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REVIEW

Reintroducing beavers *Castor fiber* to Britain: a disease risk analysis

Simon J. GIRLING* *Veterinary Department, Royal Zoological Society of Scotland, 134 Corstorphine Road, Edinburgh, EH12 6TS, UK. Email: sgirling@rzss.org.uk*
Adam NAYLOR *Veterinary Department, Royal Zoological Society of Scotland, 134 Corstorphine Road, Edinburgh, EH12 6TS, UK. Email: anaylor@rzss.org.uk*
Mary FRASER *G&F Training and Consultancy, Perthshire, PH2 9QD, UK. Email: mary.fraser7@btinternet.com*
Róisín CAMPBELL-PALMER *Edinburgh, EH7 6NH, UK. Email: rcampbellpalmer@gmail.com*

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*Correspondence author.

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ABSTRACT

1. Eurasian beavers *Castor fiber* are potential hosts for a range of infectious diseases and parasites, including those typical of common European rodents. A number of infectious organisms are potentially zoonotic and may be notifiable under animal health legislation. The official trial beaver reintroductions to Scotland, the retrospectively licensed releases in England, and the increasingly obvious presence of large numbers of unlicensed illegally released animals have highlighted potential disease risks.
2. We aimed to conduct a disease risk analysis, based on peer reviewed publications, for selection and health screening of Eurasian beavers prior to release into the wild in Britain.
3. Adapted from the International Union for the Conservation of Nature's 'Guidelines for Disease Risk Analysis', a four-step process was used to formulate a disease risk analysis: 1) problem description; 2) hazard identification based on literature review; 3) risk assessment, which resulted in categorisation of pathogens into low, medium, and high risk; and 4) risk management: identification of mitigating measures, followed by risk re-evaluation in light of the reported effectiveness of the mitigation measures.
4. The highest-risk pathogens identified in the literature review process included: parasites, specifically *Cryptosporidium parvum*, *Echinococcus multilocularis, Eimeria* spp., *Fasciola hepatica, Giardia* spp., *Trichinella britovi*; bacteria, specifically *Escherichia coli*, *Franciscella tularensis*, *Mycobacterium avium*, *Salmonella* spp., *Yersinia* spp.; a fungus *Chrysosporium parvum* (*Emmonsia parva*); and terrestrial rabies virus. Most could be mitigated by sourcing beavers from Britain. The rest could be mitigated by pre-release testing procedures that are already established.
5. The risk of introducing significant disease to humans, domestic animals, or wildlife by releasing into the wild in Britain a beaver that was captive-bred in Britain or a wild beaver from Scotland, based on the current evidence of disease incidence, and assuming the use of robust, peer reviewed, pre-release health screening techniques, can be viewed as low.

INTRODUCTION

Interventional conservation methods, such as translocations and reintroductions, have been increasingly employed to assist species' survival and ecosystem restoration (Seddon et al. 2014). Whilst there appears to be popular support for the concept of wildlife reintroductions, it is important to recognise that the way in which these reintroductions have taken place has been varied, in terms of method and legality. The International Union for Conservation of Nature's (IUCN) 'Guidelines for Reintroductions and Other Conservation Translocations' and 'Guidelines for Wildlife

Disease Risk Analysis' were developed to facilitate and improve the success and long-term acceptance of reintroductions, and are widely accepted to be effective codes for best practice (IUCN/SSC 2013, 2014).

The importance of animal health in conservation programmes is increasingly recognised, as the success of any reintroduction can be significantly reduced by infectious disease (Viggers et al. 1993, Ewen et al. 2015). Despite this recognition, the implementation and development of pre-reintroduction and post-release veterinary health programmes (i.e. disease risk analyses and disease surveillance programs, respectively) tends to receive less investment than other aspects of release projects, such as genetic management (Jamieson & Lacy 2012). Pre-reintroduction and post-release health assessments are recommended, as translocated animals can potentially introduce new pathogens into the release area (Cunningham 1996, Kock et al. 2010).

Driven to virtual extinction throughout Eurasia by the fur trade in the 19th century, the Eurasian beaver *Castor fiber* now once again inhabits large tracts of its native range, as a result of the cessation of hunting, natural expansion from relict populations and proactive translocation projects (Nolet & Rosell 1998, Halley et al. 2012). In over 26 countries in Eurasia there have been more than 200 beaver release projects, the histories of which are complicated and often lacking in documentation (Macdonald et al. 1995, Nolet & Rosell 1998, Halley & Rosell 2002, Halley 2011, Halley et al. 2012). Few projects have well-documented health surveillance, disease, and mortality figures, with Nolet et al. (1997) an exception.

From a health and biosecurity perspective, beavers have historically been considered to present no greater risk to human, livestock, or other wildlife health than any other native mammal. However, the identification of the zoonotic parasite *Echinococcus multilocularis* in England in a wild-caught captive beaver directly imported from Bavaria (Barlow et al. 2011) and, more recently, a beaver testing positive for the parasite at pre-release screening (B. Gottstein, personal communication) illustrates the risk of introducing non-native parasites and diseases. Although intended for conservation purposes, poorly managed beaver releases could result in serious health risks and have significant consequences, not only for human and animal health, but also for public support of future reintroduction projects.

Beaver reintroduction to Britain (mainland England, Scotland and Wales), where historic evidence of Eurasian beavers is apparent, has not been without its controversies, and health risks seem to have attracted particular concerns. Reintroduction of the Eurasian beaver is currently being actively considered in all countries of Britain. A trial reintroduction, the Scottish Beaver Trial, was carried out in Knapdale, Argyll, from 2010 to 2015. This was the first official reintroduction of a mammal species to Britain in modern history. Despite recommendations for a more comprehensive process of restoration, the return of the beaver to Britain has been a haphazard affair, highlighted by the presence of sizeable populations (113 active territories; Campbell-Palmer et al. 2018) of beavers from unlicensed releases along the Rivers Tay and Earn catchment areas in Scotland, as well as pockets of smaller family groups in England (e.g. the River Otter, Devon).

Disease risk analysis is a rigorous method used to evaluate whether important health-related risks are associated with a proposed activity, such as the translocation of wild animals (Leighton 2002). As part of any responsible reintroduction programme or trial, pre- and post-release health assessments are essential to ensure that health and welfare legislation is complied with.

