Assessing the probability of introduction and transmission of Lumpy skin disease virus within the United Kingdom

V. Horigan[1*], P. M. Beard[3, 4], H. Roberts[2], A. Adkin[1], P. Gale[1], C. A. Batten[3], L. Kelly[1, 5]

[1] Department of Epidemiological Sciences, Animal and Plant Health Agency, Woodham Lane, New Haw, Surrey, KT15 3NB, UK

[2] Exotics and Risk Team, Animal and Plant Health Agency, Area 5B, Nobel House, 17 Smith Square, London SW1P 3JR

[3] The Pirbright Institute, Ash Road, Pirbright, Woking, GU24 0NF

[4] The Roslin Institute and Royal (Dick) School of Veterinary Studies, Easter Bush, Midlothian EH25 9RG, United Kingdom

[5] Department of Mathematics and Statistics, University of Strathclyde, 26 Richmond St, Glasgow G1 1XH, UK

[*] Author to whom correspondence should be addressed; E-Mail: verity.horigan@apha.gsi.gov.uk; Tel.: +44 02084152256; Fax: +44 01932 357445

Short Title: Probability of incursion of Lumpy skin disease virus into the United Kingdom

Introduction

The geographical expansion of animal diseases traditionally thought of as exotic to the European continent, for example, African swine fever (ASF), and lumpy skin disease (LSD), are causing increasing concern to European Union (EU) member states (MS). The steady movement of these diseases across European boundaries has required the EU to put surveillance activities and mitigation programmes in place to prevent further spread. Despite these preventive controls which significantly reduce the likelihood of spread, rare geographical random jumps of pathogens can, and do, occur with the consequence that introduction of an emerging disease into an EU MS may go undetected for a certain period of time during which silent spread could occur. This has been demonstrated with the 2006 Bluetongue virus (BTV) serotype 8 appearance in the Netherlands [1] and the 2016 diagnosis of besnoitiosis in Ireland [2, 3].

For the United Kingdom (UK), situated on the north western perimeter of Europe, national surveillance of emerging exotic diseases has been assisted by the predominantly east to west/south to north direction of spread allowing the progressive reporting of outbreaks in individual MSs to be monitored and continually reassessed. The data generated by these outbreaks can be used in risk assessments with particular emphasis on the probability of introduction from continental Europe to the UK [4]. The island status of the UK needs to be accounted for when assessing the probability of disease incursion with the surrounding water boundary likely to affect pathogen incursion via routes such as vector movements [4] and wild animals [5].

Lumpy skin disease came to particular prominence in 2016 as an exotic disease that emerged as a major threat to European cattle populations. It is a viral disease of cattle (*Bos indicus and B. taurus*) and water buffalo (*Bubalus bubalis*) and is categorised as a notifiable disease by the World Organisation for Animal health (OIE) [6]. The disease is present in most, if not all, African countries and is now considered endemic in Turkey [7]. Since 2012, LSD has spread from the Middle East to south east Europe, affecting EU MSs (Greece and Bulgaria) and several other countries in the Balkans. This spread has been rapid, possibly aided by civil unrest and the breakdown of veterinary services in countries such as Iraq and Syria [8]. Since 2015 in south east Europe there have been over 7,600 outbreaks with 12,800 affected animals [7]. Indirect production losses are incurred by control and eradication measures and restrictions/total ban of international trade of live cattle and their products.

Lumpy skin disease has never been reported in the UK but, given the current situation within the EU, assessing the probability of incursion is important to inform surveillance activities and national policy regarding risk mitigation. This qualitative assessment focuses on the probability of LSD virus (LSDV) introduction into the UK within the time period June 2017 to June 2018. The probability of onward transmission, were disease incursion to occur within the UK, was also assessed. Factors with high uncertainty were identified to emphasise their impact on the assessment conclusions and future research requirements.

Such research would assist risk assessors in making more robust conclusions for national preparedness and mitigation strategy prioritisation.

Material and Methods

Risk Questions:

The risk questions to be addressed were:

- *What is the probability of introduction of LSDV into the UK within the next year*?*
- *What is the probability of onward transmission of LSDV within the UK, should it be introduced within the next year*?*

**'within the next year' is here on in interpreted as being from 1st June 2017 to 1st June 2018*

Risk framework:

The approach used was based on the framework set out by the OIE [9]. The variables (i.e. probabilities and their associated uncertainties) are expressed qualitatively as negligible, very low, low, medium, high and very high [10, 11] and defined as: *negligible*, so rare that it does not merit to be considered; *very low*, very rare but cannot be excluded; *low*, event is rare but does occur; *medium*, event occurs regularly; *high*, event occurs very often; and *very high*, event occurs almost certainly.

Risk Pathway:

The risk pathway highlighting the potential routes of introduction of LSDV into the UK within the next year is shown in Figure 1. Disease introduction was defined as the presence of an LSDV positive vector or animal/animal product in the UK and included the probability of detection at post-import testing. Onward transmission to UK cattle, given introduction has occurred, is described in the second pathway (Figure 2) using the outputs from Figure 1 (infected live animals, contaminated animal products and infected vectors) as sources of LSDV. The primary routes of introduction and onward transmission considered were based on literature reviews and expert opinion.

The qualitative estimates for the combined probability of introduction ***and*** onward transmission for individual routes i.e. live animals, animal products and vectors were derived using a matrix approach as described previously [12].

Parameterisation

Data used to estimate the pathway probabilities are summarised in Table 1. Data used for these estimates can be found in the Appendix. An overview of the data required for each route is presented.

Live animals

This route considers animals in which LSDV infection has been documented i.e. domestic cattle and water buffalo. For completeness exotic wildlife such as African buffalo, wildebeest and impala are also assessed acknowledging the very limited detection of LSDV seropositive results in documented studies [13-15]. The probability that an infected live animal is consigned (i.e. intra-community trade) or exported (i.e. from outside the EU) to the UK was estimated from the number of animals arriving from each country of origin and the presence of LSDV infection in those countries. These data were then combined with the probability of the infected animal surviving the journey from its country of origin and the probability of it being detected at destination, depending on the incubation period, clinical infection and post-import test sensitivity. Countries for which post-import testing within the UK is required for compliance checks and those in which an LSD outbreak has been reported to the OIE for the years 2015 – 2016 are referred to as 'at risk' countries hereon in. Both illegal and legal trade were assessed. The final estimate is the probability that an infected animal enters the UK from any other country of origin.

