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REVIEW

# Diseases shared between wildlife and livestock: a European perspective

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**Abstract** Wildlife diseases are in fashion. This is creating an explosion of related knowledge. Despite this, the dynamics of both wildlife and diseases and the changes in livestock and wildlife management make it increasingly difficult to overview the current situation of wildlife diseases in Europe. This paper aims to discuss the available management possibilities and to highlight current research priorities. One area that causes severe concern to authorities is diseases largely under control in domestic populations but still existing as a reservoir in wildlife. Multihost situations are also of concern for wildlife management and conservation, as diseases can affect the productivity and density of wildlife populations with an economic or recreational value. Concern about emerging diseases is rising in recent years, and these may well occur at the fertile livestock–wildlife interface. Wildlife-related zoonoses are a diverse and complex issue that requires a close collaboration between wildlife ecologists, veterinarians and public health professionals. A few risk factors can be identified in most of the relevant wildlife diseases. Among them are (1) the introduction of diseases through movements or translocations of wild or domestic animals, (2) the consequences of wildlife overabundance, (3) the risks of open air livestock breeding, (4) vector expansion and (5) the expansion or introduction of hosts. Wildlife disease control requires the integration of veterinary, ecology and wildlife management expertise. In addition to surveillance, attempts to control wildlife diseases or to avoid disease transmission between wildlife and livestock have been based on setting up barriers, culling, hygienic measures, habitat management, vector control, treatments and vaccination. Surveillance and descriptive studies are still valuable in regions, species or diseases that have received less attention or are (at least apparently) emerging. Nonetheless, limiting the research effort to the mere reporting of wildlife disease outbreaks is of limited value if management recommendations are not given at the same time. Thus, more experimental approaches are needed to produce substantial knowledge that enables authorities to make targeted management recommendations. This requires policy makers to be more aware of the value of science and to provide extra-funding for the establishment of multidisciplinary scientific teams.

**Keywords** Conservation · Management · Mutual transmission · Wildlife diseases · Zoonoses

## Introduction

Wildlife diseases are in fashion. This was recently highlighted by the H5N1 avian flu crisis, which has put

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the role of wildlife diseases worldwide on the front-pages of the newspapers (Anonymous 2006). This and other recent zoonotic events (West Nile fever in North America, severe acute respiratory syndrome, etc.) have greatly increased the general public's interest in wildlife disease issues, and as a result, game managers, conservationists and governmental agencies have increased attention to wildlife disease surveillance and control. This contrasts with the virtual ignorance of this subject only a few years ago (Simpson 2002). The increased interest fuelled by mass media risks to reduce the problem to science fiction. By contrast, however, it is a complex situation that requires intense social and scientific debate (Angulo and Cooke 2002; Artois 2003). In the last two decades, ecologists, forest engineers and other professionals have joined veterinarians to form multidisciplinary research teams. This has triggered a scientific debate with an explosion of wildlife disease-related knowledge as evidenced by the increase in scientific papers published in peer-reviewed journals (Fig. 1). It has also led to a new approach to understanding disease agents in relation to the environment, and with a view to parasite host interactions, a whole new field grouped under the synonym "disease ecology" (Hudson et al. 2001).

Among the most intriguing aspects of this new scientific branch is the link between wildlife pathogens, environment and human activities. This web of factors creates a dynamic situation where new pathogens or new hosts emerge, changes in population density or host behaviour affects disease prevalence and disease agents can suddenly boost their virulence and widen their host range. In this wide spectrum of interactions exists yet another complicating factor due to the increased risk of contact between wildlife, livestock and humans. This is because, on one hand, animal welfare politics and consumer requirements are moving the animal breeding industry from more intensive to more extensive farming systems, and on the other hand, wildlife populations are increasingly managed through feeding, translocations and even fencing, thus becoming more and more like extensively raised livestock with limited sanitary care (Fig. 2). These situations increase the exchange of pathogens or vectors (e.g. Laddomada et al. 1994; Gortázar et al. 2006). In addition, human activities have an influence on endangered and unmanaged wildlife, as the loss of certain habitats or food resources lead different species to exploit alternative resources (e.g. Iberian lynx feeding on tuberculosis (TB)-infected carrion, Perez et al. 2001; storks and kites foraging on rubbish dumps, Tortosa et al. 2002; Blanco et al. 2006). This creates another interface for human/livestock pathogens to become established and sustained in new hosts.

Some pathogens do exclusively infect a single host species. These pathogens are frequently specialised, highly coevolved parasites with limited effect on the primary host's population (Crawley 1992; Vicente et al. 2004a, b), or the possible secondary hosts are just unknown. These are generally, in the absence of environmental changes, considered less relevant from the wildlife management and conservation and domestic animal perspective.

Many parasites, especially if environmental changes occur, can infect multiple host species and these are primarily responsible for emerging infectious disease outbreaks in humans, livestock and wildlife (Woolhouse 2002). Moreover, the ecological and evolutionary factors that constrain or facilitate such emergences are poorly understood. Fenton and Pedersen (2005) proposed a conceptual framework based on the pathogen's between- and within-species transmission rates to describe possible

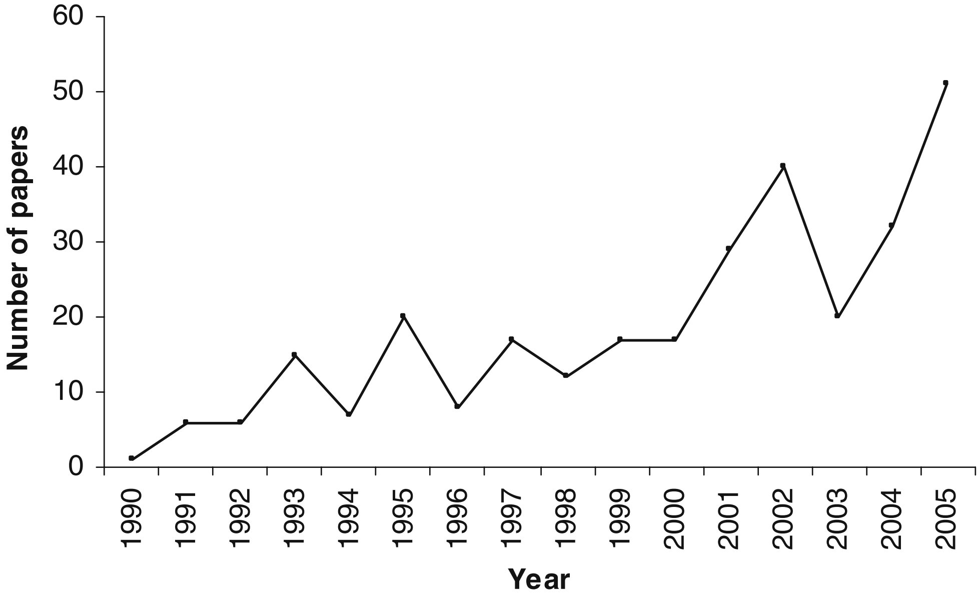

**Fig. 1** Number of papers with the words "parasite" or "disease" and "wildlife" in their title or abstract, found in the ISI Web of Knowledge database, between 1990 and 2005