In order to assess the quantitative level of risk associated with the reintroduction of the Eurasian beaver to Britain, a disease risk analysis was performed. We aimed to combine historic literature on diseases of the Eurasian beaver with more recent literature resulting from disease screening as part of the trial reintroduction of beavers to Scotland and surveillance of beaver populations elsewhere in Britain. The end-goal of the disease risk analysis was to provide efficient and cost-effective disease prevention and mitigation strategies for future reintroductions. The framework we used follows the IUCN's 'Guidelines for Wildlife Disease Risk Analysis' (IUCN/SSC 2014).

METHODS

Following the IUCN's 'Guidelines for Disease Risk Analysis', a four-step process to formulate the disease risk analysis was carried out (IUCN/SSC 2014).

Step 1: problem description

During the official reintroduction of beavers to the wild in Scotland (the Scottish Beaver Trial), knowledge of which infectious diseases can affect and be transmitted by beavers was significantly expanded, but this information has still not been fully elucidated (Goodman et al. 2012, Campbell-Palmer et al. 2015b, c, d, Goodman et al. 2017). Ongoing concerns over possible inadvertent introduction of infectious diseases, including zoonoses that may adversely affect domestic animals and wildlife, have led to a slow-down on further reintroductions in the UK (Barlow et al 2011, Goodman et al. 2017). The identification and quantification of risks associated with these diseases have been highlighted by central and devolved governments in the UK as vital to a pre-release

disease risk analysis, following the IUCN's 'Guidelines for Disease Risk Analysis' (DEFRA 2012, IUCN/SSC 2014).

Step 2: hazard identification based on literature review

In an attempt to identify all the infectious disease hazards associated with a beaver reintroduction, a literature search on reported disease in captive and wild beavers was performed with the use of CAB ABSTRACTS, BIOSIS, and MEDLINE databases (Woodford 2000, Goodman et al. 2012). The literature search was focussed on the Eurasian beaver, but also took into account diseases reported in North American beavers *Castor canadensis* and other semi-aquatic and terrestrial rodents (Order Rodentia), with an emphasis on those in the northern hemisphere and Europe. This was done in order to cover those diseases which theoretically may occur in the Eurasian beaver but which have yet to be reported. To ensure coverage of the widest range of potential pathogens within the risk assessment process, we reviewed just over 700 papers.

Step 3: risk assessment

For each identified hazard, a qualitative risk assessment was determined, based on available scientific literature, so as to allow ranking of hazards into low-, medium-, and high-risk bands (OIE 2012, IUCN/SSC 2014). Each hazard was assessed using the following criteria (see Table 1):

1. Hazard severity – assessed by the severity of the disease caused (from subclinical to fatal) in beavers, wildlife, domestic animals or humans, and the degree of medical intervention required.
2. Likelihood of occurrence – assessed on the likelihood of recrudescence of subclinical disease and the introduction of a novel pathogen, based on whether the pathogen had previously been reported in *Castor fiber* (very likely), *Castor canadensis* (likely) or other semi-aquatic/related northern hemisphere rodent species (possible), and in all other rodent species (unlikely).

After assignment of hazard severity and likelihood of occurrence scores, these values are multiplied together to obtain the risk band (see Table 1).

Step 4: risk management

For any hazard severity assessed by the above process and ranked as low, no further risk management was carried out and the overall risk was considered low. For all other hazards, risk management strategies were assessed (see Tables 2-6). Management strategies to prevent the introduction of pathogens included identification of diagnostic testing methods which could produce a high degree of sensitivity and specificity (>85%), allowing the exclusion of infected beavers from release. The presence of the pathogen in Britain was also considered at this stage, in order to assess the possible impact of inadvertent pathogen release. If the hazard could be effectively excluded through diagnostic testing and/or the pathogen is already widespread in Britain, then the post-management risk was considered to be low (see Tables 2-6).

Table 1. In the risk assessment, scores on a scale of 1–5 for the likelihood of occurrence (top row) and for the hazard severity (left column) were multiplied to give the overall hazard severity score, on a scale of 1–25, as shown in the table. Risk bands for pre-management strategy were allocated to the overall score as follows: 1–8: low risk, 9–12: medium risk, 13–25: high risk

	Likelihood of occurrence →				
↓ Hazard severity	1. Remote (almost never)	2. Unlikely (occurs rarely)	3. Possible (could occur, uncommon)	4. Likely (recurrent occurrence episodes)	5. Very likely (occurs frequently)
1. Trivial (subclinical or no treatment required)	1	2	3	4	5
2. Minor (minor discomfort, basic first aid only)	2	4	6	8	10
3. Moderate (short-term treatment)	3	6	9	12	15
4. Serious (supportive feeding, intensive treatment)	4	8	12	16	20
5. Fatal (single or multiple)	5	10	15	20	25

Table 2. Summarised disease risk assessment for haemo- and endoparasites in beavers for translocation. The table is laid out to take into consideration risk factors for each pathogen, such as: whether the pathogen has been reported in Eurasian beavers, North American beavers or other rodents (i.e. a decreasing risk scale); whether the pathogen is zoonotic; whether the pathogen has been associated with domestic animal or other wildlife disease and so may have other serious implications if introduced; and whether the pathogen is already present in Britain. If the risk assessment band is then considered low, no further risk management strategy is considered. If the risk assessment band is considered medium or high, suggestions for risk management strategies are given based on peer-reviewed publications to convert the risk band post-management strategy to low. See the text for details of specific pathogens, and Table 1 for the categorisation of risk bands for pre-management strategy.

