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Animal movements and the spread of infectious diseases

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Domestic and wild animal population movements are important in the spread of disease. There are many recent examples of disease spread that have occurred as a result of intentional movements of livestock or wildlife. Understanding the volume of these movements and the risks associated with them is fundamental in elucidating the epidemiology of these diseases, some of which might entail zoonotic risks. The importance of the worldwide animal trade is reviewed and the role of the unregulated trade in animals is highlighted. A range of key examples are discussed in which animal movements have resulted in the introduction of pathogens to previously disease-free areas. Measures based on heightened surveillance are proposed that mitigate the risks of new pathogen introductions.

Animal movements and disease transmission

Infectious diseases are transmitted between hosts by a variety of mechanisms, including direct, airborne and vector-borne transmission. Control of animal-to-animal transmission of disease agents is a key concept in infectious disease epidemiology; however, a more sensible approach might be to prevent the types of contact that lead to transmission in the first place. In humans, it is often difficult to prevent contacts, particularly with the ease of long-distance travel [1]. However, in livestock and animals, movements can be the subject of legislation or strict controls and there is a real opportunity to reduce disease transmission. The importance of animal movements is, of course, well understood and international regulations [e.g. from the World Organisation for Animal Health (OIE; Box 1)] exist to mitigate the risks involved [2]. In spite of these regulations, outbreaks occur regularly as a result of both legal and illegal animal movements.

In this review, we examine several issues that relate to the movement of domestic and wild animals and discuss the risks that these movements entail – at local, regional and global scales – with regard to the spread of disease. First, we present data on livestock movements at a global level, and highlight the scale of wildlife movements as a result of translocation by humans. Second, we provide key

case studies of animal and animal-to-human (zoonotic) disease introductions in different parts of the world that have resulted in subsequent disease transmission and new outbreaks, with an emphasis on how introduction of the disease agents could have been prevented either through intervention or regulation.

International trade and transport

The trade in livestock, wildlife and animal products is enormous and complex, and occurs on many different scales. There are no overriding rules to control these movements and much of the trade is still based on bilateral agreements between countries. However, countries that are members of the World Trade Organization are bound by the Sanitary and Phytosanitary Agreement (http://www.wto.org/english/tratop_e/sps_e/spsagr_e.htm), which concerns food safety and animal and plant health regulations. Countries are encouraged to base their sanitary and phytosanitary measures on existing international standards. The international standards relating to animal health and zoonoses were developed by the OIE and are stated in the aquatic and terrestrial animal health codes (http://www.oie.int/eng/normes/fcode/en_index.htm and http://www.oie.int/eng/normes/mcode/a_summry.htm, respectively). The aim of the codes is to assure the sanitary safety of the international trade in terrestrial animals and their products by detailing the health measures that should be used by the veterinary authorities. The important role of a good veterinary infrastructure to minimize the risks of disease spread has been emphasized [3].

The relevant legislation for international wildlife trade [4] relates to three main areas: animal health, animal welfare and the international movement of endangered species. The animal health regulations relevant for livestock trade (see earlier) also apply to non-domesticated animals. However, additional regulations exist for wildlife to protect endangered species from overexploitation from trade, in the form of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) and the Convention on Biological Diversity (CBD). Detailed guidelines have also been developed by the World Conservation Union (IUCN) to minimize disease risks associated with the intentional movement

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Available online 7 February 2006

Box 1. Useful web addresses**International organizations**

Food and Agriculture Organization: www.fao.org
 World Health Organization: www.who.int
 World Organization for Animal Health: www.oie.int
 World Trade Organization: www.wto.int
 African Union–Inter African Bureau for Animal Research:
www.au-ibar.org
 Organization for Economic Co-operation and Development:
www.oecd.org

International regulatory bodies

Council of Europe: www.coe.int
 European Union: europa.eu.int
 Convention on International Trade in Endangered Species of Wild
 Fauna and Flora: www.cites.org

World Conservation Union: www.iucn.org
 Convention on Biological Diversity: www.biodiv.org
 International Air Transport Association: www.iata.org