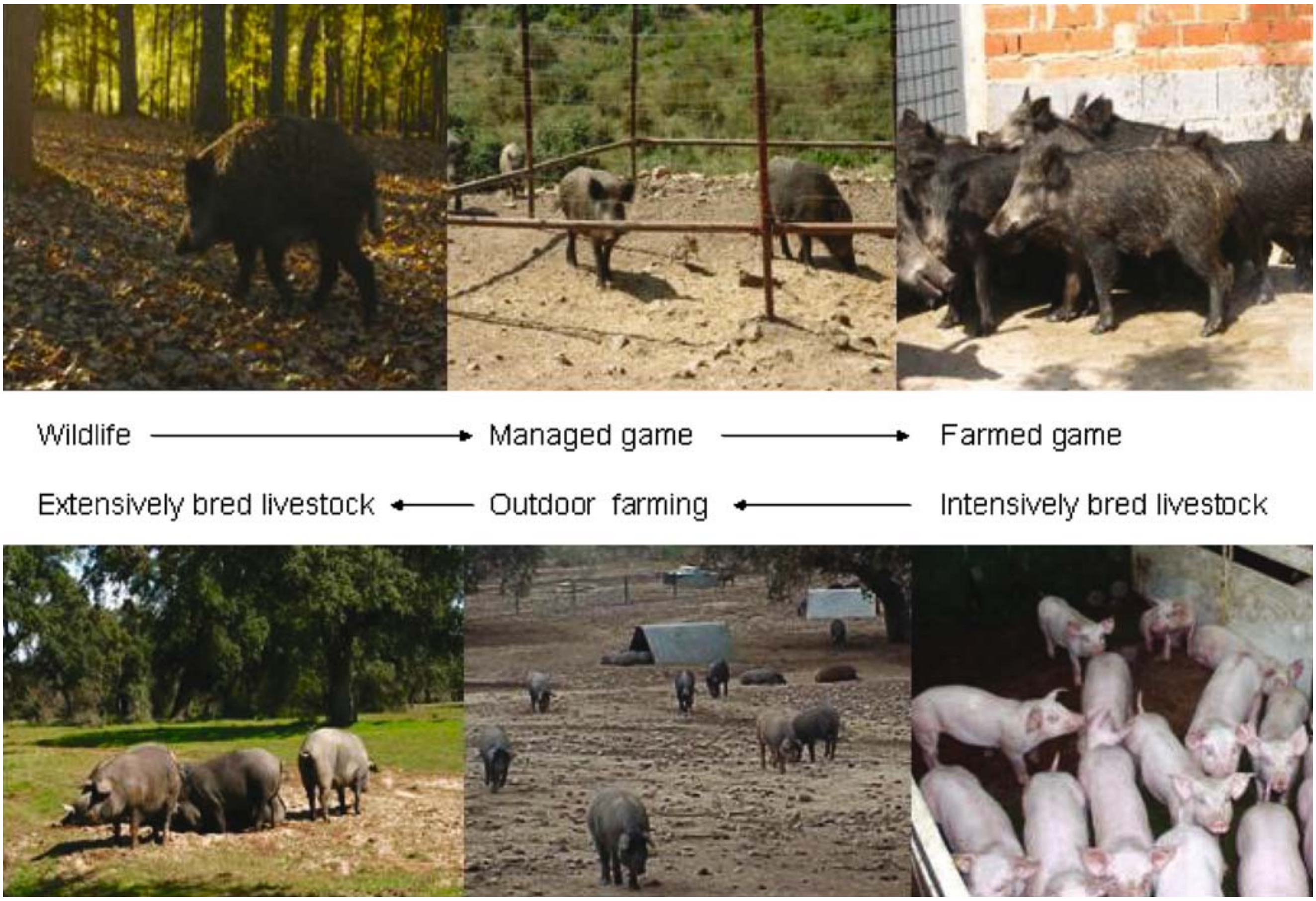

**Fig. 2** Changes in wildlife management (towards more intensive models) and in livestock production (towards more extensive models) complicate the epidemiology of shared diseases. These situations increase the exchange of pathogens or vectors

configurations of a multihost-pathogen community that may lead to disease emergence. Spill over and apparent multihost situations are those where, without between-species transmission, the disease would not persist in the target host. In true multihost situations, the pathogen can independently persist in either host population in the absence of the other.

Along with the mentioned growth in wildlife research and knowledge, the dynamics of both wildlife and diseases and the changes in livestock and wildlife management make it increasingly difficult to overview the current situation of wildlife diseases. This paper reviews some of the most relevant wildlife diseases from a European perspective, aiming to discuss the available disease management possibilities and to highlight current research priorities.

## The wildlife–domestic animal interface

This issue has been reviewed by Frölich et al. (2002) and Simpson (2002). A non-exhaustive list of relevant multihost situations regarding European wildlife is shown in Table 1. From the veterinary health perspective, true multihost situations in diseases that are notifiable, eradicated or almost under control in domestics are the worst, because a single spill over from wildlife to livestock may have severe consequences not only on health, but also on economy. Examples include bovine TB (Phillips et al. 2003) and avian influenza (Alexander 2000). Multihost situations are of less concern if the disease is not yet under control in domestic animals, as for example porcine circovirus type 2 (Vicente et al. 2004a, b) or toxoplasmosis (Gauss et al. 2006), and if adequate vaccines or treatments are available and extensively used in domestics, as for example in the case of porcine parvovirus and erysipelas (Ritzmann et al. 2000).

Sometimes problems arise when wildlife and domestic animals share disease agents whose antibodies cross-react with relevant diseases. For example, antibodies against pestiviruses other than classical swine fever may be found in pigs and in wild boar (Langedijk et al. 2001), causing alarm in animal health authorities.