The estimate of the probability that onward transmission of LSDV could occur within the UK from the introduction of an infected animal considers transmission via local competent vectors, directly via animal to animal or indirectly via fomites, iatrogenic, germplasm, feed or water (Figure 2). Onward transmission from an infected animal depends upon the animal remaining sub-clinically infected or differentially diagnosed whilst still being viraemic for a sufficient time period for transmission to occur. Duration of viraemia, percentage of sub-clinically infected animals and virus survival in the environment were, therefore, all considered.

In general, there are very few non-EU countries which are approved for the export of cattle to the European Union. The list of countries is in Regulation (EU) 206/2010 and includes Canada, Chile, Switzerland, Greenland, Iceland and New Zealand for bovidae. Otherwise, exotic ungulates may be moved between approved bodies (e.g. zoos and collections) only if they are risk assessed and suitable testing and quarantine procedures are in place.

Animal products

The probability that an LSDV infected product enters the UK from any affected country was estimated by combining the probabilities of an infected product being consigned or exported to the UK, survival time of the virus within the product and whether or not it would be detected at destination. The animal products considered were germplasm; hides and skins; meat and milk products. The assessment considers the presence of contamination in the product at source and any reduction in viral load which may occur during the time taken for travel to the UK including any processing effects. Both illegal and legal trade/ imports were assessed.

Onward transmission of LSDV from animal products was considered to be either via a native competent vector or using infected germplasm as the source. Data on UK vector competency and survival and transmissibility of LSDV in germplasm were used to estimate the probability.

Vectors

Whether or not an infected vector could be introduced to the UK would depend upon the type of vector and the environmental conditions. It is currently unknown which vectors are involved in transmission of LSDV and whether transmission is mechanical, biological or both. Because of this knowledge gap, high uncertainty surrounds how far vectors can travel e.g. different modes of transport could potentially be involved [16-18], and for how long virus can survive in/on the vector. It was assumed that only vectors in countries where infected cattle were reported, or in their bordering countries, were infected.

Onward transmission via a vector could be possible either through an incoming infected vector contacting susceptible UK cattle or a native competent vector contacting an infected animal or contaminated animal product. The probability was estimated using data on UK vector competence and UK cattle density.

Results

Probability of introduction

The probability of introduction of LSDV into the UK via each route considered was calculated by combining the relevant steps in the risk pathway (Figure 1) as described previously [12]. The probability was estimated to be very low for vectors and both illegal and legal trade of livestock, skins/hides and meat/milk products. All other routes were considered to have a negligible probability of introduction (Table 2).

No animals were consigned from ‘at risk’ countries (see Table 1) to the UK in the last 12 months. In order for the UK to legally trade an infected animal, the disease would need to have spread undetected into one of the UK’s trading partners and would, therefore, in all likelihood, be at a very low prevalence. The numbers of animals traded by the UK from the MSs concerned, were also relatively low (See Appendix). It is likely that the highest risk would be from breeding or production stock rather than slaughter animals as they would have a longer period of time to make further contacts with other live animals or vectors. Based on these considerations, the probability that an infected animal is legally consigned to the UK within the next year was considered to be very low. Although LSD has been endemic in Africa for decades no actual cases have been reported in wildlife and prevalence by antibody detection has been reported to be very low [13-15] suggesting that exotic animals (i.e. non-livestock) are unlikely to be important in the epidemiology of LSD. The import from third countries of such animals is covered by strict regulations under EU rules and the risk of introduction via the exotic animal route was thus estimated as negligible.

The probability that an infected animal survives the journey from the country of origin to the UK was considered to be high given the relatively low mortality rate but the probability that an infected animal is not detected on arrival was considered to be very low for ‘at risk’ countries due to the post-import testing regime in place. For animals consigned from non-risk countries the probability was assessed as medium assuming that only 50% of infected animals show clinical symptoms [19] and that no testing on arrival would occur.

No bovine germplasm (semen or embryos) were traded from ‘at risk’ countries during the year 2016. It is likely that once an LSD outbreak has been confirmed in a herd all animal products, including semen, would be destroyed. The probability of LSDV infected germplasm being legally consigned to the UK was therefore considered to be negligible. The probability of any virus surviving in semen was, however, estimated to be high as it was assumed that semen will be transported as frozen straws thereby preserving any virus within it [20].

For the year 2016 the number of intra EU imports of hides into the UK is not known as they are not recorded in TRACES, but instead rely on commercial documentation. Imports from third countries (i.e. those outside of the EU) were from Australia, China and the USA. The probability of untreated LSD infected animal hides or skins being legally exported to the UK from a third country was therefore considered to be very low. Untreated products consigned from within the EU must only originate from a country which is approved for the import of fresh or frozen meat or products for human consumption [21] and be destined for an approved processing plant within the EU. Otherwise, skins and hides must be processed in an EU approved establishment in the country of origin. Skin/hides are likely to be transported to the UK via trucks and ships with temperatures below 37^{o}C and in the dark; hence it is likely that little or no inactivation of the virus would occur during transport [22] particularly in those products which do not undergo specific inactivating treatment [19]. The probability of virus surviving in infected hides/skins was therefore assessed to be high but the probability of not being detected on import was considered to be low due to the identifiable nodules and scabs on the products.