National regulatory and research bodies

United Kingdom Department for the Environment, Food and Rural
 Affairs: www.defra.gov.uk
 United Kingdom PET Passport Scheme:
www.defra.gov.uk/animalh/quarantine/index.htm
 United Kingdom Foresight Project: www.foresight.gov.uk
 United States Animal and Plant Health Inspection Service:
www.aphis.usda.gov
 United States Centers for Disease Control: www.cdc.gov
 University of Edinburgh: www.ed.ac.uk

of wildlife for conservation or game management purposes: for example, the supplementation of populations, reintroduction of endangered species, removal of problem animals and the release of confiscated animals [4] (Table 1).

The volume of international trade

The international trade in livestock is big business; for example, in 1996, China exported US\$ 48 million, US\$ 294 million and US\$ 121 million worth of cattle, swine and poultry, respectively [5]. In 1999, Sudan exported 1 616 363 sheep, 435 cattle, 40 501 goats and 159 483 camels, mainly to Egypt and the Middle East [6]. The Food and Agriculture Organization (FAO) Global Livestock Production and Health Atlas (GLiPHA; <http://www.fao.org/ag/aga/glipha/index.jsp>) also provides data on live livestock imports for most countries of the world. For example, Australia exported 895 982 heads of cattle, 5 421 408 sheep, 2976 horses, and 5 asses in 2000 (Table 2), with large numbers of live sheep exported to the Middle East [7].

Unregulated (illegal or informal) trade is, by its nature, difficult to quantify, although available data for some regions of the world show that unregulated trade is substantial. Although there are no official records, it has been documented that, for example, 75 000 head of cattle move from Somalia to Kenya annually, and that up to 850 000 goats move from Somalia to the Middle East (which accounts for >95% of all goat imports from the eastern Africa region) [8]. Indeed, in the case of cattle trading with

Kenya, political instability resulted in a large increase in the value of unofficial trade. This coincided with a collapse in the animal health infrastructure of Somalia and a resulting lack of animal export controls. Diseases known to have been circulating in Somalia include both zoonotic and non-zoonotic infectious diseases: anthrax, babesiosis, brucellosis, contagious bovine pleuropneumonia, contagious caprine pleuropneumonia, foot and mouth disease (FMD), heartwater, peste des petits ruminants, rabies, Rift Valley fever, rinderpest and trypanosomiasis, among others [9]. Unofficially traded animals are a much greater risk factor for disease spread because they are not necessarily subject to veterinary controls. It has been reported that much of the human brucellosis problem in Saudi Arabia, which has an incidence of 40 cases per 100 000 people nationally, is the result of unscreened and unregulated imports that come mainly from Africa [10]. The picture that emerges from a consideration of these various data sources is one of a highly interconnected world in which animals move locally, regionally and across large international distances.

Trade in wildlife and wildlife products

The global wildlife trade is also huge, with an annual turnover estimated at billions of dollars and involving hundreds of millions of individual plants and animals (<http://www.traffic.org/25/wild1.htm>). Precise estimates of its scale are difficult because much is conducted through informal or illegal networks but recent figures suggest that ~40 000 live primates, four million live birds,

Table 1. Laws and other measures relevant to the trade and movement of domestic and wild animals^a

Level	Animal health	Animal welfare	Endangered species
International	World Trade Organization and Sanitary and Phytosanitary Agreement International Animal Health Code and International Aquatic Animal Health Code (World Organization for Animal Health - OIE)	International Air Transport Association regulations International Animal Health Code and International Aquatic Animal Health Code (World Organization for Animal Health - OIE)	CITES CBD IUCN guidelines
Regional	European Union directives (numerous)	European Union Regulation (transport of animals) Council of Europe Convention (transport of animals)	European Union and CITES regulation
National	Laws on control of disease and movement	Anti-cruelty laws, welfare codes	Laws implementing CITES and CBD, species protection
Sub-national	Local restrictions on animal movement		

^aAdapted from Ref. [4].