Despite increasing knowledge, in many cases, the available information is still not sufficient to decide if a given “disease–wildlife species–livestock” triangle is of concern for animal health authorities or for wildlife managers (Simpson 2002). This may be the case, for example, for bluetongue, a vector-borne viral disease

**Table 1** Agent, host, current situation in Europe, relevance and main risk factors of diseases shared with European wildlife

| Disease | Agent | Wildlife host (domestic) | Situation in Europe | Relevance | Main risks |
|---|---|---|---|---|---|
| HP avian influenza | Virus | Waterfowl, marine and other birds (LPAI; poultry, domestic anatidae) | LPAI prevalent in wild aquatic birds, H5N1 reported in wild birds in many countries, limited outbreaks in domestic fowl, true multihost | Heavy economic impact, zoonosis, conservation concerns | Movement of wild and domestic animals, movement of untreated animal products, wet markets, open air farming |
| Newcastle disease | Virus | Pigeons, waterfowl, other birds (poultry) | Widespread in wild birds, sporadic outbreaks in open air domestic birds, especially pigeons and game birds, domestics may function as source for outbreaks in wild birds, true multihost | Economic impact, zoonosis, conservation concerns | Movement of wild and domestic animals and fomites, open air farming |
| West Nile fever | Virus | Wild birds (equines, domestic anatidae) | Endemic in Mediterranean Basin, more important in eastern Europe, European strain less pathogenic, locally detected in wild birds, sporadic local cases in horses and man | Vector borne zoonosis, conservation concerns | Vector expansion, movement of wild and domestic animals, open air farming |
| Rabbit haemorrhagic disease and myxomatosis | Virus | Wild rabbit (domestic rabbit) | Endemic in wild rabbits, shared between wild and domestic rabbits, true multihost | Economic impact (rabbit industry, vaccination expenses, mortality), conservation concerns | Movement of wild and domestic animals |
| African swine fever | Virus | Wild boar (domestic pig) | Locally endemic in pigs, apparently no true reservoir role of wild boars, apparent multihost | Heavy economic impact | Movement of wild and domestic animals, Open air farming |
| Classical swine fever | Virus | Wild boar (domestic pig) | Affects domestic pigs in several central and eastern European countries, wild boar acts as reservoir (oral vaccination), true multihost | Heavy economic impact | Movement of wild and domestic animals, wildlife overabundance |
| Aujeszky's disease | Virus | Wild boar (domestic pig) | Endemic in domestic pigs in several countries, strain differences suggest that wild boar, despite high prevalence, is no reservoir for indoor pigs, true multihost? | Heavy economic impact, conservation concerns | Movement of wild and domestic animals, wildlife overabundance, open air farming |
| Bluetongue | Virus | Wild ruminants (cattle, sheep and goats) | Expanding among domestic ruminants in Mediterranean countries, increasingly detected in wild ruminants (reservoir role unknown in Europe) | Heavy economic impact | Vector expansion, movement of wild and domestic animals |
| Bovine viral diarrhea, alpha herpesvirus, malignant catarrhal fever | Virus | Cervids (domestic ruminants) | Endemic in domestic ruminants, low prevalences in deer, apparent multihost? | Economic impact | Unknown |
| Rabies | Virus | Fox, racoon dog, wolf, other mammals (dog and other domestic mammals) | Strong inter-country differences in situation, oral vaccination successful, but possibly re-emerging, true multihost | Zoonosis | Expansion or introduction of hosts, movement of wild and domestic animals |
| Canine distemper | Virus | Wild carnivores (domestic carnivores) | Endemic in wild and domestic canid populations, spill over to other carnivores, true multihost, spillover and potential emerging disease | Conservation concerns | Movement of wild and domestic animals |
| Salmonellosis | Bacteria | Wild vertebrates (poultry, all livestock) | Presence in wildlife mostly due to exposure to human/ livestock residues, huge between-country differences in prevalence in livestock, true multihost | Heavy economic impact, zoonosis | Wildlife overabundance, open air farming |

| | | | | | |
|---|---|---|---|---|---|
| Tuberculosis | Bacteria | Wild boar, red and fallow deer, badger, other wild mammals (cattle, goats and extensively bred pigs) | Prevalences decreased throughout Europe, but asymptotic, endemic in badgers, wild boar and deer in several countries, strong debate on reservoir culling as a TB control option, wildlife vaccination trials scheduled, true multihost | Heavy economic impact, zoonosis | Movement of wild and domestic animals, wildlife overabundance, open air farming |
| Paratuberculosis (Johne's disease) | Bacteria | Wild ruminants, rabbit, other wild mammals (domestic ruminants) | Endemic in domestic ruminants, locally high prevalences in wildlife species, including deer and rabbit among others, increasingly reported in wildlife, true multihost? | Heavy economic impact, zoonosis? | Wildlife overabundance, movement of wild and domestic animals |
| Brucellosis (*B. abortus* and *B. melitensis*) | Bacteria | Wild ruminants (domestic ruminants) | Strong inter-country differences in situation, no true wildlife reservoir in Europe, spillover | Heavy economic impact, zoonosis | Movement of wild and domestic animals |
| Swine brucellosis | Bacteria | Wild boar, European brown hare (domestic pig) | Present in domestic pigs, particularly in open air systems, not yet controlled, true multihost | Economic impact, zoonosis | Open air farming |
| Tularemia | Bacteria | Hares, voles and other mammals (rarely domestics) | Endemic in wild mammals in many European countries, true multihost | Zoonosis | Movement of wild and domestic animals |
| Infectious kerato-conjunctivitis | Bacteria | Wild caprinae (sheep and goat) | Endemic in sheep and goat, Self limiting in wild caprinae, apparent multihost | Conservation concerns | Movement of wild and domestic animals |
| Trichinellosis | Parasite | Wild boar and other mammals (domestic pig) | Endemic in wild mammals (wild boar, carnivores...) and sporadic in domestic pigs (backyard), true multihost | Zoonosis | Open air farming |
| Leishmaniosis | Parasite | Wild canids (dog) | Wolf and especially fox may act as reservoirs for domestic dogs, endemic and expanding in the Mediterranean Basin, true multihost | Zoonosis | Vector expansion, movement of wild and domestic animals |
| Echinococcosis/ hydatidosis | Parasite | Wild and domestic canids (definitive hosts) | Wolf (granulosus) and fox (multilocularis), wild herbivores as intermediate hosts, domestic sheep-dog cycle, true multihost | Zoonosis | Expansion or introduction of hosts |
| Sarcoptic mange | Parasite | Wild mammals (domestic animals) | Little relevance in domestics (treatment), but self-sustained in abundant wildlife (true multihost), spillover to endangered wildlife | Conservation concerns | Movement of wild and domestic animals, wildlife overabundance |
| Trichomonosis | Parasite | Pigeons, game birds, other birds (poultry) | Endemic in wild and domestic pigeons, true multihost, spillover to endangered raptors | Conservation concerns | Wildlife overabundance |
| Toxoplasmosis | Parasite | Wild mammals and birds (all livestock) | Widespread, true multihost, | Zoonosis, | Open air farming, |
| Tick-borne diseases | Virus, bacteria and parasites, | Wildlife (domestic animals) | Most are shared between domestics and wildlife, wildlife may act as reservoirs or favouring tick numbers, true multihost | Economic impact, some are zoonoses | Vector expansion, wildlife overabundance, movement of wild and domestic animals |

*LPAI* Low pathogenic avian influenza

recently emerging in Europe that affects domestic and wild ruminants, and even of well-known cattle viral diseases, such as infectious bovine rhinotracheitis or other bovine viral diseases, where the actual role of deer still needs further clarification (Frölich et al. 2002). The recent foot-and-mouth disease outbreak in the UK showed that deer, at least at the densities existing in the UK, are not a true reservoir for this disease, as culling of infected livestock resolved the problem, but what would have happened if wild boar were abundant?

