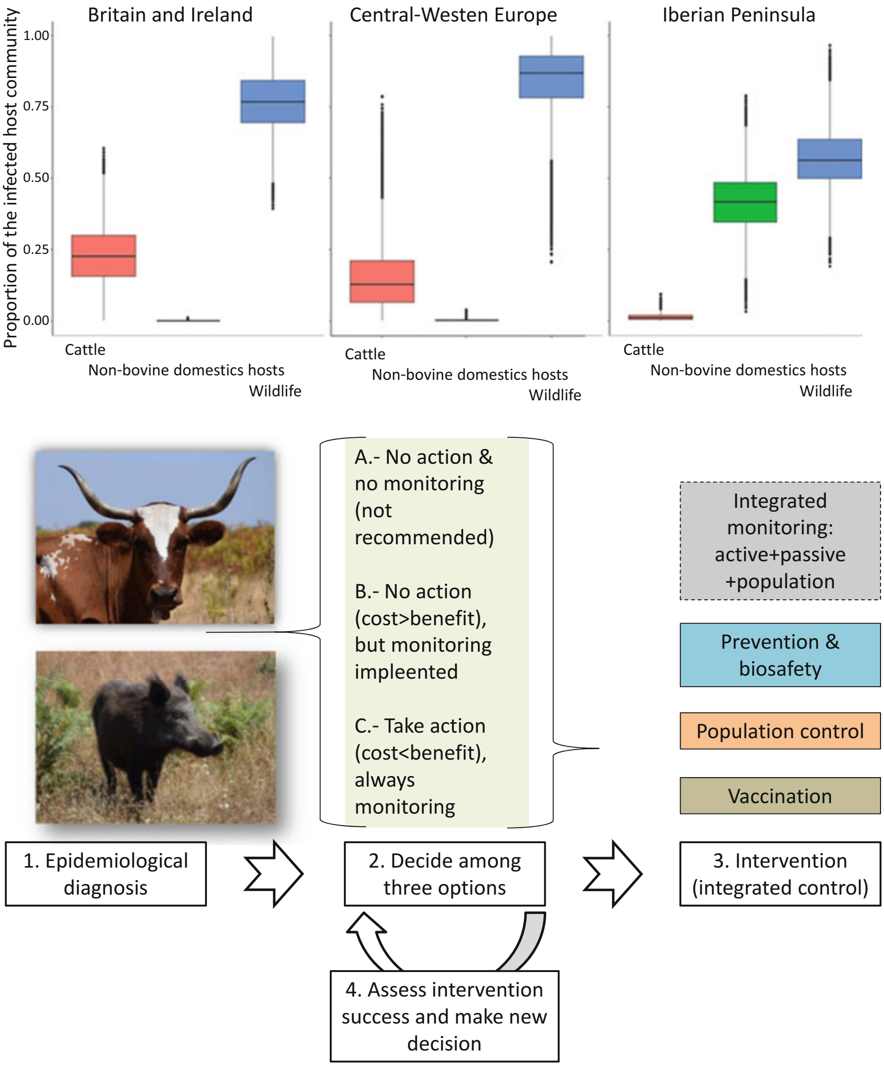

Fig. 5 Upper panel: Boxplots of the proportion of *Mycobacterium tuberculosis* complex infected cattle, non-bovine domestic hosts, and wildlife in the host community by region (Source: Santos et al. 2020), evidencing that cattle are just a small part of the total number of infected hosts. Lower panel: Flowchart representing a proposal for animal tuberculosis management in Europe, with a One Health perspective. The main steps are (1) carry out an epidemiological diagnosis, (2) decide whether to act or not, (3) intervention (ideally, integrating several tools), and (4) assess intervention success to make new management decisions (Source: modified from the Spanish Action Plan on Wildlife TB PATUBES, Ministry of Agriculture, Spain)

Box 2 African Swine Fever Emergence: The Consequence of Overabundance

African swine fever and its current situation in Europe is a relevant One Health case-study. As this chapter is written, ASF not only survives since the 1970s on the Italian Mediterranean island Sardinia, but has emerged since 2007 first in Georgia, expanding through Russia, Ukraine and Belarus to Poland, Lithuania, Latvia and Estonia in 2014, with posterior expansion to Moldova and Romania in 2017, to Hungary and Bulgaria in 2018, with further expansion to other countries in south-eastern Europe. The Czech Republic is again ASF-free after successfully controlling a local ASF outbreak that started in 2017 in wild boar, while a second long-distance jump still affects Belgium (since 2018, although almost under control), very close to France and Luxembourg. Despite the long-standing idea that wild boar do not significantly contribute to ASF maintenance, the current European situation demonstrates the opposite, namely that wild boar are able to maintain ASF circulation in many parts of Europe, even in the absence of domestic pigs and even at relatively low population density (EFSA AHAW Panel 2018).