Concerning milk and milk products, while there is some experimental evidence that conditions equivalent to the low temperature / long time pasteurisation method inactivate capripoxvirus (62^{o}C for 30 minutes) [23, 24] there is no available data on pasteurisation at 72^{o}C; furthermore, the presence of fat, protein and other solids in milk may protect the virus thereby decreasing the inactivation rate compared to that of virus in a laboratory buffer. There is therefore insufficient evidence on both the presence of virus in milk and whether pasteurisation inactivates LSD virus to a negligible level. However, the OIE code

[25] recommends that pasteurisation of milk or any combination of control measures with equivalent performance as described in the Codex Alimentarius Code of Hygienic Practice for Milk and Milk Products [26] is a suitable prerequisite to import of these products. There is no public health risk of LSD from meat products and therefore the trade in meat is not subject to risk management procedures. The probability of meat/milk products infected with LSDV being consigned to the UK was therefore considered to be very low with the probability of LSDV surviving in these products also assessed as very low assuming that all dairy products would be pasteurised for human consumption in accordance with the OIE recommendations. The probability of infected germplasm or meat and milk products not being detected on arrival was considered to be high as no physical signs of contamination will be evident and no post-import tests are currently carried out.

In order to estimate the probability of introduction of LSDV into the EU via the illegal movement of animals, the number of animals that need to be moved to have a probability of introduction of LSDV into Europe of greater than 0.95 was calculated to be above 1,300 (for country seroprevalence equal to 30%), or above 7,800 (for country seroprevalence equal to 5 %) i.e. a large and likely improbable number of animals [27]. The logistics and costs involved of illegally transporting cattle from mainland Europe to the UK is another mitigating factor against this event occurring. Contradicting this is the high chance of virus survival and the fact that no post-import testing would be carried out on illegally transported animals. As such the probability that an LSDV infected livestock animal is illegally transported to the UK was considered to be very low. The probability is reduced to negligible for exotic animals due to the assumption that non-livestock animals are not important in terms of LSDV transmission and do not act as a reservoir of disease.

For illegal products, the probability of infected germplasm being consigned to the UK was considered to be negligible due to the availability of cheap and health tested products legally available in the UK. The probability for meat and milk products was assessed as very low although it is unknown whether large scale consignments might occur or whether illegal trade or imports may only be occurring as goods for personal consumption. The probability of illegally importing untreated hides/skins was also estimated as very low. Although these products can be of high value, thereby increasing the likelihood of them being imported as a commodity for onward sale, it was assumed that hides spoiled by skin lesions would not be selected for export. The probability that animal products illegally consigned from the EU into the UK are not detected was assessed as high for germplasm and meat/milk products and medium for hides/skins. The latter has a slightly higher likelihood of being detected due to the size of the product and the probability that they will be shipped as bulk imports rather than personal imports. There are no checks carried out on passengers and trade products for intra EU trade.

The possibility of long term virus survival in vector populations cannot be excluded with certainty [28]. Vectors have been previously implicated in transboundary cases of LSD e.g. the first cases in Greece were suspected of coming from Turkey via vector movement [29]. However, these are neighbouring countries unlike the UK and mainland Europe which are separated by a ~ 33 km stretch of water. Modelling of LSDV transmission suggests that vector borne transmission is responsible for short distance transmission only [30]. For this reason the probability that an infected vector will reach the UK successfully within the next year was assessed as being very low.

Uncertainty associated with the probability of introduction of LSD virus into the UK

Qualitative uncertainty scores for the routes of introduction are shown in Table 3. The highest levels of uncertainty were associated with the introduction of LSDV via legal and illegal meat and milk products and via vectors. High uncertainty surrounds all of these estimates due to the lack of robust scientific evidence and lack of data on the numbers involved. The uncertainty associated with the vector route is high due to the unknown vector species involved (and therefore its associated mode of entry to the UK) and whether biological transmission or only mechanical transmission is involved which will influence virus survival on or within the vector.

A level of medium uncertainty was derived for the trade of infected livestock to the UK as the complete movement history of the animals is unknown and the time between disease incursion within a country and disease detection, which is dependent on the clinical signs and the methods of surveillance and post-import test sensitivity, was unknown and likely to be variable. During this window movement of potentially infected animals could occur. The uncertainty score for exotic animals, however, was considered to be very low due to the robust scientific data available on the very low levels of natural infection in this population.

The lack of data on the number of hides traded around the EU and undergoing different preservation treatments and the effect of those treatments on LSDV makes it difficult to estimate virus survival. An assessment of medium uncertainty for the virus surviving the journey on these products was therefore assumed. However, there was low uncertainty concerning the probability of not being detected on arrival as nodules and scabs are likely to be evident on the product thereby identifying infected items.

Uncertainty surrounding the probability that an LSDV infected livestock animal or exotic animal is illegally imported to the UK was considered to be low. Conversely, a high level of uncertainty was associated with the probability of animal products being illegally imported into the UK due to the unknown number of illegal consignments.

Probability of onward transmission

The probability of onward transmission of LSDV, assuming introduction to the UK, and the associated uncertainty for all of the assessed routes is shown in Table 4. The probability of direct animal to animal transmission was considered to be very low as the basic reproduction number (R_0) of this mode of transmission has been calculated to be 0.36 [30], i.e. infection is unlikely to be able to spread in a population. Studies have demonstrated direct transmission from infected animals to be inefficient with lack of spread from infected animals to naïve animals housed together [31]. Transmission of this type would also be dependent on a situation when high densities of cattle are in close contact e.g. communal grazing or cattle markets which have been associated with the occurrence of LSD. For exotic animals, there are very low numbers of seropositive animals reported in the literature [13-15] and serological positivity does not necessarily imply that the virus replicates in the animals and is excreted; thus, they may not be able to transmit the virus and represent an end-point for disease [27]. The probability of onward transmission of LSDV from exotic animals was therefore assessed as being negligible.

If infected cattle remain undetected, further iatrogenic spread may occur if unhygienic practices (e.g. use of contaminated hypodermic needles and surgical equipment) takes place [32]. It is assumed that in the UK good veterinary practice is undertaken for both herd wide testing and vaccination campaigns requiring the use of needles; the probability of iatrogenic transmission was therefore assumed to be very low.

For other live animal routes, only transmission of LSDV via semen has been demonstrated; disease itself was not transmitted [33]. The probability of onward transmission via germplasm was therefore assumed to be very low. The probability of onward transmission via fomites, food or water was assumed to be low due to the lack of evidence of this transmission occurring but acknowledging the potential of the virus to survive for long periods at ambient temperatures (for up to 6 months if protected from sunlight), and the fact it survives well at cold temperatures.