Parasitic diseases shared between wildlife and domestic animals have been reviewed by Simpson (2002). None of them alone is as relevant, as some of the viral diseases, but all together, cause huge economic losses, and wildlife may complicate attempts of parasite control in domestics. For example, *Neospora caninum* infection is present in wildlife, especially in red deer. This has important implications in the prevalence of infection in cattle farms (Almeria et al. 2007).

In summary, wildlife reservoirs need to be considered in the management of domestic animal health, and more scientific knowledge is strongly needed due to the changing nature of environment, disease agents and hosts.

## Diseases affecting wildlife management and conservation

Multihost situations are also of concern for wildlife management and conservation, as diseases can be a threat for endangered species or affect the productivity and density of wildlife populations with an economic or recreational value (Gortázar et al. 2006). Viral diseases of birds that are shared between domestic flocks and wild birds can affect economically relevant game birds (e.g. avian pox and red-legged partridge, Buenestado et al. 2004), or endangered birds, often boosting vaccination of captive individuals (e.g. West Nile encephalitis, Siegal-Willott et al. 2006). Domestic and wild pigeons carry *Trichomonas gallinae*, a protozoan parasite that can be transmitted to their predators, including endangered raptors, especially when other traditional prey items become scarce (Real et al. 2000; Hofle et al. 2004). For example, it has been shown in wood pigeons that the parasites reduce body condition even in clinically healthy infested animals and thus makes them more susceptible to predation (Villanúa et al. 2006a, b). Other parasites can be transported by game bird releases from farms to the field (Millan et al. 2004a, b) and eventually affect endangered bird species. For example, this has been suggested in the case of a typical partridge capillarid nematode (*Eucoleus contortus*) found in a little bustard (Villanúa et al. 2007a, b). Anthelminthic treatment is not 100% effective (Villanúa et al. 2007a, b). The stress associated to the release of game birds, along with the end of any antiparasitic treatments, increases parasite excretion of these birds after release, increasing the transmission probability to wild birds (Villanúa et al. 2006a, b).

Two viral diseases of lagomorphs, myxomatosis since the 1950s and rabbit haemorrhagic disease since the 1990s, have caused a severe decline in rabbit numbers throughout continental Western Europe. Among the causes of the problem are translocations of domestic rabbits and voluntary or involuntary transmission of the virus to wild rabbits (Angulo and Cooke 2002). The combined effects of these diseases, probably exacerbated by hunting, have contributed largely to the adverse situation of many rabbit predators, such as the Iberian lynx and many raptors (Angulo and Villafuerte 2004; Williams et al. 2007). This is probably one of the best examples of the huge effect that shared wildlife diseases can have on conservation and on management.

Among carnivores, diseases shared between livestock and wildlife can cause mortality of valuable endangered species. Metapopulation theory suggests that dispersed and reduced populations of endangered wildlife are more prone to extinction through stochastical events, such as disease outbreaks (Macdonald 1993). This means that even apparent multihost situations or occasional spillovers may affect the conservation of rare species. For example, Aujeszky's disease, a viral disease of swine and wild boar that can affect most mammals except man and primates, has been proposed as a risk for carnivore conservation (e.g. Banks et al. 1999; Vicente et al. 2005). Several Iberian lynx have died due to bovine TB in their last two strongholds in southern Spain (e.g. Perez et al. 2001). Consumption of infected prey or infected carcass remains is suspected as the way of transmission. Canine distemper in felids is an example for the potentially devastating effect of a pathogen in new host species (e.g. Vanmoll et al. 1995). It is diagnosed frequently in European wildlife (Baumgartner et al. 2003) and considered a serious concern for the conservation of Iberian lynx. Along with wildlife reservoirs such as the red fox, domestic dogs probably contribute to the risk of endangered wildlife getting in contact with the virus (Frölich et al. 2000). The same may occur with several other viral diseases of carnivores, but most situations are still insufficiently known. Disease monitoring is therefore an important element of recovery plans for rare species that are potential victims of epizootic pathogens (Macdonald 1993).

Among ungulates, two diseases shared between wild caprine (such as chamois and ibex) and domestic sheep and goats have important consequences on wildlife numbers and animal welfare. One is keratoconjunctivitis due to *Mycoplasma conjunctivae* in alpine chamois (Giacometti et al. 2002), and the second is sarcoptic mange (*Sarcoptes* *scabiei*), affecting several populations of mountain ungulates in Europe (e.g. Rossi et al. 2007). In both cases, the disease is suspected to spread from domestic livestock to wildlife and is responsible for repeated outbreaks that affect hunting harvest and population dynamics.

Even disease control measures can affect conservation and animal welfare, as shown by the badger culling debate in relation with TB control (Delahay 2006; Karesh et al. 2005) and by the adverse effect of fox den gasing, a measure to control rabies, on badger populations (Woodroffe et al. 2005). Culling of wild or captive endangered birds is a risk in the current avian flu crisis (Webster et al. 2006; Olsen et al. 2006).

Finally, disease transmission between wildlife and livestock can undermine conservation efforts if wildlife is seen as the source of a disease affecting livestock or human health (Brook and McLachlan 2006).

## Wildlife-related emerging diseases

Potential emerging infectious diseases are those where the pathogen will become self-sustaining in the new host once the initial (environment, host- or pathogen-related) barrier to infection has been crossed. Concern about emerging diseases is rising in recent years, and these may well occur at the fertile livestock–wildlife interface (Cunningham 2005). Wild animals are the most likely source of new emerging infectious diseases that put at risk the health of human beings and livestock (Anonymous 2004).

Chronic wasting disease, for example, a transmissible spongiform encephalopathy of North American cervids, could become an emerging disease in Europe if the geographical barrier is crossed (for example, importing diseased deer from North America). Prion diseases are not a real problem in European wildlife, but testing is ongoing (Schettler et al. 2006). Another example of a potential emerging disease is Rift Valley fever, a mosquito-borne zoonotic viral disease leading to serious economic losses in livestock, particularly sheep, in Africa. Global climatic change, vector expansion or movements of domestic animals may eventually bring this disease to Europe. In addition, a number of flaviviruses that exist in tropical and subtropical America may eventually be imported through travellers or translocated animals. The host diversity of these viruses in their native range (De Thoisy et al. 2004), along with the current expansion of vectors such as *Aedes albopictus* in the Mediterranean (Mitchell 1995), may eventually cause outbreaks in Europe.