There are several possibly contributing factors which may explain this, but the main driver is clear: wild boar overabundance. In Spain, a country that managed to get ASF-free in 1995, wild boar numbers have increased ten times in the last 35 years. Similar wild boar population growths have been recorded in all other European countries with data for this period. This huge increase in wild boar numbers is mainly a consequence of habitat change, with an increase in cover (Spain, for instance, increased its forest surface by 33% in the last 15 years) and an even steeper increase in crops that provide food and shelter, such as maize. Along with these favourable land-use changes, hunter numbers are slowly declining in most of Europe (Massei et al. 2015) and this is an enriched solution for the perfect storm.

Intervention is difficult. First, proper (integrated) disease and population monitoring need to be set up, and wild boar are no easy targets. Innovative methods for passive surveillance (such as boxes for easy pre-paid sample submission by hunters) are helping to improve the likelihood of early detection, and all efforts are made to improve population monitoring (www.enetwild.com). Once this is in place, and given the absence of applicable vaccines, the remaining options for intervention are biosafety and population control. Biosafety means avoiding ASF virus entry, good hunting hygiene and farm protection. In already infected areas it also includes carcass removal and destruction. Modelling (e.g. O'Neill et al. 2020) and field evidence suggest that a combination of culling and infected carcass removal is the most effective method to eradicate the virus, and that early implementation of these control measures will reduce infection levels. Regarding wild boar population control, the available options are few and sometimes complex to implement: increase the recreational hunting pressure, use professional shooters to cull (additional)

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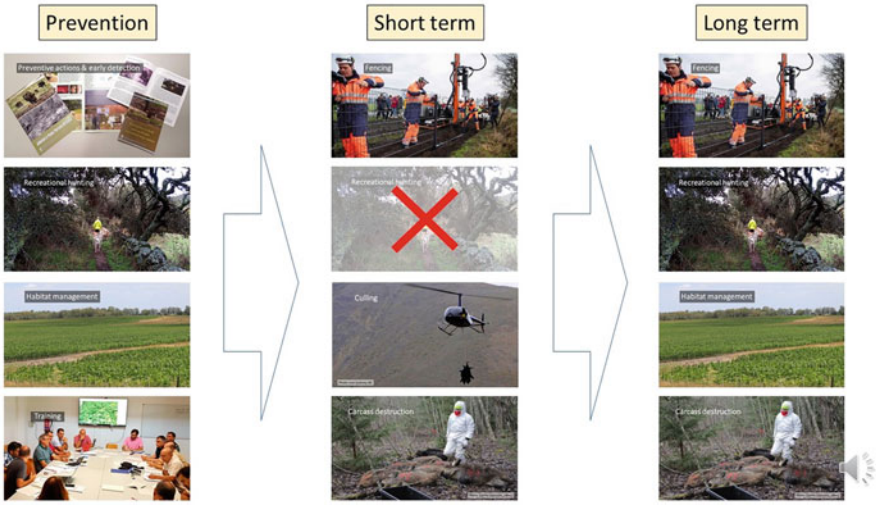

Fig. 6 Options available for African swine fever prevention and control depend on the epidemiological situation (see Fig. 6). In ASF-free regions, prevention should include information, training, and stakeholder engagement to maximise the likelihood of early detection, as well as hunting and habitat management to manage wild boar overabundance. During local outbreaks, short-term intervention options include fencing, culling and carcass destruction. In endemic regions, available tools include fencing, hunting, habitat management and carcass destruction. Culling and fast removal of animal carcasses are critical for the control of the ASF in wild boar. Drivers of virus maintenance will change depending on factors such as temperatures, wild boar density and management, and availability of obligate scavengers contributing to carcass removal (O'Neill et al. 2020)

Box 2 (continued)

wild boar, and act on the habitat carrying capacity for wild boar through feeding bans and crop-protection (i.e. fencing). The latter is possibly the most sustainable and efficient tool, but also the most challenging one to implement. One difficulty is that this needs close collaboration between veterinary authorities, hunters, the environment authorities in charge of regulating hunting activities, and farmers and agriculture authorities. Population control presents additional challenges since hunters are almost by definition amateur, and since hunting and culling faces increasing opposition in Europe.