Table 2. Examples of the volume of live imports of different livestock species from a range of countries in 2002^a

Country	Sheep	Pigs	Chickens	Cattle
Belgium	52 261	693 891	136 254	61 054
UK	0	231 427	3512	5966
USA	139 162	5 741 275	6952	2 505 279
China	3022	1163	1002	11 432
Brazil	495	1368	1372	19 242
Mozambique	28	768	6784	1809
Egypt	68 195	Data not available	5537	92 492
India	0	9432	0	4674
Philippines	447	1366	2529	117 146

^aSource: FAO GLIPIHA, available at <http://www.fao.org/ag/aga/glipha>.

640 000 live reptiles and 350 million live tropical fish are traded globally each year [11]. In Asia, the substantial regional trade in wild animals is estimated to result in several billion direct and indirect contacts among wildlife, humans and domestic animals each year [11].

Despite the widespread recognition of the risks of disease transmission associated with wildlife translocation, and the legislation and regulation in place to minimize disease risks [4,12–14], new diseases continue to emerge as a result of wildlife trade. Here, we present key examples from the past five years that illustrate the continuing threat to human, livestock and wildlife health.

Severe acute respiratory syndrome (SARS) and highly pathogenic avian influenza (e.g. H5N1) are emerging infections that have the potential for pandemic spread with massive public health and economic consequences. Both diseases are maintained in wildlife reservoir hosts: H5N1 in wild fowl and SARS in horseshoe bats (*Rhinolophus* species) in China [15,16]. For SARS, the trade in bats is likely to have brought infected animals into contact with susceptible amplifying hosts such as the masked palm civet (*Parguma larvata*) at some point in the wildlife supply chain, establishing a market cycle in which susceptible people and animals could subsequently become infected [15,16]. For avian influenza, these 'wet markets' could also function as network hubs for potential cross-species transmission. However, the international trade in birds also poses considerable risks for long-distance transmission of H5N1, as highlighted by the detection of infected hawk eagles imported illegally from Thailand to Belgium [17]. The disease risks of the wild bird trade have been brought into sharp relief by the importation of H5N1-infected birds destined for the UK pet market [18] and, at the time of submission of this review, a temporary ban on the importation of wild birds had been implemented by the UK government.

The recent detection of *Pseudamphistomum truncatum* (an opisthorchid fluke parasite) in the English otter population has been linked with the introduction of two freshwater fishes: the sunbleak (*Leucaspis delineatus*) and the topmouth gudgeon (*Pseudorasbora parva*), which can function as intermediate hosts for the fluke. These species were newly introduced into the UK by an ornamental fish supplier in Hampshire in the mid-1980s and their escape led to the colonization of many river systems in southern England [19].

The translocation of amphibians is implicated in the emergence of amphibian diseases such as chytridiomycosis

and ranavirus infections, which might be a major contributing factor in the widespread decline and extinction of amphibian species worldwide [20]. Chytridiomycosis, which has been associated with amphibian mortalities and population declines in Central America and Australia, has also been linked to the introduction of cane toads (*Bufo marinus*) into Australia [20]. Also, chytridiomycosis has appeared recently in the UK, with confirmed cases in an established breeding population of North American bullfrogs (*Rana catesbeiana*), which is an introduced species [21]. Recent movements of *R. catesbeiana* and *B. marinus* might also have disseminated ranaviral diseases such as tadpole oedema virus [20]. In Australia, where *B. marinus* was introduced to Queensland in 1935, ranaviral antibodies can be identified in this species throughout its geographic range [22].

In addition to the well-recognized threat that animal translocations and invasions into new geographic areas pose for species extinctions and biodiversity, the large wildlife trade clearly poses great dangers for the emergence of human and animal pathogens. It is doubtful whether the disease risks associated with the international wildlife trade, let alone additional welfare and conservation-related problems, can ever be justified simply to supply a demand for pets or recreational hunting. The dilemma is perhaps more acute in areas where the wildlife trade is associated with food and medicines, particularly in Asia, where the trade could be an important element in rural livelihoods and food security. In addition, translocation of wildlife can be an important tool for both conservation and animal welfare.