Recent cases of wildlife-related emerging diseases include the HP avian flu crisis, affecting waterfowl and other bird species in different continents, including Europe (Chen et al. 2005; Kwon et al. 2005; Brown et al. 2006), West Nile virus in Eastern and Mediterranean Europe (Bakonyi et al. 2006), and leishmaniosis, which has spread into several new areas in Europe (Ferroglio et al. 2006).

Other than viral diseases, mycobacterial infections constitute frequent emerging or re-emerging disease agents in wildlife. Bovine TB due to *Mycobacterium tuberculosis* complex is increasingly important in wild ungulates, especially the wild boar, in Mediterranean Europe (Bollo et al. 2000; Vicente et al. 2006), but see also Machackova et al. 2003 for central and eastern Europe), and paratuberculosis (*M. avium paratuberculosis*) is now considered highly prevalent among wild rabbits and other wildlife in Scotland (Daniels et al. 2003), red deer in the Italian Alps (Fraquelli et al. 2005) and other wildlife elsewhere. In the case of Mediterranean wild boar populations, increasingly artificial management, such as fencing, feeding, watering and translocations, has been suggested as a possible cause for TB re-emergence (Vicente et al. 2007). In both cases, re-emergence of these mycobacterial diseases constitutes a severe barrier to eradication in livestock.

A new pestivirus, close to the border disease virus cluster, has recently been found in Pyrenean chamois, *Rupicapra pyrenaica* (Arnal et al. 2004, Frölich et al. 2005), and is apparently linked with important mortalities in the eastern third of these mountains. Research is going on to investigate the association of this pestivirus with disease in Pyrenean chamois and to reveal the source of this disease emergence (Hurtado et al. 2004). Sarcoptic mange, another disease of wild caprine, is present in many European mountain habitats and continues to expand to new areas (e.g. Rossi et al. 2007). Other strains of *S. scabiei* do affect carnivores (Gortázar et al. 1998), wild boar (Kutzer 1986) and humans (Green 1989). In contrast, cases in deer are extremely rare. Despite this, a yearly increasing number of red deer die due to mange in northern Spain, in an area where chamois mange is endemic. For example, two cases of roe deer mange have been found in the same region in 2006. This suggests a possible disease emergence in new hosts that is currently under investigation.

In summary, actual or potential emerging diseases deserve attention, including the study of the underlying causes for the emergence of infectious diseases, which are often related to anthropogenic and environmental changes (Kuiken et al. 2003; Cunningham 2005).

## Wildlife-related zoonoses

Rabies is the most classical wildlife-related zoonosis. In Europe, the red fox is the main reservoir of this viral disease. Rabid foxes can transmit the virus to wild and domestic mammals and humans or infect pets or livestock that can in turn infect humans. After causing serious concern in the second half of the twentieth century, rabies control was almost achieved through intense oral vaccination campaigns of foxes (Artois et al. 2001). This was the first sound success of wildlife vaccination as a disease control measure and proved to be preferable to the traditional methods based on fox population reduction. Despite this success, rabies appears to be re-emerging in some parts of Europe. This can be explained by a relaxation of vaccination campaigns in apparently rabies-free regions, an increase in fox densities and the expansion of new rabies hosts such as the racoon dog, *Nictereutes procyonoides* (Holmala and Kauhala 2006). In addition, bat rabies has been recorded in several European countries, even with a few fatal human cases (Calisher et al. 2006).

Bovine TB is mainly a disease of domestic cattle and goats, but can affect many other domestic and wild species, as well as humans. The existence of wildlife TB reservoirs is the main limiting factor for controlling this disease in livestock (Phillips et al. 2003). Rabies and bovine TB share several characteristics. Both are worldwide important zoonoses that cause significant mortality in developing countries. In Europe, human mortality due to these diseases is very limited due to the existing measures to control them in their animal hosts (dog and fox vaccination in rabies, testing and culling of infected livestock in TB) and to the existence of general preventive public health measures. Control measures in wildlife are quite expensive and even unpopular and make these diseases still relevant despite their limited impact on human health. in addition, at least in the case of bovine TB, some under-reporting of cases may exist. For example, most *M. tuberculosis* complex strains of caprine and bovine type, isolated from wild ungulates in southern Spain, have also been identified in humans (Gortázar et al. 2005), but in too many occasions these may be diagnosed as human TB if molecular typing is not performed.

In other, more recent (or recently detected) zoonoses, such as HP avian flu and, to a lesser extent, West Nile and other flaviviruses, Hanta virus or E-hepatitis, the role of wildlife in the epidemiology is still not completely understood and urgently deserves more research. In any case, wildlife has a relevant role in the spreading of diseases and as disease carriers over large distances and between countries, as is evident in the case of wild animal movements (Smith et al. 2006; Calisher et al. 2006).

Tularaemia is an example of a disease that, similarly to rabies, is mainly maintained in wildlife populations (e.g. invertebrates, rodents, hares), with occasional spill over to other animals and to humans. As eradication seems impossible, surveillance and hygienic preventive measures are needed to avoid outbreaks. One example occurred in 1998 with the Iberian hares (*Lepus granatensis*) of Spain (Puertas et al. 1999). On that occasion, the existence of a tissue bank with frozen spleen samples allowed to reveal the presence of the disease agent (*Francisella tularensis*) in hares shot several years before the 1998 outbreak. Wildlife monitoring data showed that the disease emergence was apparently linked to a sudden increase in Iberian hare numbers, rather than to the importation of infected European brown hares (*L. europaeus*), as suggested (Artois 2003). This example shows how relevant it is not only to set up wildlife disease surveillance schemes, but also to bank tissues. It also underlines the need to combine disease surveillance with the monitoring of wildlife abundance and the study of wildlife ecology (Gortázar et al. 2007).

*Salmonella* species are infectious agents causing numerous cases of human illness and important losses to the livestock industry each year. The two most common serovars, *S. enteritidis* and *S. typhimurium*, are well known to have different animals as reservoir for the disease in Europe: poultry in the former and pigs and cattle in the latter. In Europe, there are large differences in salmonellosis prevalence (De Jong and Ekdahl 2006). Wildlife is infected with these serovars through exposure to human or livestock residues and then transport the agents back to the farms. Wildlife can also host a variety of other salmonella serovars that are of zoonotic interest (Millan et al. 2004a, b).

Along with the nematodes of the genus *Trichinella*, the cestodes *Echinococcus granulosus* and *E. multilocularis* are the parasitic helminths of greatest zoonotic concern. *E. granulosus* not only has a domestic dog–sheep (and other livestock) cycle, but also a sylvatic wolf–wild ruminant (and other herbivores) one. These cycles may get linked through dogs consuming carcass remains of hunted game and wolves consuming livestock as carrion or as prey (e.g. Sobrino et al. 2006). *E. multilocularis* has no domestic cycle, and human cases occur through contact with contaminated fox faeces in endemic areas. In recent years, increases in the urban fox population have been observed in many countries of the northern hemisphere. As a result, *E. multilocularis* has entered the urban environment. Controlled baiting with the anthelminthic praziquantel showed that a pronounced reduction in *E. multilocularis* egg contamination is feasible in urban areas where the organism is highly endemic (Hegglin et al. 2003).