There are several lessons to be learned from the ASF experience for the next disease emergence in Europe. First, since wildlife are involved in most of the relevant diseases, a better monitoring of wildlife populations, integrated with passive and active wildlife disease surveillance, is an urgent need for every country and at the EU level (see Box 3). Second, the epidemiology of shared multi-host infections is still insufficiently known, and insights from experimental interventions are only exceptionally available. The ASF crisis, but also the endemic animal TB one described in Box 1, provide opportunities for setting up and testing improved monitoring and intervention tools to cope with diseases at the interface (Fig. 6).

Box 3 Why Do We Need Denominator Data for Disease Surveillance? ENETWILD, a Network Providing Reliable Data on Species Distribution and Abundance of Wildlife for Risk Assessment in Europe

Risk assessment for pathogens of interest for humans and livestock requires the availability of presence and abundance data on wildlife which can represent reservoirs for pathogens. Many European countries and organisations collect spatial data on the distribution and abundance of wildlife, but each one has its own specific characteristics with respect to the methodology used, the type of data acquired, the repository implemented and their accessibility. This particularly applies for mammalian species, whereas there exist pan-European ornithological organisations and programs which study the population, distribution and demographics of European birds in order to inform conservation and management efforts, and hopefully, disease prevention and management (e.g. https://www.ebcc.info/what-we-do/pecbms/). The European Food Safety Authority (EFSA) funds ENETWILD (www.enetwild.com), a project to collect comparable data at the European level in order to analyse risks of diseases shared between wildlife, livestock and humans, data that are also essential in conservation and wildlife management. This project attempts to improve the European capacities for monitoring wildlife populations, developing standards for data collection, validation and, finally, create and promote a data repository. The objectives of ENETWILD were initially specifically focused on wild boar due to the African swine fever outbreak.

The harmonisation of the European data framework for wildlife (distribution and abundance) is a key milestone since it opens the space to aggregate these data from the whole of Europe. Initially, the project developed standards for presence/abundance data of the required species under the criteria of being effective for filtering data by quality as needed to produce high-quality maps and models, and compatible with existing biodiversity data collection systems in order to guarantee interoperability between them, thus widening the possible use of such data within a global framework of wildlife monitoring (https://efsa.onlinelibrary.wiley.com/doi/10.2903/sp.efsa.2020.EN-18419). The standards allow aggregating data on occurrence, abundance and hunting statistics of wildlife in Europe, either as raw data or as results of statistical estimation. These data come from a large community of administrations, researchers, hunters and wildlife managers. The ENETWILD consortium also aims defining the spatial interface between wildlife and livestock in Europe. The first

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Box 3 (continued)
case being addressed is that of wild boar and domestic pigs (Fig. 2, Chapter "Host Community Interfaces: The Wildlife-Livestock"), which is essential to evaluate the risk for ASF spread across wild and domestic populations. A first report describes the different sources of data for domestic pigs in Europe and develops a preliminary risk map of possible spatial interaction between both groups (https://efsa.onlinelibrary.wiley.com/doi/10.2903/sp.efsa.2020.EN-1834).

The organisation and collection of wildlife hunting statistics and their analysis are essential not only for hunting management but also for developing wildlife policies. On a large spatial scale, hunting data statistics are available and, potentially, comparable across Europe for use in the predictive spatial modelling of wild boar abundance. But the procedures, methods and type of data collected concerning hunting bags (official statistics) can show a great heterogeneity between countries and regions. At present, each country and organisation collects hunting data using its own different procedure, and acquires different types of data that are later implemented in different repositories with variable accessibility: this hampers the comparison and common use of data across Europe (https://efsa.onlinelibrary.wiley.com/doi/abs/10.2903/sp.efsa.2018.EN-1523). The sources of hunting statistics providing quantitative information on wild boar (and by extension, for other big game species) in Europe are lacking or are not harmonised across Europe, as well as incomplete, dispersed and difficult to compare. A feasible effort is needed to achieve harmonisation of data in a short time for the most basic statistics at the hunting ground level, and the coordination of the collection of hunting statistics must be achieved first at the national and then at the European level. For these purposes, the following is recommended: countries should collect data at hunting ground level; efforts should be focused on data-poor countries (e.g. Eastern Europe), and the data should be collected at the finest spatial and temporal resolution, i.e. at hunting event level (Fig. 7).

Conclusions and Perspectives

Europe is probably the place where human activities have had the deepest impact on the environment and, as a consequence of the agricultural and hunting activities, also on wildlife populations. Such changes are still in act, but respect to the past, nowadays the trend is reversing with an increase of rewilding both in terms of wooded or forested areas and wild animal populations distribution and abundance.