Case studies of disease threats

Movement of pets

In February 2000, the UK adopted the Pet Travel Scheme (PETS) to enable pets with the appropriate documentation to move between the UK and certain countries. This represented the first major change in UK quarantine regulations since the 1901 Importation of Dogs Act. The scheme is primarily designed to prevent the importation of rabies, with secondary measures to prevent the introduction of the cestode parasite *Echinococcus multilocularis*, which is currently endemic in continental Europe and can be transmitted from canids to humans to cause potentially fatal alveolar echinococcosis. Eighty-one countries now qualify under the scheme but quarantine remains the only option for non-listed countries. The PETS is a model for the use of legislation to minimize risks: the risks of importing rabies under the scheme are small. However, other zoonotic diseases continue to pose a substantial risk and there are few formal checks for these under the system. Figure 1 shows the volume of dog and cat movements into the UK following the introduction of the PETS.

Leishmania infantum is the predominant cause of both visceral and cutaneous leishmaniasis throughout the Mediterranean region, including southern France, Portugal, Spain, Italy, Greece, Turkey and North Africa [23]; the main reservoir host is the domestic dog. Seropositivity rates of canine leishmaniasis can be >30% [24] in the Mediterranean, with patterns of infection that reflect the

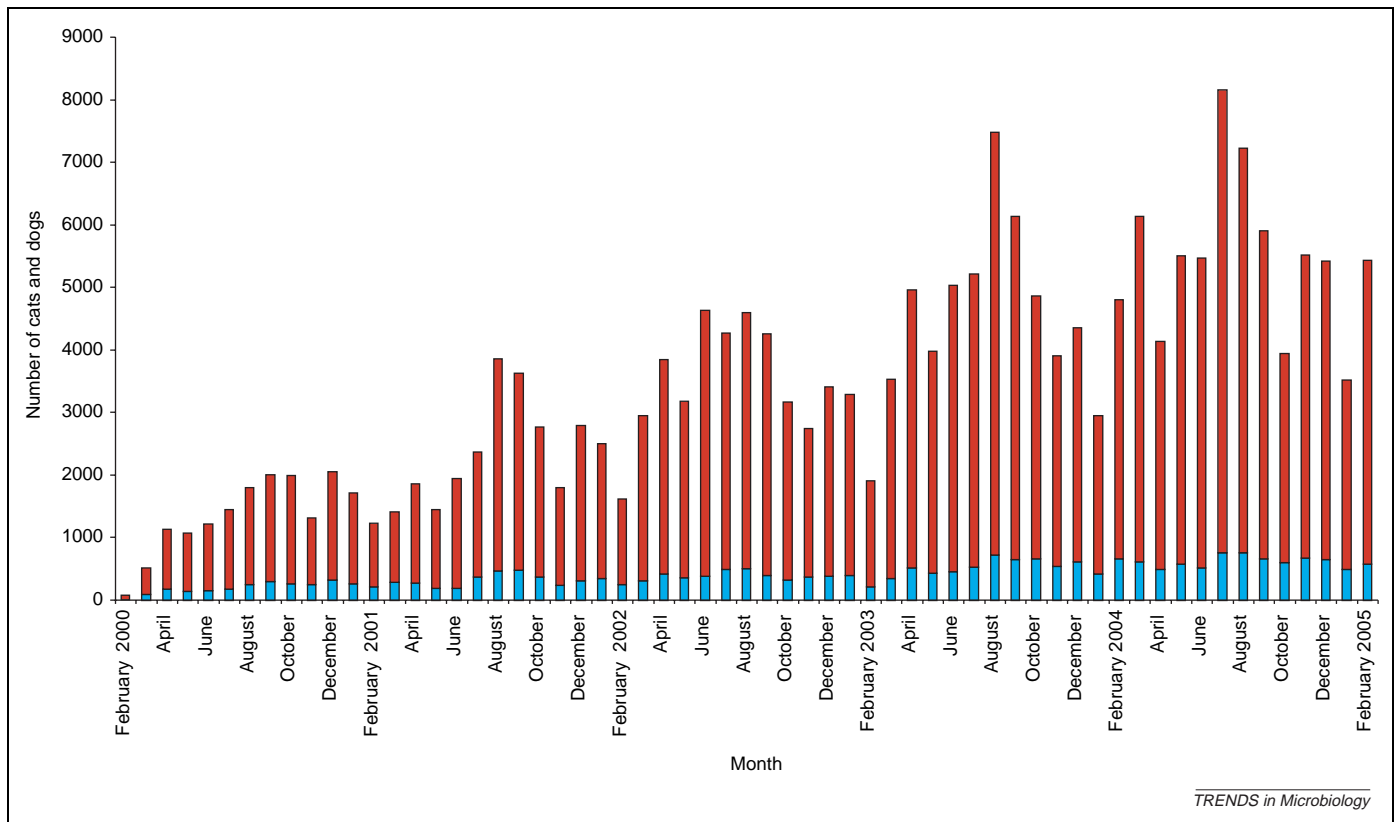


Figure 1. Monthly totals of cats and dogs entering England as part of the PETS between February 2000 (start of scheme) and February 2005. Total entries over this period numbered 210 989 cats and dogs. Red bars, dogs; blue bars, cats. Data obtained from the Rabies and Equine Division, Department for Environment, Food and Rural Affairs (DEFRA).

distribution of the sand fly vector (*Phelbotomus* species) [25,26]. In Brazil, where canine visceral leishmaniasis is an important emerging disease, canine infection in endemic areas can be as high as 67% [27]. To control the disease, a mass culling of seropositive dogs has been adopted in several areas but has not been effective [28]. A feasible alternative to culling dogs is to fit collars treated with the insecticide deltamethrin; preliminary results have shown a large drop in the number of bites by sand flies and infection rates in dogs [29–31]. This might be the only way to control the increasing spread of canine visceral leishmaniasis and could be