Finally, tick-transmitted diseases are among the most frequent wildlife-related zoonoses in the northern hemisphere. The agents are varied and include tick-borne encephalitis virus, *Anaplasma phagocitophylum* (the causative agent of human granulocytic ehrlichiosis), Lyme disease and several others. In most of these, wildlife hosts play a role either as disease reservoirs or by increasing the tick numbers (Lindgren et al. 2000; De la Fuente et al. 2005).

In summary, wildlife-related zoonoses are a diverse and complex issue that requires a close collaboration between wildlife ecologists, veterinarians and public health professionals.

## Identifying the risks

A few general risk factors can be identified in most of the wildlife diseases listed in Table 1. Among them, the most frequent one is the introduction of diseases through movements or translocations of wild or domestic animals. Examples include HP avian flu (poultry and exotic bird trade and waterfowl movements), myxomatosis (voluntary disease translocation) and food-and-mouth disease in the UK (involuntary disease translocation). The European continent, for historical reasons, has been a source of disease spread across the world (for example, bovine TB, a European cattle disease nowadays present worldwide). In turn, introduction of exotic species into Europe also conveys important risks of introduction of previously inexistent diseases, especially when foreign species range in or share habitats with native susceptible species, leading to situations where the native species become endangered (McInnes et al. 2006). For example, this is the case of the North American wapiti (carrying the trematode *Fascioloides magna*, highly pathogenic in the red deer, Novobilsky et al. 2006), the grey squirrel (carrying a pox virus highly pathogenic in the red squirrel, McInnes et al. 2006) or the American mink (carrying viral diseases that can threaten native mustelids, Yamaguchi and Macdonald 2001). Exotic wildlife is introduced for recreational hunting (wapiti, *Sylvilagus*, Barbary sheep), as a pet (water turtles) or garden animal (grey squirrel), for direct economic exploitation (American mink) or by accident (birds).

Overabundance of wildlife is a second relevant risk factor for wildlife diseases. European examples include TB (Vicente el al. 2007) and classical swine fever (Rossi et al. 2005) in wild boar and salmonellosis (Pennycott 1998) and trichomoniasis (Höfle et al. 2004) in relation with wildlife feeding. The assessment of overabundance and the available management tools have been discussed recently (Gortázar et al. 2006).

Open air farming also constitutes a risk situation. Some alternative livestock species are reared more extensively and thus are more prone to share diseases with wildlife, such as salmonellosis (e.g. Pennycott 1998). This includes farmed deer, game birds, ducks and geese. In recent years, animal welfare concerns have also promoted an increasing extensification of traditionally indoor-raised poultry and swine, increasing the transmission risks of diseases, such as HP avian influenza (Fouchier et al. 2004) or Aujeszky's disease and swine brucellosis (Ruiz-Fons et al. 2006).

The expansion or introduction of vectors, including the consequences of global change, can benefit certain diseases (Mitchell 1995). For example, tick species are expanding northwards (Lindgren et al. 2000), and bluetongue vectors, such as *Culicoides imicola*, are found in new locations and in growing abundances in Mediterranean Europe, creating the conditions for the expansion of this viral disease of ruminants (Purse et al. 2005).

Finally, the expansion or introduction of hosts has been linked to disease risks in several occasions. This was already mentioned in the case of the racoon dog and rabies, but may also apply for cases such as the introduced grey squirrel (Duff et al. 1996) and the newly established (escaped) wild boar populations in the UK (Williams and Wilkinson 1998).

Risk situations are frequently linked to human effects on wildlife abundance and distribution. Hence, diseases must be considered in any wildlife management programme with the same degree of relevance as factors such as habitat or genetics.

## The control of disease in wildlife populations

This subject has been reviewed by Wobeser (1994 and 2002) and Artois (2001 and 2003). In addition to surveillance, three basic forms of disease management strategies for wildlife are known: prevention of introduction of disease, control of existing disease or almost impossible eradication (Wobeser 2002). In any option, integration of veterinary, ecology and wildlife management expertise through multidisciplinary teams is strongly recommended (Artois 2003).

Wildlife disease control begins with surveillance, knowing which diseases are present, their past and current distribution and the trends in their prevalence. In Europe, wildlife disease surveillance is addressed by a series of regional, national and international schemes. Currently, parts of Europe benefit from wildlife surveillance efforts (frequently limited to a few diseases), while in other parts, no surveillance is done at all. Proper implementation of a complete surveillance effort must be a priority of the veterinary authorities, as it is accepted that those countries that conduct disease surveillance of their wild animal populations are more likely to detect the presence of infectious and zoonotic diseases and to swiftly adopt countermeasures (Morner et al. 2002).

Among the preventive actions, the most important one is by restricting translocation of wild animals to prevent movement of disease (Wobeser 2002). This includes the movement and release of farm-bred "wildlife", an increasingly popular game management tool that needs a careful sanitary control (Fernandez de Mera et al. 2003). In this field, a more intense collaboration between governmental or supragovernmental agencies devoted to animal health and to wildlife management is needed. But even the movements of domestic animals can easily cause the introduction of new diseases or new vectors (e.g. rabbit haemorrhagic disease introduced from China into Germany, Angulo and Cooke 2002).

Attempts to control disease in wildlife populations, or to avoid disease transmission between wildlife and livestock, have been based on a variety of methods. These include setting up barriers, improving hygienic measures, culling, habitat management and feeding bans, vector control, treatments and vaccination (Wobeser 2002; Artois 2003; Karesh et al. 2005; Gortázar et al. 2006).

Setting up barriers to prevent wildlife contact with domestic livestock, or vice versa, is rather infrequent, and its use is limited to certain risk situations. For example, it may make sense to avoid badgers on cattle farms in TB endemic areas (Garnett et al. 2002) or to prevent wild boar contact with open air bred pigs or other livestock (Parra et al. 2005).

Hygienic measures, such as correct disposal of the hunting carcasses and carcass remains, should become compulsory in every country and for every hunting modality (Almeria et al. 2007). However, research to assess the true risks of such management in every particular situation is needed in favour of the conservation of some wildlife species that usually survive very fragmentally and at the edge of their possibilities in Europe.