Pathogen	Reported in *Castor fiber?*	Reported in *Castor canadensis?*	Reported in other rodents?	Zoonosis?	Wildlife or domestic animal impact?	Risk band pre-management strategy	Present in Britain?	Risk management strategies	Risk band post-management strategy
Anaplasma phagocytophilum	No	No	Low prevalence or absence in rodents (Wiger 1979, Healing 1981). Field voles *Microtus agrestis* main reservoir in Britain (Bown et al. 2003)	Yes	Yes	LOW (score 3)	Yes	None	LOW
Babesia microti, Babesia divergens	No	No	*Babesia microti* common in North American rodents and less common in Northern Europe. *Babesia divergens* more common in Europe (Bown et al. 2008)	Yes	Yes	MEDIUM (score 12)	Yes	Blood smear assessment and PCR (Wilson et al. 2015, Tolkacz et al. 2017)	LOW
Bartonella spp.	No	No	Reported in wild rodents (Birtles et al. 2001) including water voles *Arvicola terrestris* (Oliver et al. 2009)	Yes	No	MEDIUM (score 9)	Yes	Blood smear assessment and PCR (Morick et al. 2009)	LOW
Haemobartonella (Mycoplasma) spp.	No	No	Infection rates of 77% in Polish common voles *Microtus arvalis* and 63% in bank voles *Myodes glareolus* (Bajer et al. 2001, Pawelczyk et al. 2004)	No	No	LOW (score 6)	Yes	Blood smear assessment and PCR (Goncalves et al. 2015)	LOW
Hepatozoon spp.	No	No	Commonly seen in Muridae; found in circulating leucocytes and body organs (Yarto-Jaramillo 2015)	No	No	LOW (score 2)	Yes	Blood smear assessment and PCR (Rigo et al. 2016)	LOW

(Continues)

Table 2. (Continued)

Pathogen	Reported in *Castor fiber?*	Reported in *Castor canadensis?*	Reported in other rodents?	Zoonosis?	Wildlife or domestic animal impact?	Risk band pre-management strategy	Present in Britain?	Risk management strategies	Risk band post-management strategy
Trypanosoma spp.	No	No	Reported in South American rodents; *Trypanosoma lainsoni* in spiny tree rat *Mesomys hispidus* (Naiff & Barrett 2013), *Trypanosoma cruzi* and *Trypanosoma rangeli* in *Aegialomys, Akodon, Cavia, Mus, Rattus, Rhipidomys, Sciurus, Handleyomys, Hoplomys, Proechimys,* and *Transandinomys* (Ocano-Mayorga et al. 2015)	No	Yes	LOW (score 2)	Yes	Blood smear assessment and PCR (Ortiz et al. 2018)	LOW
Calodium (Capillaria) hepatica	Reported in the wild in Russia and in captivity in Russia and Hungary (Fuehrer 2014b)	Reported in the wild in Columbia and USA (Fuehrer 2014b)	Common in Muroidea (Fuehrer, 2014a)	Yes	No	LOW (score 5)	Yes	Use wild or captive-bred beavers from Britain as source population. PCR testing and endoscopic examination of the liver	LOW
Coccidiosis (*Eimeria, Isospora* spp.)	Reported in one young beaver (Goodman et al. 2012)	No	Common in many rodents but host-specific and generally subclinical infections (Yarto-Jaramillo 2015)	No	No	HIGH (score 15)	Yes	Faecal parasitology	LOW
Cryptosporidium spp.	Infection reported in Poland (Bajer et al. 1997) and UK (Goodman et al. 2012)	Infection reported in North America (Isaac-Renton et al. 1987)	Common in rodent species, such as *Cryptosporidium muris* in mice and *Cryptosporidium wrairii* in guinea pigs *Cavia porcellus*, not thought to be zoonotic (Bajer et al. 1997)	Yes (*Cryptosporidium parvum*)	Yes	HIGH (score 15)	Yes	Faecal parasitology (+/– acid fast staining) or real-time PCR	LOW
Cysticercosis or coenuriasis	Found during a survey of Scottish beavers (Campbell-Palmer et al. 2015a)	No	Rodents are intermediate hosts for many tapeworms; carnivores (e.g. domestic cat, dog) are the definitive host (Yarto-Jaramillo 2015)	No	Yes	LOW (score 5)	Yes	None	LOW

(Continues)

Table 2. (Continued)

Pathogen	Reported in *Castor fiber?*	Reported in *Castor canadensis?*	Reported in other rodents?	Zoonosis?	Wildlife or domestic animal impact?	Risk band pre-management strategy	Present in Britain?	Risk management strategies	Risk band post-management strategy
Echinococcus multilocularis	Found in a captive animal in England imported from the wild in Bavaria, Germany (Barlow et al. 2011)	No	Reported in field and water voles; common in specific areas of Europe e.g. Bavaria, Germany (Miller et al. 2016)	Yes	Yes	HIGH (score 20)	No (except captive beaver reported by Barlow et al. 2011)	Use wild or captive-bred beavers from Britain as source population, or carry out testing protocol (Gottstein et al. 2014, Campbell-Palmer et al. 2015a)	LOW
Enterocytozoon bieneusi	No	No - negative results in 16 beavers tested (Guo et al. 2014)	Positive in 21 of 49 Sciuridae and 17 of 71 Cricetidae in a study in New York State (Guo et al. 2014)	Yes	Yes	LOW (score 4)	No	None	LOW
Fasciola hepatica	Found in 2 of 20 beavers (Shimalov & Shimalov 2000)	No	Recorded in coypu *Myocastor coypus* (Dracz et al. 2016)	Yes	Yes	HIGH (score 15)	Yes	Faecal parasitology	LOW
Giardia spp.	Yes – incidence 0–8% in the wild in Poland (Bajer et al. 2008); not detected in post-introduction site monitoring (Mackie 2014)	Prevalence 7–16% (Erlandsen et al. 1990)	Common in rodent species (Olsen & Buret 2001)	Yes	Yes	HIGH (score 15)	Yes	Faecal parasitology	LOW
Rodentolepis (Hymenolepis) nana	No	No	Common in Muridae and Cricetidae (Yarto-Jaramillo 2015)	Yes	No	LOW (score 4)	Yes	Faecal parasitology	LOW

(Continues)

Table 2. (Continued)