recommended as a control measure for dogs leaving and re-entering the UK under PETS. Quarantine is not effective in preventing the introduction of leishmaniasis due to the long incubation period of the disease. Outbreaks of leishmaniasis have occurred in dogs in the USA as a result of Mediterranean-based military personnel who have returned home with their pets. In addition, there has been an apparent increase in the incidence of leishmaniasis in US hunting dogs [32] – although the cause remains unclear, it could be a result of either animal movements or spread of the vector. The chances of leishmaniasis becoming established in domestic dogs in the UK are small because, currently, *Phelbotomus* species are not known to be present in the UK. However, if climate change does affect air temperatures substantially, the sand fly vector could become established in the UK and, potentially, could maintain

endemic leishmaniasis and other ‘exotic’ parasitic diseases [33], the introduction of which would probably result from the movement of domestic pets.

In addition to leishmaniasis, diseases such as heartworm (*Dirofilaria immitis*), babesiosis (*Babesia canis*), ehrlichiosis (*Ehrlichia canis*) and echinococcosis (*Echinococcus granulosus* and *E. multilocularis*) are all likely to be moved with domestic pets into the UK and elsewhere [23,34]. The responsibility falls on domestic pet owners in such a situation who should ensure the use of anthelmintics – agents that destroy or expel parasitic intestinal worms – and, possibly, insecticide-treated collars. Owners should also be advised about preventative measures before pet travel.

E. multilocularis is common in red foxes in Hokkaido, northern Japan, where the prevalence of infection in foxes is as high as 40% and high worm burdens are recorded in some individuals [35]. DNA sequencing of parasite isolates from this area show that it was probably introduced in the 1960s from a neighbouring island [36] through the movement of infected foxes. This disease now presents an important public health problem, with a human incidence of 0.33 per 100 000 people [35], or ~10 cases annually. Domestic dogs have become part of the transmission cycle and close contact between humans and their pets is a major risk factor. A recent risk analysis [37] showed that the movement of pet animals between Hokkaido and the rest of Japan is likely to result in

further geographical spread of the parasite, particularly because there are few movement controls or programmes for screening and treatment.