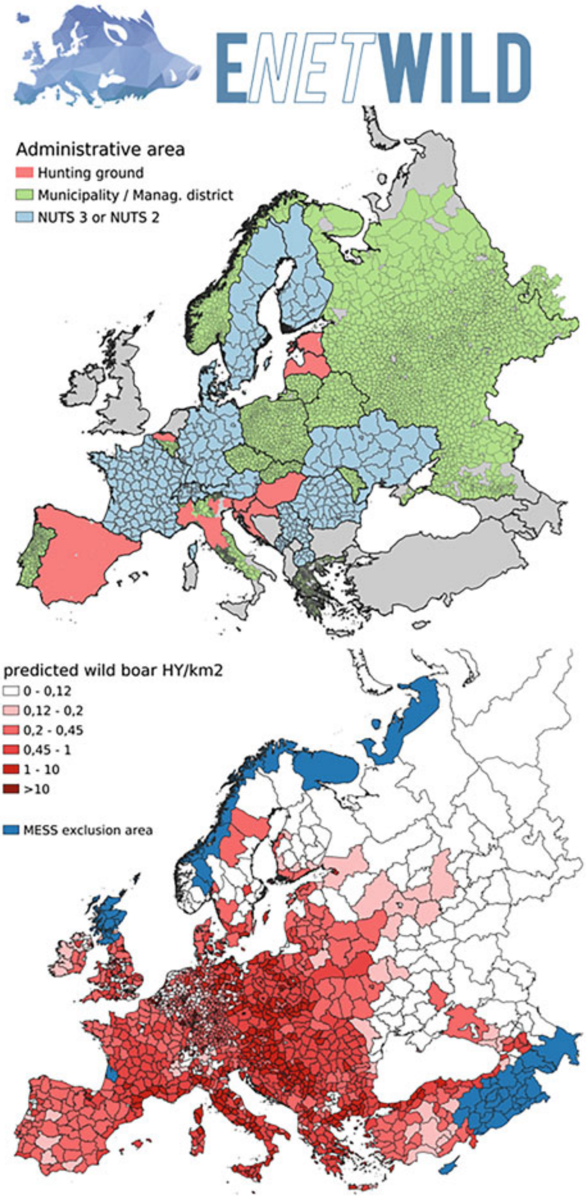

Fig. 7 Top: Spatial distribution and resolution of hunting bags data collected for wild boar by ENETWILD (June 2020). Bottom: output of wild boar spatial model for abundance (hunting yield by km^2, https://enetwild.com/reports-docs/)

At the same time global changes, such as global warming and an increase of movement of humans, animals and trade, represent a risk for the emergence/re-emergence of vectors or pathogens. Human behaviour and activities are at the base of such changes, and, due to the deep social and cultural changes that European citizens are facing, they have evidenced the increased importance of the human-livestock-wildlife-diseases interface all across the continent. The increase of wildlife abundance, at least for some species, the changes in livestock breeding and the extension of urban areas represent a culture media that favours disease emergence of re-emergence both in animals and also for many zoonoses. In the last decade, there was an increase of reports on the spread of vectors to new areas, both for a natural expansion in Europe (i.e sandflies have moved thousands of kilometres to the North) or because of accidental introductions (i.e alien mosquitoes species) or migration from other continents (i.e *Hyalomma* ticks from Africa). Such trends pose a serious threat for both the animal and human health and represent a good example of the need of a One Health approach that include wildlife diseases monitoring and diseases mitigation actions in political decisions and plans. After centuries where wildlife, due to the human activities that greatly reduced the habitats available for wild species, was a marginal player for pathogen spread, the changes that occurred in the last decades have reversed this role. Unfortunately, this new scenario is not fully recognised by policymakers and citizens, that still consider wildlife as "sign of nature" without understanding the complex link of the One Health, even if recently there are signs of a change. The expansion in the Carrying Capacity of the environment for certain species, and the subsequent rise in population abundance of those species, has not been matched with an increase in the Cultural Carrying Capacity (Decker et al. 2012) of authorities and citizens. The new green deal that represents Europe's biggest challenge for the coming years must include monitoring of wildlife abundance as well as monitoring of vectors and of diseases in wildlife, as well as integrate wildlife diseases management in plans and action. Generally speaking, European authorities have had a passive approach towards diseases in wildlife and only the emergence of local or more widespread emergencies have raised the interest of politicians and managers for this topic. Nowadays there are signs of a change that aim to change this attitude favouring a more open and holistic approach where wildlife and wildlife diseases are a key point in animal health, but also, in a wider view, for the One Health policy.

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