The probability of a competent vector contacting an LSDV infected skin/hide or meat product was considered to be negligible. Lumpy skin disease virus is considered to be transmitted mainly through haematophagus vectors which do not bite bloodless hides or skins; therefore, even if the virus on or in insufficiently treated hides was imported, further transmission would not take place [27]. Meat is not considered to be a significant risk for transmission for LSDV [28] and untreated hides/skins go straight to a designated processing plant for treatment; the transmission route between an infected meat product or hide/skin and a susceptible animal was considered unlikely [6].

The probability that a native vector would contact an LSDV infected animal was considered to be high depending on the competence of native vectors in the UK for transmitting the virus and the co-occurrence of such a vector and infected host. Whilst the competency of vectors in the UK is currently unknown the fact that the disease has moved steadily up from southern Africa through many different climatic zones involving potentially many different vectors suggests that it is also likely to be transmitted by vectors present in the UK. The probability of an infected vector contacting a susceptible host and initiating onward transmission was also assessed as high. Proximity to livestock, warm temperatures and vector abundance are among the main risk factors for LSD spread. The R_0 value induced by indirect transmission has been estimated at 15.7. Sensitivity analysis showed that this result was robust to a wide range of assumptions regarding mean and standard deviation of incubation period and regarding the existence of sub-clinically infected cattle [30]. This indirect transmission was assumed to be vector mediated and the efficiency of transmission of an infected vector to a naïve animal was therefore assumed to be high.

Uncertainty associated with the probability of onward transmission of LSD virus within the UK

Very little is known about the probability of transmission of LSDV via fomites, feed or water and, as such, uncertainty associated with this route of transmission is high. Transmission via these routes could occur under any situation when high densities of cattle come in close contact but in the natural setting it is difficult to differentiate this type of indirect transmission from vector mediated transmission within a herd. Similar high uncertainty was associated with onward transmission via direct animal to animal contact and germplasm due to lack of robust scientific evidence of natural transmission in the field and the need for more extensive experimental studies.

Regarding vector mediated routes, there is high uncertainty surrounding the ability of an incoming infected vector to initiate onward transmission due to lack of robust evidence on which vector species are involved in transmission and, therefore, what effect temperature and other environmental conditions would have upon efficiency of transmission. There was considered to be slightly less uncertainty (medium) about whether or not vectors native to the UK would be competent to transmit LSDV due to the speed with which LSD has moved geographically suggesting many different vectors are competent transmitters.

When the probabilities of introduction and onward transmission were combined [12], exotic animals, germplasm, hides/skins and meat/milk products were considered to have an overall negligible probability with regards to disease incursion (Table 5). For livestock and vectors the overall probability was considered to be very low as dictated by the very low probability of introduction into the UK despite the high probability of onward transmission should an introduction event occur. As stated previously, these probabilities are associated with often high uncertainty due to lack of robust scientific evidence.

Discussion

This risk assessment has estimated the probability of incursion into, and onward transmission of LSDV within, the UK. In doing so it has highlighted those knowledge gaps with significant impact on the uncertainty associated with the overall conclusions. Whilst the assessment was UK centric the knowledge gaps are generic and relevant to the uncertainty surrounding the probability of introduction and spread in any geographical region. Overall the probability of LSDV being introduced to the UK was considered, at most, to be very low for all routes with the exception of exotic animals and germplasm (negligible). The probability of onward transmission was considered highest for vector mediated routes either via contact of an infected vector with a susceptible cattle or contact of a competent native vector with infected cattle. The probability of onward transmission is, however, likely to be reduced once the first case of LSD has been detected if vaccination is undertaken. Risk-based vaccination, to avert the spread of the disease, may even be carried out in the UK if LSD is detected in mainland northern Europe as has recently been recommended with regard to countries that have not yet been affected by LSD but are considered at risk [34].

For the live animal import or trade route, it was considered that entry of disease would require infected animals entering the UK from a country which was currently not classed as ‘at risk’ and where no UK post-import testing for LSDV is required. Such countries would be those which had previously imported or consigned animals from an ‘at risk’ country or those that were in close enough proximity to infected countries whereby virus could have entered their cattle populations as a result of transboundary vector and/or cattle movements. Infection and exportation of an animal to the UK would rely on a series of events whereby infection goes undetected and the animal selected for export comes from the same herd (or neighbouring herd to allow for short distance vector transmission) which had previously imported an animal from an ‘at risk’ country. This very low risk is, however, likely to be mitigated by the regulated vaccination of cattle carried out by countries currently affected by LSDV and their neighbouring countries.

In the unlikely event that the disease spreads undetected into western continental Europe (to Germany or the Netherlands for example), the likelihood of consigning an infected animal into the UK from a country that is erroneously believed to be uninfected, could increase due to subclinical or incubation period infection. Using the European Food Safety Authority (EFSA) model, if seroprevalence of LSDV in the country of origin was 5%, but currently undetected, the import of 140 or 7,809 animals from that country would give a probability of introduction of 5% or 95% respectively. The highest number of cattle imported into the UK during 2016 was 4,074 from the Republic of Ireland (ROI). According to the same EFSA model, if seroprevalence of LSDV was 5% and undetected in the ROI then the probability of introduction into the UK would be ~ 75% using 2016 trade data [27]; this scenario is, however, extremely unlikely due to the control and prevention measures put in place by EU MSs.

Within the UK, preliminary outbreak assessments are undertaken by the Government on notification of a disease outbreak from the EU or OIE. These assessments indicate the threat of the disease incident at present and in the future and are used to inform the Governments’ advice and consideration of preventative controls. For LSD, however, medium to high uncertainty surrounds the probability of introduction to the UK via several of the routes assessed here. These are the initial stages of the risk pathway and therefore all assessments made consequential to these probabilities are underpinned by high uncertainty. Previous risk assessments have so far assumed 2 routes of spread, that is, direct and indirect but they can only assume that the more rapid local spread is vector borne and longer distance transmission is direct spread due to cattle movements [30, 35]. The accuracy of the calculation of R_0 for LSDV, i.e. the number of cases one infected case can generate over the course of its infectious period, could be greatly improved if the vectors involved in transmission were definitively identified. This would allow for vector abundance to be taken into account [36], the influence of the extrinsic incubation period (if any) [37] and the ratio of host to vector species when calculating R_0 [38].