Rabies

Rabies is a prime example of an infectious disease in which transmission can be enhanced by animal movements. Flores Island in Indonesia was free of rabies until 1997 [38]; in that year, three dogs were imported from a rabies-endemic area and this was sufficient to result in 113 human deaths (mainly children) and the culling of almost 50% of the dog population in some areas as part of an unsuccessful control campaign [39]. Flores Island is now endemic for rabies, which has become a major public health issue, and dealing with its introduction has incurred a high cost.

Translocation of raccoons from Florida to Virginia for hunting purposes [40] also led to the emergence of raccoon rabies in the mid-Atlantic states of the USA, with thousands of animal cases that resulted in enormous expenditure on rabies post exposure prophylaxis and oral vaccination programmes [41]. France now has rabies-free status because terrestrial rabies has been eliminated through a long-term concerted effort to vaccinate foxes [42]. However, the risk is ever present and, in 2001, contacts with an illegally imported rabid domestic dog resulted in 21 people requiring post-exposure prophylaxis [43].

Bovine tuberculosis

Since the 1950s, the UK has conducted regular bovine tuberculosis (bTB) testing of cattle herds [44]. Herd breakdowns – the occurrence of bTB in a previously bTB-free herd – have become more common since 1993 and the causes of these breakdowns are the subject of intense debate. Molecular evidence (analysis of spoligo-type data) from bTB isolates in the UK [45] indicates an important role for cattle movements in the long-distance spread of disease and the establishment of novel strains in new geographic areas. While also highlighting environmental, wildlife and other factors in the short-range spread of bTB in the UK, Gilbert *et al.* [46] quantified the strong association between the proportion of inward movements from infected areas and the breakdown of herds, which highlighted the strong predictive power of cattle movements for later disease distributions. The importance of contact networks in the spread of infectious diseases of livestock in the UK has been clearly highlighted [47]; in addition, a small proportion (20%) of farm holdings contributes to the majority (80%) of movements. If one of these high-contact farms was infected with bTB, its impact on long-range spread to many other farms would be substantial. A thorough understanding of livestock contact networks at different scales is essential in predicting such spread.

Trypanosomiasis in domestic animals and humans

Trypanosoma evansi (the tabanid-transmitted pathogen responsible for surra in livestock) has spread in south east Asia, particularly in the Philippines where there is high mortality in those areas in which the parasite has been

detected. This spread has been blamed on the movements of livestock as part of herd-improvement programmes [48]. Similarly, another trypanosome species (*Trypanosoma brucei rhodesiense*) caused an outbreak of human sleeping sickness in a previously unaffected area of Uganda. This was caused by movement of the cattle reservoir of the trypanosome parasite through markets without proper screening or disease control. Veterinary and public health services are now struggling to control a rapidly spreading sleeping sickness epidemic in humans [49]. These introductions would have been entirely preventable if local authorities had been alerted to the risks and if resources were made available to administer prophylaxis or treatment to the animals. The integrated management of disease threats (e.g. the treatment of animals as a means of preventing disease spread to humans) would be a cost-effective and efficient use of resources, particularly where zoonotic diseases are concerned.

Foot and mouth disease

In late January or early February 2001, FMD was introduced to a pig farm in the north of England. Disease spread through this pig herd probably occurred with three waves of infection and amplification. However, FMD was not notified to the authorities until it was identified during a routine meat inspection at an abattoir in the south east of the country (several hundred miles away) on 19 February; FMD was confirmed on 20 February [50]. At the time of disease identification in the abattoir, the virus had already spread to a neighbouring farm where sheep and cattle were infected, probably by airborne spread [51]. Sheep from this farm were sold to a local market on 13 February and sold again two days later at a larger market [52]. By the time the first case was confirmed, an estimated 30–79 farms had been infected across the UK [52,53]. Rapid tracing identified the pig farm but a movement ban for the whole of the UK was delayed for three days (although all international movements were stopped immediately). This three-day delay might have caused a further 17 farms to become infected, mostly from contacts with markets [54]. The virus spread to France through the movement of infected sheep before the ban. In addition, calves bound for the Netherlands were in a vehicle next to these sheep at a stopping point and it is thought that the virus was transmitted between these two consignments – FMD was confirmed in the Netherlands on 21 March [55]. This outbreak clearly demonstrates the risks associated with large-scale movements of animals over long distances across international borders. Given modern abattoirs and chilling transport units, the question arises as to why this sort of live animal movement is necessary at all.