Pathogen	Reported in *Castor fiber?*	Reported in *Castor canadensis?*	Reported in other rodents?	Zoonosis?	Wildlife or domestic animal impact?	Risk band pre-management strategy	Present in Britain?	Risk management strategies	Risk band post-management strategy
Stichorchis subtriquetrus	Yes (Goodman et al. 2012, Campbell-Palmer et al. 2013, Máca et al. 2015)	No	No	No	No	LOW (score 5)	Yes	None	LOW
Travassosius rufus	Prevalence 82% in Czech Rep. (Máca et al. 2015), 93% in Polish beavers (Drózdz et al. 2004)	No	No	No	No	MEDIUM (score 10)	No	Faecal parasitology	LOW
Trichinella britovi	Found in one beaver in Latvia (Seglina et al. 2015)	*Trichinella spiralis* (Russia, Romašov 1969) and *Trichinella nativa* (Dick & Pozio 2001) reported in North American beavers	Yes – rats in particular; brown rat *Rattus norvegicus* and black rat *Rattus rattus* (Dick & Pozio 2001)	Yes – requires digestion of raw beaver meat	Yes	HIGH (score 15)	No	Use wild or captive-bred beavers from Britain as source population	LOW

RESULTS

Results of the hazard identification, risk assessment, and risk management steps in the disease risk analysis are shown in Tables 2-6.

Haemoparasites

As can be seen from Table 2, no haemoparasites have been reported in beavers, leading to low risk bands for all hazards (Cross et al. 2012).

Endoparasites

As can be seen from Table 2, the highest-ranking endoparasite hazard is *Echinococcus multilocularis*, a zoonotic parasite of serious health concern that is regarded as one of the most pathogenic parasitic zoonoses in the northern hemisphere (Eckert et al. 2000, Vuitton et al. 2003). Although it is established in many countries in central Europe, other European countries are presently deemed free of this parasite, including the UK, which employs strict measures to prevent entry (DEFRA 2012). *Echinococcus multilocularis* has been identified in Eurasian beavers from Switzerland, Austria, Serbia and, more recently, in a captive imported beaver in England (Janovsky et al. 2002, Cronstedt-Fell et al. 2010, Barlow et al. 2011, Ćirović et al. 2012, Wimmershoff et al. 2012). Diagnosis of *Echinococcus multilocularis* in intermediate (non-egg-shedding) hosts such as beavers has historically been via post-mortem examination. Campbell-Palmer et al. (2015a) found that laparoscopic examination combined with ultrasound investigation for real-time diagnosis of *Echinococcus multilocularis* in beavers would allow the direct rapid identification of any abdominal lesions. Additionally, submission of blood samples for immunoblotting can be undertaken to identify early cases, raising combined test sensitivity to 85% (Gottstein et al. 2014). It is possible to reduce the risk from a low level to a negligible level by sourcing beavers for British introductions from pre-existing British (predominantly Scottish) free-ranging beaver populations that have been shown to be free of infection, or to use beavers that were captive-bred in the UK (DEFRA 2012, Campbell-Palmer et al. 2015d).

Other endoparasites are either considered non-pathogenic and host-specific (e.g. *Stichorchis subtriquetrus*) or are found at a low level and may easily be detected by pre-release faecal screening (e.g. *Fasciola hepatica*, *Cryptosporidium parvum*, *Giardia* spp.), making their risk band for post-management strategy low.

Ectoparasites

As can be seen from Table 3, no ectoparasite has been associated with significant pathogenicity in Eurasian beavers, and all ectoparasites are easily screened for in a pre-release examination, making all risk bands for post-management strategy low.

Bacterial pathogens

As can be seen from Table 4, the most significant bacterial pathogen from a zoonotic aspect is *Franciscella tularensis*, which is not found in Britain and has only been reported sporadically in Eurasian beavers (Mörner 1992, Schulze et al. 2016). The use of Eurasian beavers that were either captive-bred or wild-born in Britain as a source population would therefore reduce the risk for this pathogen to low (Mörner 1992, Schulze et al. 2016).

Leptospira spp. have been reported regularly in rodents and at a low level in beavers. Leptospirosis has been associated with *Yersinia* spp. infections and mortalities in Eurasian beavers in one introduction, although whether leptospirosis or yersiniosis was the cause of the mortalities was unclear (Nolet et al. 1997). In beavers tested in Britain, infection was identified but appeared not to be associated with clinical disease (Goodman et al. 2012, Campbell-Palmer et al. 2015b, 2015d). Based on these reports, it is theoretically possible that beavers could pose a potential source of *Leptospira* spp. infection to other animals, post-release, but persistent carrier status has yet to be demonstrated and seropositivity levels were considered low. This, combined with the ubiquitous nature of *Leptospira* spp. in Britain, makes the risk of leptospirosis associated with Eurasian beaver reintroduction low.

Salmonella spp. have been reported from Eurasian beavers in continental Europe, but not currently from beavers anywhere in Scotland (Romasov 1992, Rosell et al. 2001, Goodman et al. 2012, Campbell-Palmer et al. 2015d). Pre-release screening (by faecal culture) and/or using beavers from a captive-bred or Scottish source reduces the risk for post-management strategy for *Salmonella* spp.

Other bacterial potential pathogens that have resulted in the occasionally reported death of Eurasian beavers include strains of *Escherichia coli*, *Yersinia pseudotuberculosis*, *Yersinia enterocolitica*, and *Mycobacterium avium*. Pathogens that have been reported in rodent species other than beavers and which are potential risks to wildlife and humans include *Erysipelothrix rhusiopathiae*, *Brucella* spp. and *Listeria monocytogenes*. All of these pathogens have been reported in Britain, and all may be screened for in live beavers through faecal culture, polymerase chain reaction (PCR) or acid-fast staining, meaning any risk for post-management strategy is low.

Table 3. Summarised disease risk assessment for ectoparasites in beavers for translocation. The table is laid out to take into consideration risk factors for each pathogen, such as: whether the pathogen has been reported in Eurasian beavers, North American beavers or other rodents (i.e. a decreasing risk scale); whether the pathogen is zoonotic; whether the pathogen has been associated with domestic animal or other wildlife disease and so may have other serious implications if introduced; and whether the pathogen is already present in Britain. If the risk assessment band is then considered low, no further risk management strategy is considered. If the risk assessment band is considered medium or high, suggestions for risk management strategies are given based on peer-reviewed publications to convert the risk band post-management strategy to low. See the text for details of specific pathogens, and Table 1 for the categorisation of risk bands for pre-management strategy.