This risk assessment acknowledges that the current understanding of the epidemiology of LSD and the potential pathways for the introduction and further dissemination has a number of limitations. Therefore, any inferences made have varying degrees of uncertainty which needs to be acknowledged. The key uncertainties associated with the transmission of LSDV have been summarised elsewhere [27], but how they impinge on risk assessment is highlighted here. The highest uncertainty was found to be associated with the current data available on vector species, transmission rates via all routes and illegal trade of animal products. The matrix method used here to calculate the probabilities of introduction and onward transmission dictates that the product of two probabilities is, at most, the minimum of the two values [12]. If, therefore, the lowest probability within a pathway has high uncertainty associated with it the overall probability calculated may be artificially skewed towards underestimation.

The results here show that for the period June 2017 to June 2018 the overall probability of introduction and onward transmission of LSDV to the UK is very low. However, perhaps of more value are the uncertainty estimates surrounding the probabilities of the pathway stages and on which research should be targeted to make conclusions more robust.

Acknowledgements: This work was funded by the Department for Environment, Food and Rural Affairs (Defra), the Scottish and Welsh Governments from the GB surveillance budget under project ED1043/5.

Table 1: Summary of data used to estimate probabilities of Lumpy skin disease virus introduction and onward transmission (see supplementary information for further details)

Data requirement	Estimate	Source
'At risk' countries (countries with an OIE reported LSD outbreak 2015 – 2016)	African continent countries, Albania, Armenia, Bahrain, Bulgaria, Former Republic of Macedonia, Georgia, Greece, Iran, Iraq, Kazakhstan, Kuwait, Montenegro, Oman, Russian Federation, Saudi Arabia, Samoa, Serbia, Turkey	Wahid (OIE)
Countries consigning cattle to UK	Austria, Belgium, Denmark, Finland, France, Germany, Italy, Luxembourg, Netherlands, Norway, Poland, Republic of Ireland, Spain, Switzerland	Traces
EU MSs which consign cattle from LSD affected countries	Austria, Belgium, Czech republic, Germany, Italy, Netherlands, Poland, Portugal, Spain	Eurostat
Livestock animals considered	Cattle; water buffalo	
Seroprevalence of LSDV in cattle	23% - 31% by virus neutralisation test	[39]
'At risk' countries: UK post-import testing required	Bulgaria, Croatia, Greece, Hungary, Romania, Slovakia, Slovenia	Animal and Plant Health Agency Operations manual
Import test used	Real time PCR	[40]
Import test sensitivity/specificity	63 DNA copies/100%	[40]

Mortality rate	0.4% - 10%	[25, 27]
Morbidity rate (intraherd)	10% - 50%	[7]
Incubation period	28 days	[25]
Duration of viraemia	1-12 days	[28]
Presence of clinical signs	50%	[19]
Seroprevalence of LSDV in exotic animals	0.69% by virus neutralisation test	[13-15]
Survival time of virus in semen	42 days (viral DNA 159 days) (longer if frozen)	[41]
Third countries which export germplasm to the UK	Australia; United States of America	Traces
Viral levels in skin lesions	8.1 – 8.3 $\log_{10}$ PFU/g	[42]
Survival time of virus in skins/hides	>18 days	[19]
Third countries which export hides/skins to the UK	Australia; China; USA	Traces
Survival time of virus in meat/milk products	Unknown	-
Vector species involved	Unknown	
Vector spread rate of LSDV	<10–15 km/week	[35]
Virus survival time in vector	2-6 days	[43, 44]
R_0 of direct animal to animal transmission	0.36	[30]
Environmental survival	6 months at ambient temperature	[27]
Virus susceptibility	No significant reduction at pH 6.6 - 8.6 for 5 days @ 37ºC	[27]
R_0 of indirect transmission (vector?)	15.7	[30]

Table 2: Probability of introduction of Lumpy skin disease virus into the United Kingdom within the next year (1st June 2017 to 1st June 2018) via animals /animal products and vectors

Probability	**Qualitative scores**					
Legal	**Livestock**	**Exotic animals**	**Germplasm**	**Hides/skins**	**Meat and milk products**	**Vector**
Probability consigned to the UK	Very low	Negligible	Negligible	Very Low	Very low	Very low
Probability infected animal/virus survives journey	High	High	High	High	Very low	Very low
Probability not detected on arrival	At risk country: Very low Non-risk country: Medium	Very low	High	Low	High	N/A
Probability of introduction of animal/animal product/vector infected with LSDV	Very low	Negligible	Negligible	Very Low	Very low	Very low
Illegal	**Livestock**	**Exotic animals**	**Germplasm**	**Hides/skins**	**Meat and milk products**	**Vector**
Probability consigned to the UK	Very low	Negligible (Low)	Negligible	Very Low	Very low	N/A
Probability infected animal/virus survives journey	High	High	High	High	Very low	N/A
Probability infected animal/product reaches UK undetected	Low	Low	High	Medium	High	N/A
Probability of introduction of animal/animal product infected with LSDV	Very low	Negligible	Negligible	Very Low	Very low	N/A

Table 3: Uncertainty surrounding the estimates for probability of introduction of Lumpy skin disease virus into the United Kingdom within the next year

Probability	**Uncertainty scores**					
Legal	**Livestock**	**Exotic animals**	**Germplasm**	**Hides/skins**	**Meat and milk products**	**Vector**
Probability consigned to the UK	Medium	Very low	Low	Medium	High	High
Probability infected animal/virus survives journey	Low	High	Medium	Medium	High	High
Probability not detected on arrival	At risk country: Very low Non-risk country: High	Very low	Low	Low	Low	N/A
Illegal	**Livestock**	**Exotic animals**	**Germplasm**	**Hides/skins**	**Meat and milk products**	**Vector**
Probability consigned to the UK	Low	Low	Very low	Medium	High	N/A
Probability infected animal/virus survives journey	Low	Medium	Medium	Medium	High	N/A
Probability infected animal/product reaches UK undetected	Medium	Medium	High	High	High	N/A