In Africa, livestock are one of the few tradable commodities available to millions of poor households, particularly those living in the more arid regions of sub-Saharan Africa. There are well-established trade routes across the continent that supply the large coastal populations of west and central Africa and the Arabian peninsula. These animal movements are of major importance for the dissemination of new strains of FMD and

other diseases such as Rift Valley fever [56]. Modern DNA sequencing techniques make it possible to compare isolates and identify probable sources of infection. For example, these techniques enabled the tracing of outbreaks caused by the SAT2 FMD serotype as it spread up the east African coast into Saudi Arabia through cattle movements from Somalia and Eritrea [57] and its subsequent spread west into Cameroon [58]. In these regions, herdsman are nomadic or semi-nomadic and move with their animals on a seasonal transhumance in search of grazing, which brings different herds into contact with one other and increases the risk of spread of FMD [59].

Concluding remarks

The movements of domestic and wild animals are complex and profitable but are extremely risky from a disease perspective. Movements can result in the introduction of exotic animal diseases or human pathogens, which might themselves have important economic and/or public health impacts. One example occurred in 2003 when humans in the USA became infected with monkey pox [60], which originated from the importation of wild west African rodents. Minimizing such risks should be a high priority and, in some cases, this might involve preventing the animal trade altogether: from the perspective of disease introductions and animal welfare, it is difficult to justify the movement of exotic birds or mammals simply for the pet trade. Attempting to ban such movement, however, is likely to drive it underground, which makes risk-mitigation far more difficult. With livestock, there is a strong case for trading only in livestock products – a commodity-based approach – rather than live animals themselves [61] but this, of course, is dependent on the appropriate investment and infrastructure being available to process animal products and to provide adequate quality assurance.

For diseases linked to livestock, such as FMD, bovine tuberculosis and sleeping sickness, markets have an important role in the dissemination of infectious organisms. Markets serve as contact nodes between infected herds and the ease of transportation can result in the widespread dissemination of animals that have been in contact in a market. Contact nodes such as quarantine facilities, markets and ports of entry can also result in the transmission of agents between individuals and species, with rapid subsequent dissemination. Better communication between scientists, livestock traders, livestock keepers and decision makers is required to avoid this.

The key issue that requires most attention is to acquire a better understanding of the risks of global movements. Simple risk assessments that focus on the individual country trying to protect itself from disease introductions are no longer sufficient and passive detection of disease at ports of entry is an increasingly dangerous strategy as the volume of movements increases. A holistic understanding of risk at the global level is required to understand disease risks by species and by country, supplemented by an efficient global surveillance network in which different animal species are regularly screened, particularly before moving from their source areas. Control of disease threats should be dealt with locally rather than when movement

has already occurred, which requires knowledge of species, volumes moved and fine-scale information on point of origin. Knowledge of movement routes is the key to predicting the pattern of spread of infectious diseases of humans [62], and similar data could be crucial to understand animal disease risks. Databases already exist [63–65] that list pathogens, hosts and probable risks of emergence; additional layers of information on the movements of host species and their impacts on the risks of emergence should be added, and the information should be made publicly available. Such global cooperation and international level disease control will lead to better risk management and mitigation.

Acknowledgements

E.M.F. and S.C. are funded by the UK Department for International Development (DFID), although the views expressed are not necessary those of DFID. We thank Philippe Ankers of Vétérinaires sans Frontières (VSF)-Suisse for supplying some key reference material.

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