Wildlife culling is almost never an effective means of controlling a wildlife-related disease. Moreover, it is a subject of intense scientific and social debate (e.g. badger culling for TB control, Donnelly et al. 2006). Only in the case of island populations, when geographical barriers limit animal dispersal or in the case of introduced species (pest species, where legal and social constraints to culling are minimal) or to cope with a point-source wildlife disease outbreak (centering culling on the disease focus, plus an outer ring of vaccination), is culling and eradication an option. By contrast, population reduction is a goal in many disease control efforts. This is a temporary measure, except if habitat modification is used to reduce host density more permanently or to alter host distribution or exposure to disease agents (Wobeser 2002; Acevedo et al. 2007; Gortázar et al. 2006). Selective culling is limited to situations in which affected individuals are readily identifiable (Wobeser 2002). This has been used in several attempts to control mange in wild ungulates, but obviously with little success, as not all individuals with visible lesions are detected, and not all infected individuals show visible lesions. For example, chamois mange spread in the Cantabrian Mountains (Spain) could not be controlled by culling visibly infected individuals (Fernandez-Moran et al. 1997, and unpublished reports). Social structure disruption with increased movement and, therefore, increased contact rate (at intra- or interspecific level, Donnelly et al. 2006) may be counterproductive consequences of depopulation, which could be followed by rapid recovery of population size, even with increased population turnover through compensatory reproduction (e.g. wild boar and swine fever after high hunting pressure, Guberti et al. 1998). Ultimately, the best management choice must run in parallel with intense campaigns that convince and inform the society (farmers, hunters, the general public, etc).

Habitat management to cope with diseases may have opposite goals. For example, feeding bans can reduce the habitat carrying capacity for ungulates and eventually reduce population density and aggregation, two key factors in infectious disease transmission (Acevedo et al. 2007; Vicente et al. 2007). The identification and correction of overabundance situations are key actions in the control of many infectious diseases (Gortázar et al. 2006). By contrast, it can be useful to improve rabbit habitat (even with supplementary feeding) to reach higher population density and improve herd immunity against diseases such as rabbit haemorrhagic disease (Forrester et al. 2003).

Vector control has sometimes proven helpful in field experiments (e.g. with rabbit fleas and myxomatosis, Trout et al. 1992), but vector diversity and other factors may limit the effectiveness of this management in more complex environments (Osacar et al. 2001).

Treatment of wildlife is increasingly frequent, especially against parasites in economically valuable game species. For example, Spanish ibex (*Capra pyrenaica*) have been treated against sarcoptic mange with ivermectin (Leon Vizcaino et al. 2001), and wood pigeons (*Columba palumbus*) have been treated against trichomonas with dimetridazole (Hofle et al. 2004). Anthelminthic treatments are frequent in ungulates and in game birds (Fernandez de Mera et al. 2004; Rodriguez et al. 2006; Villanúa et al. 2007a, b). In many cases, however, the actual effectiveness of these treatments is unclear, and ethical and public health issues need to be addressed. For example, the use of antibiotics in game species may affect meat hygiene. Exceptions include the already mentioned treatment of foxes against *E. multilocularis* (Hegglin et al. 2003).

Wildlife vaccination is exceptional, and it is normally limited to the most relevant diseases (those that cause serious economic losses, are almost under control in domestics and where wildlife reservoirs are paramount). In Europe, this is the case of fox rabies (Artois et al. 1993), classical swine fever (Kaden et al. 2002) and, probably soon, bovine TB. Vaccination of rabbits against myxomatosis and haemorrhagic disease with a recombinant live

**Table 2** Examples of wildlife vaccination in Europe

| Disease | Vaccine | Target reservoir | Countries | Results | Conflicts |
|---|---|---|---|---|---|
| Rabies | Recombinant vaccinia virus | Red fox, racoon dog | Central and Eastern Europe | Success, but some re-emergency | Increase in fox populations |
| Classical swine fever | Attenuated classical swine fever virus | Wild boar | Central Europe | Variable | Changes in wild boar hunting |
| Aujeszky's disease | Attenuated AD virus | Wild boar | Spain | Not known! | ? |
| Bovine TB | Attenuated *M. bovis* mutant (BCG) | Badger (others in future) | UK and Ireland (others in future) | Field test running in Ireland, success in New Zealand | Conflicts with livestock skin testing and vaccine safety |
| Distemper | Attenuated | Harbour seals | The Netherlands | Success | |
| Myxomatosis and Rabbit Haemorrhagic disease | M: attenuated and heterologous, RHD: inactivated M + RHD: life recombinant M | Rabbit | Spain | Contradictory when using traditional vaccines | Conservation, recombinants |

Based on Osterhaus et al. 1988; Artois et al. 1993; Angulo and Cooke 2002; Kaden et al. 2002 and Lesellier et al. 2006

vaccine has risen concerns among the scientific community (Angulo and Cooke 2002). In contrast to culling, oral vaccination has the advantages of being painless, thus avoiding animal welfare problems, and does not cause behavioural problems such as increased dispersal or immigration. Vaccination makes sense if the huge investment is the only way to control a disease in its wildlife reservoir, if the costs are clearly outbalanced by the costs of remaining passive and provided that the effectiveness and safety of the vaccine have been tested in captivity. In most cases, vaccination needs to be combined with other management measures, and the ecology of the host species needs to be considered carefully (Table 2).

In summary, management of diseases of wild animals usually requires a change in human activities (Wobeser 2002), and a sound scientific basis is strongly needed before suggesting any corrective measures that can create or increase conflicts between the different stakeholders: veterinary authorities, hunters, conservationists, livestock breeders and the general public (Fig. 3). Moreover, the success of any wildlife disease management action must be assessed critically, including an analysis of the costs, of the ecological consequences and of the animal and human health and welfare benefits.

## European priorities in wildlife disease research

Top ranking wildlife diseases to research on are those where (1) wildlife has a high probability of substantially

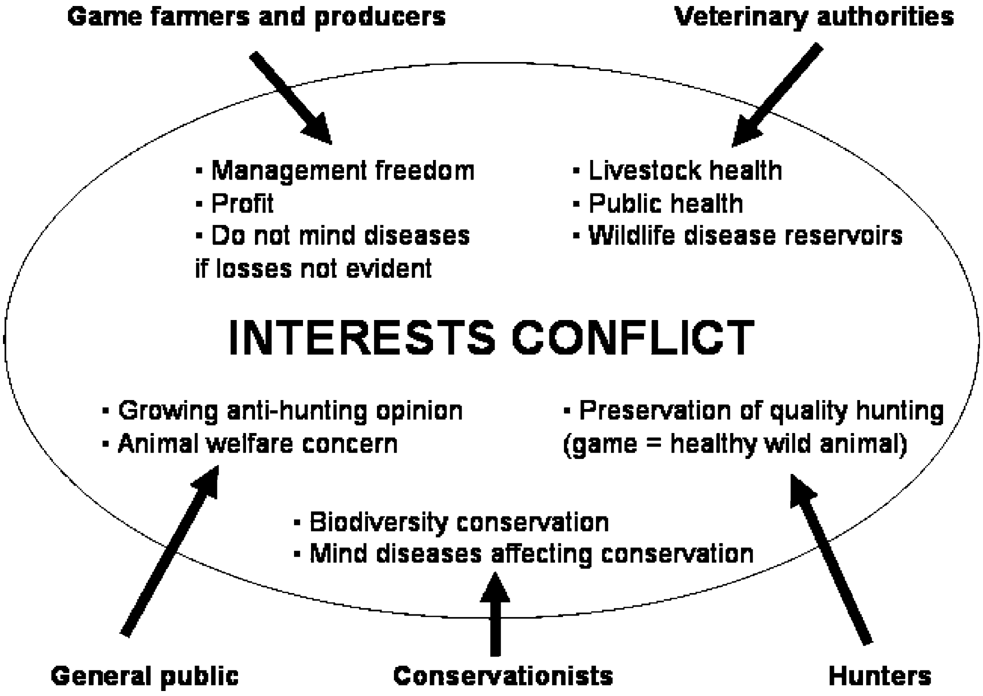

**Fig. 3** The interests conflict regarding wildlife disease control in game species. A sound scientific basis is strongly needed before suggesting any corrective measures that can create or increase conflicts between the different stakeholders