Table 4: Probability of onward transmission of Lumpy skin disease virus within the United Kingdom during the next year (June 2017 to June 2018) via animals /animal products and vectors

Probability	Qualitative score	Uncertainty
Live animal		
Direct animal to animal transmission	Very low	High
Iatrogenic transmission	Very low	Low
Transmission via fomites, feed or water	Low	High
Transmission via germplasm	Very low	High
Transmission via native competent vector biting infected animal	High	Medium
Animal product		
Transmission via competent vector biting animal product	Negligible	Very low
Transmission via germplasm	Very low	High
Vector		
Transmission via contact with susceptible host	High	High

Table 5: Overall risks for main routes of potential introduction and further onward transmission of Lumpy skin disease virus within the United Kingdom

Route	Probability of LSDV introduction	Probability of LSDV onward transmission	Overall probability
Livestock	Very low	High	Very low
Exotic animals	Negligible	Negligible	Negligible
Germplasm	Negligible	Very low	Negligible
Hides/skins	Very low	Negligible	Negligible
Meat and milk products	Very low	Negligible	Negligible
Vectors	Very low	High	Very low

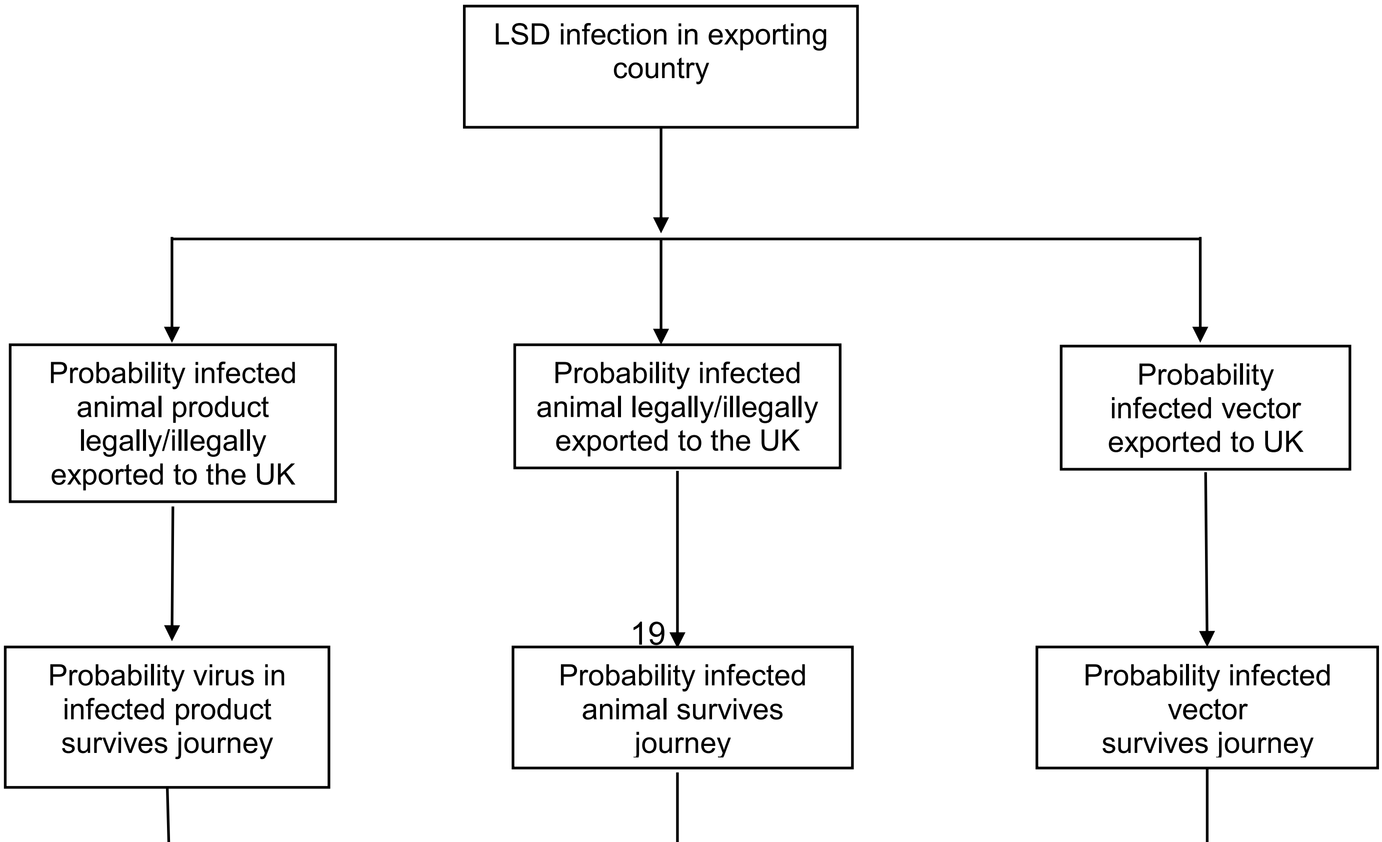
LSD infection in exporting country
Probability infected animal product legally/illegally exported to the UK
Probability infected animal legally/illegally exported to the UK
Probability infected vector exported to UK
Probability virus in infected product survives journey
Probability infected animal survives journey
Probability infected vector survives journey

Figure 1: Risk pathway for the probability of introduction of Lumpy skin disease virus into the United Kingdom within the next year. Exporting country here refers to both European Union and third countries.