Pathogen	Reported in *Castor fiber*?	Reported in *Castor canadensis*?	Reported in other rodents?	Zoonosis?	Wildlife or domestic animal impact?	Risk pre-management strategy	Present in Britain?	Risk management strategies	Risk post-management strategy
Ixodes spp.	Reported on beavers in the Scottish Beaver Trial (Goodman et al. 2012)	Animal infection 30%, lodge bedding infection 34% (Lawrence et al. 1956)	Yes (Barandika et al., 2007, Bown et al. 2008, Silaghi et al. 2012)	Yes	Yes	MEDIUM (score 10)	Yes (Barandika et al. 2007, Silaghi et al. 2012)	Pelage examination	LOW
Platypsyllus castoris	Common throughout range. Found on Scottish-born beavers (Duff et al. 2013)	Yes (Peck 2006)	No	No	No	LOW (score 5)	No	None	LOW
Leptinillus validus and *Leptinillus testaceus*	Additional Platypsyllinae species found in *Castor canadensis*, present in *Castor fiber* only where the species overlap (Peck 2006, 2007)	Yes (Peck 2007)	No	No	No	LOW (score 4)	No	None	LOW

Table 4. Summarised disease risk assessment for bacterial pathogens in beavers for translocation. The table is laid out to take into consideration risk factors for each pathogen, such as: whether the pathogen has been reported in Eurasian beavers, North American beavers or other rodents (i.e. a decreasing risk scale); whether the pathogen is zoonotic; whether the pathogen has been associated with domestic animal or other wildlife disease and so may have other serious implications if introduced; and whether the pathogen is already present in Britain. If the risk assessment band is then considered low, no further risk management strategy is considered. If the risk assessment band is considered medium or high, suggestions for risk management strategies are given based on peer-reviewed publications to convert the risk band post-management strategy to low. See the text for details of specific pathogens, and Table 1 for the categorisation of risk bands for pre-management strategy.

Pathogen	Reported in *Castor fiber?*	Reported in *Castor canadensis?*	Reported in other rodents?	Zoonosis?	Wildlife or domestic animal impact?	Risk pre-management strategy	Present in Britain?	Risk management strategies	Risk post-management strategy
Aeromonas hydrophila	No	Part of 'normal' conjunctival flora (Cullen 2003)	Opportunist pathogenicity, carrier status without disease (Lye 2009)	Yes	Yes	LOW (score 4)	Yes	None	LOW
Arcanobacterium pyogenes	Isolated in a deceased beaver but unsure if direct cause of death (Goodman et al. 2012)	No	Occasionally reported (Yarto-Jaramillo 2015)	Yes	Yes	MEDIUM (score 15)	Yes	Faecal bacterial culture	LOW
Brucella spp.	No	No (Moore & Schnurrenberger 1981)	Detected in capybara *Hydrochoerus hydrochaeris* (Lord & Flores 1983)	Yes	Yes	MEDIUM (score 12)	Yes	Serological testing	LOW
Campylobacter spp.	No	No	Reported in guinea pigs bred for food in South America (Graham et al. 2016). 4% incidence of *Campylobacter jejuni* by culture in wild rodents (Backhans et al. 2013)	Yes	Yes	LOW (score 6)	Yes	None	LOW

(Continues)

Table 4. (Continued)

Pathogen	Reported in *Castor fiber?*	Reported in *Castor canadensis?*	Reported in other rodents?	Zoonosis?	Wildlife or domestic animal impact?	Risk pre-management strategy	Present in Britain?	Risk management strategies	Risk post-management strategy
Chlamydia-like organisms	No	No	Low incidence in small mammals (Stephan et al. 2014)	No	No (rodent strains not thought to be significant zoonosis; Longbottom & Coulter 2003)	LOW (score 8)	Yes	None	LOW
Clostridium piliforme (Tyzzer's disease)	No	No	Common in captive rodents, particularly Cricetidae, in the presence of stressors (Yarto-Jaramillo 2015)	No	Yes	LOW (score 8)	Yes	None	LOW
Clostridium sordelli	No	Reported in one animal without disease (Cullen 2003)	No – natural infections not reported (Yarto-Jaramillo 2015)	No	Yes	LOW (score 4)	Yes	None	LOW
Enterobacter spp.	No	Reported in one animal without disease (Cullen 2003)	No – not reported as a pathogen (Yarto-Jaramillo 2015)	No	No	LOW (score 4)	Yes	None	LOW
Erysipelothrix rhusiopathiae	No	No	Reported in coypu *Myocastor coypus* (Kohler et al. 1987) and other rodents particularly mice (Yarto-Jaramillo 2015)	Yes	Yes	MEDIUM (score 12)	Yes	Faecal bacterial culture	LOW
Escherichia coli	Isolated in a deceased young beaver during quarantine for Scottish Beaver Trial (Goodman et al. 2012)	Commonly identified but no enteropathogenic strains reported (Wong et al. 2016)	Commonly encountered enteric bacteria in rodents - enteropathogenic strains have only been reported as part of experimental studies (Yarto-Jaramillo 2015)	Yes	Yes	HIGH (score 25)	Yes	Faecal bacterial culture	LOW

(Continues)

Table 4. (Continued)

Pathogen	Reported in *Castor fiber?*	Reported in *Castor canadensis?*	Reported in other rodents?	Zoonosis?	Wildlife or domestic animal impact?	Risk pre-management strategy	Present in Britain?	Risk management strategies	Risk post-management strategy
Franciscella tularensis	Sporadic reports in the wild (Schulze et al. 2016)	Considered a reservoir for type B form (Mörner 1992)	Reported in musk rats *Ondatra zibethicus* in North America, ground voles *Arvicola terrestris* in Russia (Mörner 1992), and voles in general (Koskela et al. 2016)	Yes	Yes	HIGH (score 25)	No	Use wild or captive-bred beavers from Britain as source population	LOW
Lawsonia intracellularis	No	No	Reported in domestic Cricetidae (Fiskett 2011)	No	Yes	LOW (score 8)	Yes	None	LOW
Leptospira spp.	Present in Scottish beavers and cause of translocation mortalities (Nolet et al. 1997, Goodman et al. 2012, 2017, Marreros et al. 2018)	Yes (Lopez-Perez et al. 2017)	Widely reported in captive and wild rodents (Yarto-Jaramillo 2015, Gelling et al. 2015)	Yes	Yes	HIGH (score 20)	Yes	Serological testing	LOW
Listeria monocytogenes	No	No	Widely reported in rodents (Yarto-Jaramillo 2015)	Yes	Yes	MEDIUM (score 10)	Yes	Faecal bacterial culture	LOW
Micrococcus spp.	No	Common isolate from North American conjunctival specimens (Cullen 2003)	Not reported as a pathogen (Yarto-Jaramillo 2015)	No	No	LOW (score 4)	Yes	None	LOW