affecting regional disease status, and (2) the disease has a strong impact on human health, economy, wildlife management and conservation (Fig. 4).

Among the diseases listed in Table 1, not all have the same economic impact than others, and only in a few of them is disease control in wildlife reservoirs paramount for the success of the general control schemes. These diseases are the most critical ones, and European research efforts are clearly biased towards them: classical swine fever, rabies, bovine TB. Research on these diseases has helped to make important management decisions and, in some cases, has opened the way to oral vaccination of wildlife. Moreover, these examples, along with the more recent HP avian flu, have contributed to the view that wildlife diseases are relevant and that multidisciplinary science can contribute to the improvement of animal and human health. Nonetheless, even more research is needed in the remaining diseases, where current knowledge is limited regarding their management.

In a number of cases, scientific evidence is currently inadequate to determine if European wildlife has a high probability of substantially affecting regional disease status, or not. This is the case, for example, of bluetongue, bovine viral diarrhoea, alphaherpesvirus infections, malignant catarrhal fever, brucellosis (*B. abortus* and *B. melitensis*) and leishmaniosis. These diseases deserve a greater research effort, to determine their relevance in relation to wildlife.

Finally, many other diseases have either a more limited impact on economy and public health, or the role of wildlife in their control is not considered relevant. This is the case, for example, of many parasitic diseases. Research on these subjects exists, in part, because macroparasites are easy to handle in experimental studies, and it provides a valuable source of basic scientific knowledge on disease ecology, which may be applied later to more relevant diseases (e.g. Hudson et al. 2001; Vicente et al. 2004a, b).

Regarding the kind of research needed in the wildlife disease field, surveillance and descriptive studies, in general, are still valuable, especially in regions, species or diseases that have received less attention. Nonetheless, limiting the effort to the mere reporting of wildlife disease outbreaks is of limited value if management recommendations are not given at the same time. Moreover, the animal health authorities and the public may perceive wildlife veterinarians as purveyors of bad news ("you got this disease") with no positive counterpart ("you can do this"). Therefore, more experimental approaches are strongly needed if the aim is to produce substantial knowledge that enables researchers to make targeted management recommendations.

Experimental studies should ideally combine indoor experiments, such as experimental infections or vaccination trials, with field experiments testing hypotheses regarding for example the effects of host aggregation and density on disease prevalence (e.g. Donnelly et al. 2006; Acevedo et al. 2007) as well as pathogen persistence. Again, a strong ecological background is needed. Mathematical modelling may help to identify those knowledge gaps that most urgently need experimental research (Morgan et al. 2006).

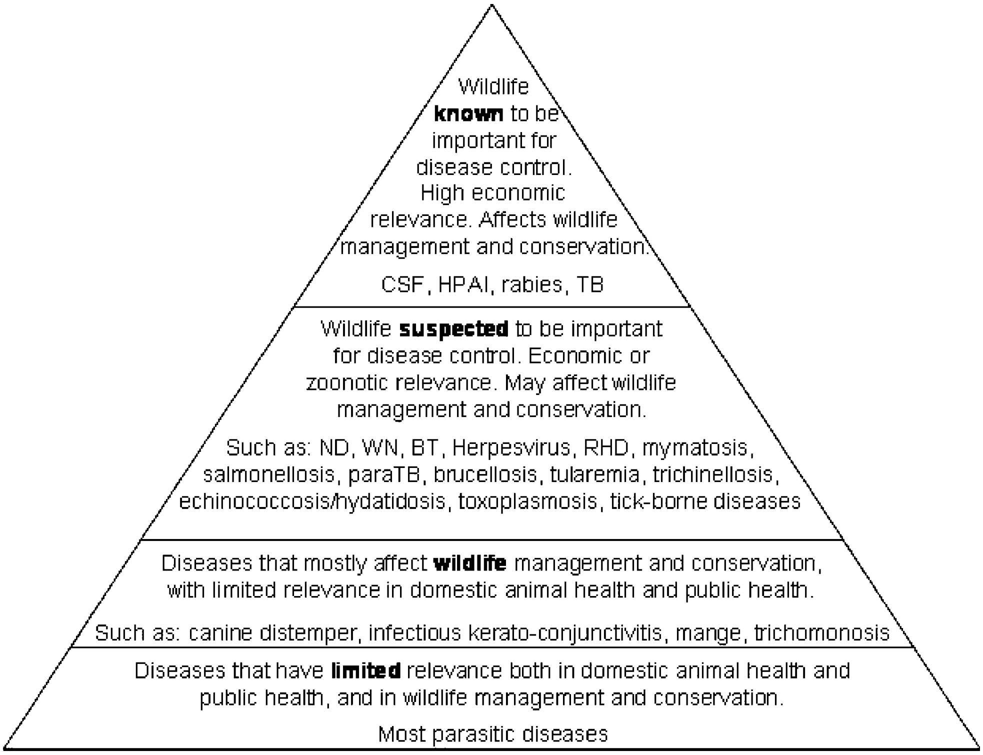

**Fig. 4** Relevance of wildlife diseases in Europe. *From top to base* diseases where wildlife is known to affect disease control chances, diseases where wildlife is suspected to be relevant, diseases mainly affecting wildlife populations and others with limited relevance but of interest for basic knowledge on disease ecology

Research effort must also be focused on the development of diagnostic tools appropriate for wildlife species (Simpson 2002). The main drawback is that experimental research requires more funding than surveillance alone, and the former needs to be carried out by multidisciplinary scientific teams, which are scarce.

## Conclusion

Three actions can help to improve our knowledge on wildlife diseases and our capacity to deal with their consequences on animal and human health as well as conservation: (1) extend surveillance schemes to the not yet included regions and taxa and improve coordination between surveillance schemes and other wildlife monitoring, (2) promote experimental and multidisciplinary research on the relevant wildlife diseases and (3) include knowledge on wildlife diseases in the curricula of the European veterinary students.

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