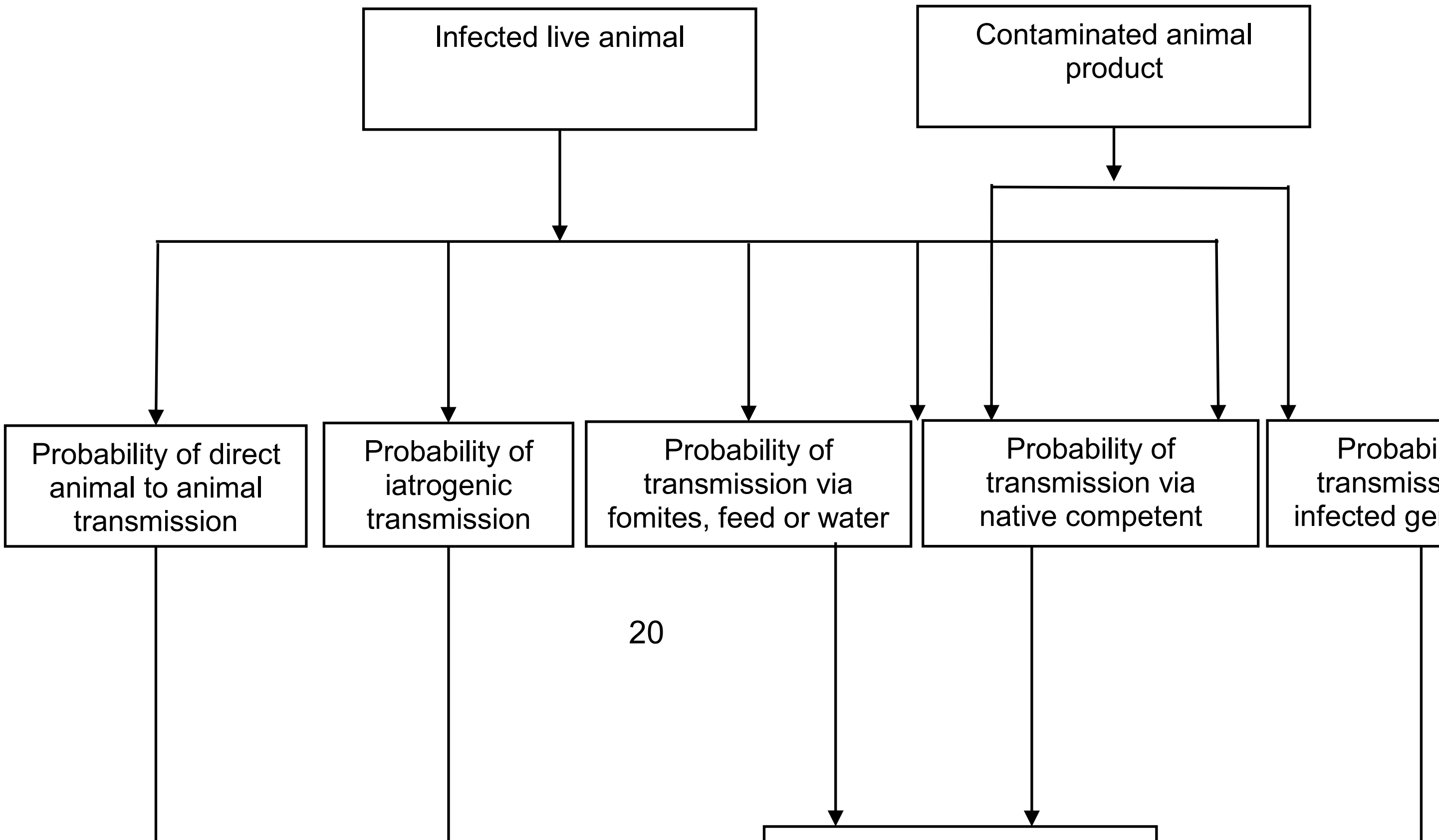

Figure 2: Risk pathway for the onward transmission of Lumpy skin disease virus should the disease enter the United Kingdom within the next year

References

1. EFSA, *Scientific Opinion of the Scientific Panel on Animal Health and Welfare on the EFSA Selfmandate on bluetongue origin and occurrence.* EFSA Journal, 2007. **480**: p. 1-20.

2. Ryan, E.G., et al., *Bovine besnoitiosis (Besnoitia besnoiti) in an Irish dairy herd.* Veterinary Record, 2016. **178**(24).

3. Alvarez-Garcia, G., *From the mainland to Ireland - bovine besnoitiosis and its spread in Europe.* Veterinary Record, 2016. **178**(24): p. 605-607.

4. Burgin, L.E., et al., *Investigating Incursions of Bluetongue Virus Using a Model of Long-Distance Culicoides Biting Midge Dispersal.* Transboundary and Emerging Diseases, 2013. **60**(3): p. 263-272.

5. Barun, A., D. Simberloff, and I. Budinski, *Impact of the small Indian mongoose on native amphibians and reptiles of the Adriatic islands, Croatia.* Animal Conservation, 2010. **13**(6): p. 549-555.

6. Tuppurainen E, *Lumpy Skin Disease.* FAO workshop report, 2015.

7. EFSA (European Food Safety Authority), *Scientific report on lumpy skin disease: I. Data collection and analysis.* EFSA Journal, 2017. **15**(4): p. 54.

8. Beard, P.M., *EDITORIAL Lumpy skin disease: a direct threat to Europe.* Veterinary Record, 2016. **178**(22): p. 557-558.

9. OIE, *Applying the OIE risk analysis framework.* Handbook on Import Risk Analysis for Animals and Animal Products. Volume 1, Introduction and qualitative risk analysis. Paris: World Organisation for Animal Health, 2004: p. 31-53.

10. EFSA, *Opinion “Migratory birds and their possible role in the spread of highly pathogenic avian influenza”.* EFSA Journal, 2006. **357**: p. 1-46.

11. FAO/WHO, *Risk characterisation of microbiological hazards in foods. Guidelines.* Microbiological Risk Assessment Series, No. 17., 2009.

12. Gale, P., et al., *Assessing the impact of climate change on vector-borne viruses in the EU through the elicitation of expert opinion.* Epidemiology and Infection, 2010. **138**(2): p. 214-225.

13. Fagbo, S., J.A.W. Coetzer, and E.H. Venter, *Seroprevalence of Rift Valley fever and lumpy skin disease in African buffalo (Syncerus caffer) in the Kruger National Park and Hluhluwe-iMfolozi Park, South Africa.* Journal of the South African Veterinary Association, 2014. **85**(1).