(Continues)

Table 4. (Continued)

Pathogen	Reported in *Castor fiber?*	Reported in *Castor canadensis?*	Reported in other rodents?	Zoonosis?	Wildlife or domestic animal impact?	Risk pre-management strategy	Present in Britain?	Risk management strategies	Risk post-management strategy
Mycobacterium avium subspecies *avium*	Single dead beaver during a Netherlands beaver reintroduction project (Nolet et al. 1997)	No	Occasional reports in immuno-compromised individuals (Yarto-Jaramillo 2015)	No (unless immuno-compromised; Christ et al. 2016)	No unless immuno-compromised	HIGH (score 25)	Yes	Acid fast staining of faeces or faecal real-time PCR	LOW
Mycobacterium avium subspecies *paratuberculosis* (Johne's disease)	No	No	No	Yes	Yes	LOW (score 4)	Yes	None	LOW
Mycobacterium tuberculosis complex (including *Mycobacterium microti* and *Mycobacterium bovis*)	No	No	*Mycobacterium microti* in wild rodent populations (Cavanagh et al. 2002, McClure 2012), *Mycobacterium bovis* in south American capybara (*Hydrochoerus hydrochaeris*; Mol et al. 2016)	Yes – NB: *Mycobacterium microti* only reported in immuno-suppressed humans (Niemann et al. 2000, Horstkotte et al. 2001)	Yes	LOW (score 6)	Yes	None	LOW
Mycoplasma spp.	No	No	Common in captive rodents, particularly *Mycoplasma pulmonis* in Muridae (Yarto-Jaramillo 2015), also in wild voles (Koskela et al. 2016)	No (murine strains not thought to be zoonotic (Piasecki et al. 2017)	Yes	LOW (score 8)	Yes	None	LOW
Pasteurella spp. (*Pasteurella multocida* and *Mannheimia haemolytica*)	No	No	Common in captive rodents. *Pasteurella multocida* gains access through wounds or respiratory tract (Yarto-Jaramillo 2015)	No	Yes	LOW (score 8)	Yes	None	LOW

(Continues)

Table 4. (Continued)

Pathogen	Reported in *Castor fiber?*	Reported in *Castor canadensis?*	Reported in other rodents?	Zoonosis?	Wildlife or domestic animal impact?	Risk pre-management strategy	Present in Britain?	Risk management strategies	Risk post-management strategy
Peptostreptococcus spp.	No	Reported in one beaver without disease (Cullen 2003)	Not reported as a pathogen (Yarto-Jaramillo 2015)	No	No	LOW (score 4)	Yes	None	LOW
Pseudomonas spp.	No	Reported in one beaver without disease (Cullen 2003)	Occasional opportunistic pathogen (Yarto-Jaramillo 2015)	No	No	LOW (score 4)	Yes	None	LOW
Rickettsia spp.	No	No	*Rickettsia akari* reported in house mice in N. America and *Rickettsia typhi* reported in rats; neither in Britain or northern Europe (Yarto-Jaramillo 2015)	Yes	No	LOW (score 8)	No	None	LOW
Salmonella spp.	*Salmonella* spp. have been identified in wild beavers in Norway (Rosell et al. 2001), Germany and Russia (Romasov 1992) but not speciated	No	Common in Muridae and Cricetidae. *Salmonella enterica* serotype *typhimurium, Salmonella enteritidis* and *Salmonella typhimurium* are common in these taxa (Yarto-Jaramillo 2015)	Yes	Yes	HIGH (score 20)	Yes	Faecal bacterial culture and/or use Scottish-born animals as source population (Campbell-Palmer et al. 2015d)	LOW
Staphylococcus spp.	No	Reported in 3/10 beavers without clinical disease (Cullen 2003)	Occasional reports of lung disease and skin disease in rodents have been recorded (Yarto-Jaramillo 2015)	No	No	LOW (score 4)	Yes	None	LOW

(Continues)

Table 4. (Continued)

Pathogen	Reported in *Castor fiber?*	Reported in *Castor canadensis?*	Reported in other rodents?	Zoonosis?	Wildlife or domestic animal impact?	Risk pre-management strategy	Present in Britain?	Risk management strategies	Risk post-management strategy
Streptobacillus moniliformis	No	No	Host is the brown rat, reported in domestic mice, gerbils and squirrels (Yarto-Jaramillo 2015)	Yes	No	LOW (score 8)	Yes	None	LOW
Streptococcus spp.	No	Reported in one beaver (Cullen 2003)	Common in captive rodents, particularly *Streptococcus zooepidemicus,* causes lymph node abscessation and lung disease (Yarto-Jaramillo 2015)	Yes	Yes	LOW (score 4)	Yes	None	LOW
Yersinia spp.	*Yersinia enterocolitica* in 17% of wild beavers in Poland (Platt-Samoraj et al. 2015) *Yersinia enterocolitica* and *Yersinia pseudotuberculosis* isolated as post-release cause of mortality (Nolett et al. 1997)	*Yersinia pseudotuberulosis* was the cause of mortality in one beaver in Washington State (Gaydos et al. 2009)	All strains commonly reported in rodents, which are significant reservoirs of *Yersinia* spp. (Yarto-Jaramillo 2015)	Yes	Yes	HIGH (score 25)	Yes	Faecal bacterial culture	LOW

Fungal pathogens

As can be seen from Table 5, no fungal organism has been associated with significant pathogenicity in Eurasian beavers with the exception of *Chrysosporium parvum* (now known as *Emmonsia parva*), which has been reported as the cause of death due to pneumonia in one animal in Sweden (Mörner et al. 1999). The organism is a ubiquitous soil-associated occasional pathogen and is found in Britain. The straightforward detection of infection (significant respiratory disease expected) and ubiquitous presence in Britain makes the risk for post-management strategy low.