14. Hamblin C, A.E., Jago M, Mlengeya T, Hipji K., *Antibodies to some pathogenic agents in free-living wild species in Tanzania.* Epidemiol Infect, 1990. **105**(3): p. 585-94.

15. Hedger RS and Hamblin C, *Neutralising antibodies to lumpy skin disease virus in African wildlife.* Comp Immunol Microbiol Infect Dis, 1983. **6**: p. 209-213.

16. Tatem, A.J., D.J. Rogers, and S.I. Hay, *Estimating the malaria risk of African mosquito movement by air travel.* Malaria Journal, 2006. **5**.

17. Barre, N. and G. Uilenberg, *Spread of parasites transported with their hosts: case study of two species of cattle tick.* Revue Scientifique Et Technique-Office International Des Epizooties, 2010. **29**(1): p. 149-160.

18. Sedda, L., et al., *A new algorithm quantifies the roles of wind and midge flight activity in the bluetongue epizootic in northwest Europe.* Proceedings of the Royal Society B-Biological Sciences, 2012. **279**(1737): p. 2354-2362.

19. Weiss KE, *Lumpy skin disease.* Virology Monographs, 1968: p. 111-131.

20. Tuppurainen E, G.N., *LUMPY SKIN DISEASE: CURRENT SITUATION IN EUROPE AND NEIGHBOURING REGIONS AND NECESSARY CONTROL MEASURES TO HALT THE SPREAD IN SOUTH-EAST EUROPE.* OIE Regional Commission, 2016.

21. EU, *COMMISSION REGULATION (EU) No 142/2011.* 2011.

22. Gale P, K.L., Snary EL,, *Qualitative assessment of the entry of capripoxviruses into Great Britain from the European Union through importation of ruminant hides, skins and wool.* Microbial Risk Analysis, 2015.

23. Ferreira, C., *“Comportamento do virus da variola ovina sob a accao de alguns agentes fisicos e quimicos.” [Effects of physical and chemical agents on sheep pox virus]. .* Anais da Escola Superior de Medicina Veterinaria., 1973. **15**: p. 7-40.

24. Datta, S., Soman, JP,, *Host range and physiochemical characterization of ‘Ranchi’ strain of goat-pox virus.* Indian J. Anim. Sci, 1991. **61**(9): p. 955-957.

25. OIE, *Lumpy Skin Disease.* Terrestial Code Chapter 11.11, 2016.

26. FAO, *CODE OF HYGIENIC PRACTICE FOR MILK AND MILK PRODUCTS.* 2009.

27. EFSA AHAW Panel (EFSA Panel on Animal Health and Welfare), *Scientific Opinion on lumpy skin disease.* EFSA Journal, 2015. **13**(1): p. 73.

28. FAO, *Report of FAO Ad Hoc Group Meeting on Lumpy Skin Disease.* 2016.

29. DEFRA, *Lumpy Skin Disease in Greece Preliminary Outbreak Assessment.* 2015.

30. Magori-Cohen, R., et al., *Mathematical modelling and evaluation of the different routes of transmission of lumpy skin disease virus.* Veterinary Research, 2012. **43**.

31. Carn, V.M. and R.P. Kitching, *AN INVESTIGATION OF POSSIBLE ROUTES OF TRANSMISSION OF LUMPY SKIN-DISEASE VIRUS (NEETHLING).* Epidemiology and Infection, 1995. **114**(1): p. 219-226.

32. Darpel, K.E., et al., *Using shared needles for subcutaneous inoculation can transmit bluetongue virus mechanically between ruminant hosts.* Scientific Reports, 2016. **6**.

33. Annandale, C.H., et al., *Seminal Transmission of Lumpy Skin Disease Virus in Heifers.* Transboundary and Emerging Diseases, 2014. **61**(5): p. 443-448.

34. FAO, *Sustainable prevention, control and elimination of Lumpy Skin Disease - Eastern Europe and the Balkans. FAO Animal Production and Health Position Paper. No. 2. Rome, Italy. .* 2017.

35. Mercier A, A.E., Bournez L, Bronner A, Calavas D, Cauchard J, Falala S, Caufour P, Tisseuil C, Lefrançois T, Lancelot R.,, *Spread rate of lumpy skin disease in the Balkans, 2015-2016.* Transboundary and Emerging Diseases, 2017.

36. Hartemink, N.A., et al., *Mapping the basic reproduction number (R-0) for vector-borne diseases: A case study on bluetongue virus.* Epidemics, 2009. **1**(3): p. 153-161.

37. Brand, S.P.C., K.S. Rock, and M.J. Keeling, *The Interaction between Vector Life History and Short Vector Life in Vector-Borne Disease Transmission and Control.* Plos Computational Biology, 2016. **12**(4).

38. Turner, J., R.G. Bowers, and M. Baylis, *Two-Host, Two-Vector Basic Reproduction Ratio (R-0) for Bluetongue.* Plos One, 2013. **8**(1).

39. Gari, G., et al., *Lumpy skin disease in Ethiopia: Seroprevalence study across different agro-climate zones.* Acta Tropica, 2012. **123**(2): p. 101-106.

40. Stubbs, S., et al., *Validation of a high-throughput real-time polymerase chain reaction assay for the detection of capripoxviral DNA.* Journal of Virological Methods, 2012. **179**(2): p. 419-422.

41. Irons, P.C., E.S.M. Tuppurainen, and E.H. Venter, *Excretion of lumpy skin disease virus in bull semen.* Theriogenology, 2005. **63**(5): p. 1290-1297.

42. Babiuk, S., et al., *Quantification of lumpy skin disease virus following experimental infection in cattle.* Transboundary and Emerging Diseases, 2008. **55**(7): p. 299-307.

43. Chihota, C.M., et al., *Attempted mechanical transmission of lumpy skin disease virus by biting insects.* Medical and Veterinary Entomology, 2003. **17**(3): p. 294-300.

44. Chihota, C.M., et al., *Mechanical transmission of lumpy skin disease virus by Aedes aegypti (Diptera : Culicidae).* Epidemiology and Infection, 2001. **126**(2): p. 317-321.