Viral pathogens

As can be seen from Table 6, no viral pathogen present in Britain has been associated with significant pathogenicity in Eurasian beavers. Therefore, ensuring that beavers used for British reintroductions have been bred in Britain should reduce the risk for post-management strategy to low.

DISCUSSION

As with all translocations, the reintroduction of the Eurasian beaver to Britain should show close adherence to Office International des Epizooties and IUCN guidelines on the quarantine and health screening of animals prior to importation (Woodford 2000). Beavers directly imported from mainland Europe without robust health screening may present a risk for introduction to Britain of non-native diseases and parasites, namely *Echinococcus multilocularis*, rabies, tularaemia, or specific parasites. Though this can be mitigated through pre-planned sourcing from particular regions deemed free from these pathogens, using British captive-bred stock or beavers from the wild in Scotland is a simple and effective means to reduce any risk to low or negligible.

It is possible that, following release, beavers may acquire common wildlife diseases and parasites already present in Britain (such as leptospirosis and giardiasis; Gaywood 2015). It is difficult to ascertain whether this would actually increase current transmission rates to other wild animals, domestic livestock, or humans, particularly given the ecology and behaviour of beavers. There has been no evidence to suggest that beaver reintroduction to Scotland has presented any additional health risks (Campbell-Palmer et al. 2015a, 2015b, 2015c, 2015d). Testing of British feral beavers (from unknown origins) for a range of parasites and diseases has found no evidence of any pathogens that may cause an increased risk to human, livestock, or other wildlife health (Campbell-Palmer et al. 2015a, 2015b, 2015c, 2015d). This mirrors findings by Rosell et al. (2001) in the Telemark region of Norway.

The presence of species-specific parasites (e.g. *Stichorchis subtrequetrus* and *Travassosuis rufus*) may not produce clinical signs in beavers at low infection levels. However, at high levels of endoparasitism, these parasites may lead to debilitation and, if combined with physiological stress associated with a translocation or reintroduction, may lead to increased mortality rates in beavers post-release.

Pre-release health management and screening recommendations

Attempts at previous disease screening protocols for beavers in Britain had been developed (Goodman et al. 2012). These protocols were applied to beavers released in the official Scottish Beaver Trial prior to their release. They were also applied retrospectively to feral beavers currently present on the River Tay and Earn catchment (Scotland) and on the River Otter (England), under license by Scottish and UK Governments (Goodman et al. 2012, Campbell-Palmer et al. 2015d). These protocols incorporate recommendations for reintroductions and translocations of wildlife by the Office International des Epizooties and World Conservation Union (Woodford 2000). In addition, a number of other diagnostic tests were undertaken to address specific concerns raised by various stakeholders, particularly relating to livestock diseases, including Johne's disease (*Mycobacterium avium* subspecies *paratuberculosis*) and bovine tuberculosis (*Mycobacterium bovis*). All findings have been published (Goodman et al. 2012, Campbell-Palmer et al. 2015a, b, c, d, Goodman et al. 2017).

Any pre-release assessment should include a veterinary clinical examination, including an assessment of body condition (Campbell-Palmer & Rosell 2015). Blood sampling is recommended from the ventral tail vein for assessment of organ function and evidence of immune system responses to disease (Girling et al. 2015). Blood smear assessment for the presence or absence of haemoparasites should also be carried out. Standard parasitology screening should be undertaken on faecal samples taken directly from the beaver's rectum. Faecal samples should undergo flotation with saturated salt solution for the identification of nematodes, coccidia and *Giardia* spp., and sedimentation techniques should be used to assess for trematode eggs (*Fasciola* and *Stichorchis* spp.). Direct microscopy enhanced by modified or acid-fast stains is preferred to identify *Cryptosporidium* spp. Standard microbiological culture for bacterial enteric pathogens, including *Salmonella*, *Campylobacter,* and *Yersinia* spp. are also useful based on European isolates, although no evidence of these pathogens has so far been found in beavers in the wild in Britain (Goodman et al. 2012, Campbell-Palmer et al. 2015b, d, Goodman et al. 2017).

Table 5. Summarised disease risk assessment for fungal pathogens in beavers for translocation. The table is laid out to take into consideration risk factors for each pathogen such as: whether the pathogen has been reported in Eurasian beavers, North American beavers or other rodents (i.e. a decreasing risk scale); whether the pathogen is zoonotic; whether the pathogen has been associated with domestic animal or other wildlife disease and so may have other serious implications if introduced; and whether the pathogen is already present in Britain. If the risk assessment band is then considered low, no further risk management strategy is considered. If the risk assessment band is considered medium or high, suggestions for risk management strategies are given based on peer-reviewed publications to convert the risk band post-management strategy to low. See the text for details of specific pathogens, and Table 1 for the categorisation of risk bands for pre-management strategy.

Pathogen	Reported in *Castor fiber?*	Reported in *Castor canadensis?*	Reported in other rodents?	Zoonosis?	Wildlife or domestic animal impact?	Risk pre-management strategy	Present in Britain?	Risk management strategies	Risk post-management strategy
Blastomycosis	No	No - associated with the environment but does not cause infection or disease (Klein et al. 1986)	Reported in juvenile mice in particular areas e.g. southern USA (Yarto-Jaramillo 2015)	Yes	No	LOW (score 6)	No	None	LOW
Candida albicans	Cutaneous candidiasis (Saez 1976)	No	Occasional reports; usually enteric, after antibiotic treatment (Yarto-Jaramillo 2015)	No	No	MEDIUM (score 10)	Yes	If giving antibiotics, faecal culture. Physical examination for cutaneous candidiasis +/– culture of lesions	LOW
Chrysosporium parvum (Emmonsia parva) and *Emmonsia crescens*	Found in a wild adult female in Sweden (*Emmonsia parva*; Mörner et al. 1999)	Yes (Erickson 1949)	Reported in several rodent species, including wood mice *Apodemus* sp., voles *Microtus* sp., and water shrews *Neomys fodiens* (Dvorak et al. 1965, Jellison 1981)	No	Yes (wildlife semi-fossorial species – considered an environmental pathogen; Bormann et al. 2009)	HIGH (score 15)	Yes	Veterinary clinical examination for signs of respiratory disease and bronchioalveolar lavage if suspected	LOW
Histoplasma capsulatum (histoplasmosis)	No	No	A few reports in chinchillas *Chinchilla laniger* and brown rats in the USA (Yarto-Jaramillo 2015)	No	No	LOW (score 6)	No	None	LOW

(Continues)

Table 5. (Continued)

Pathogen	Reported in *Castor fiber*?	Reported in *Castor canadensis*?	Reported in other rodents?	Zoonosis?	Wildlife or domestic animal impact?	Risk pre-management strategy	Present in Britain?	Risk management strategies	Risk post-management strategy
Ringworm (*Trichophyton mentagrophytes*, *Microsporum canis*, *Microsporum gypseum*, *Epidermophyton* spp.)	No	No	Common in pet rodents, often asymptomatic (Yarto-Jaramillo 2015)	Yes	Yes	LOW (score 6)	Yes	None	LOW

Echinococcus multilocularis infection of Eurasian beavers has caused considerable interest in the UK, where this pathogen does not currently exist in the wild. We recommend that, although testing using a combination of laparoscopy, ultrasound examination and serology (anti-beaver IgG immunoblotting) has an 85% sensitivity, it may be preferable to source beavers from the wild in Scotland or to use British captive-bred animals for British reintroductions, as these animals would not have been exposed to the infectious agent (egg sachets passed in the faeces of a carnivore; Gottstein et al. 2014, Campbell-Palmer et al. 2015a, 2015d).

Testing for Johne's disease was requested by the Tayside Beaver Study Groups' National Farmers' Union of Scotland representative, and has been performed by means of modified acid-fast staining of faecal smears and PCR testing (Scottish Agricultural College Consulting Veterinary Services, Scotland's Rural College). No evidence exists currently of the ability of Eurasian beavers to act as either a carrier or paratenic host to this pathogen and no evidence of the disease has so far been found in beavers in Britain (Campbell-Palmer et al. 2015a, 2015c, 2015d). For *Mycobacterium bovis* testing, a bronchoalveolar lavage can be performed. This has been carried out in the past in Britain, at the request of stakeholders, although the disease has not been reported in beavers. Our assessment, based on the available literature, ranks the risk of transmission of *Mycobacterium bovis* as low.

Post-release health monitoring recommendations

The level of post-release health monitoring should reflect the assessed level of risk. As recommended in the IUCN's 'Guidelines for Reintroductions and Other Conservation Translocations' and 'Guidelines for Wildlife Disease Risk Analysis', there should be a level of assessment to determine to what extent an establishing population is experiencing disease, adverse welfare conditions or mortality (IUCN/SSC 2013, 2014). Should any beavers be found dead, full post-mortems and collection of samples from the body (including samples for histopathology, microbiology, endoparasitology, and ectoparasitology) for further diagnostic testing should always be carried out. Any evidence of wildlife or domestic animal disease in release areas related to those pathogens previously associated with beavers should be fully investigated.

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Table 6. Summarised disease risk assessment for viral pathogens. The table is laid out to take into consideration risk factors for each pathogen, such as: whether the pathogen has been reported in Eurasian beavers, North American beavers or other rodents (i.e. a decreasing risk scale); whether the pathogen is zoonotic; whether the pathogen has been associated with domestic animal or other wildlife disease and so may have other serious implications if introduced; and whether the pathogen is already present in Britain. If the risk assessment band is then considered low, no further risk management strategy is considered. If the risk assessment band is considered medium or high, suggestions for risk management strategies are given based on peer-reviewed publications to convert the risk band post-management strategy to low. See the text for details of specific pathogens, and Table 1 for the categorisation of risk bands for pre-management strategy.

Pathogen	Reported in *Castor fiber?*	Reported in *Castor canadensis?*	Reported in other rodents?	Zoonosis?	Wildlife or domestic animal impact?	Risk pre-management strategy	Present in Britain?	Risk management strategies	Risk post-management strategy
Cowpox virus	No	No	Common in voles in Britain (Robinson & Kerr 2001)	No	Yes	LOW (score 4)	Yes	None	LOW
Encephalo-myocarditis virus	No	No	Level of 9% on real-time PCR detection of tissues in wild rodents in Sweden (Muridae and Cricetidae; Backhans et al. 2013)	Yes	Yes	LOW (score 6)	No	None	LOW
Hantavirus	No (Girling et al. 2019)	No	Reported in the Britain in Muridae (brown rat, bank vole; McElhinney et al. 2016, Bennett et al. 2010)	Yes – a low-risk pathogen to humans (Thomson et al. 2001)	Yes	LOW (score 8)	Yes	None	LOW
Lymphocytic choriomeningitis virus	No	No	Worldwide distribution. Causes chronic wasting disease in juvenile hamsters. Common in domestic mice (Yarto-Jaramillo 2015)	Yes	No	LOW (score 8)	Yes	None	LOW
Monkeypox virus	No	No	Prairie dogs *Cynomys* spp. and Gambian pouched rats *Cricetomys gambianus* (Falendysz et al. 2014, 2016)	Yes	Yes	MEDIUM (score 10)	No	Use wild or captive-bred beavers from Britain as source population	LOW
Omsk haemorrhagic fever virus	No	No	Found in Siberia (water voles and non-native muskrat *Ondatra zibetheca*; Mills & Childs 2001, Yarto-Jaramillo 2015)	Yes	No	MEDIUM (score 12)	No	Use wild or captive-bred beavers from Britain as source population	LOW
Rabies terrestrial	No	No (Krebs et al. 2002)	Yes – but not present in the UK	Yes	Yes	HIGH (score 15)	No	Use wild or captive-bred beavers from Britain as source population	LOW
Sendai virus (Para-influenzavirus 1)	No	No	Common in captive rodents (Muridae and Cricetidae; Yarto-Jaramillo 2015)	No	No	LOW (score 2)	Yes	None	LOW

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