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Cost-effectiveness of alternative disease management policies for Bacterial kidney disease in Atlantic salmon aquaculture

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ABSTRACT

Bacterial kidney disease (BKD) is a systemic infectious disorder of the Salmonidae associated with increased mortality in Atlantic salmon a necessary cause of which is infection with *Renibacterium salmoninarum*. The cost-effectiveness of various possible national management policies to control this disease is investigated. It is concluded that the control of BKD is cost-effective, and that a policy of limiting the spread of *R. salmoninarum* through the detection of BKD-affected sites, the imposition of movement restrictions on these, and the requirement to eradicate *R. salmoninarum* before movement restrictions are lifted, is economically more beneficial for this disease than alternative policies of increased or reduced stringency.

1. Introduction

Bacterial kidney disease (BKD) is a systemic (Belding and Merrill, 1935) infectious (Ordal and Earp, 1956) disorder of the Salmonidae (Sanders and Fryer, 1980) a necessary cause of which is infection with a gram-positive diplobacillus (Ordal and Earp, 1956) named *Renibacterium salmoninarum* (Sanders and Fryer, 1980); a review of the disease is available (Wiens, 2011). Substantial mortalities on Atlantic salmon production sites with BKD have been reported (Murray et al., 2012b) and the cost of the disease, although not quantified, has been described as being potentially substantial (Bruno, 1986; Munro, 2007; Wiens, 2011).

Bacterial kidney disease was listed as notifiable internationally (World Organisation for Animal Health, 2003) and continues to be notifiable under the national legislation of several states. For example BKD was first declared notifiable throughout the UK in 1978 (Diseases of Fish Order, 1978) and the minimum control-measures consistent with current legislation applying to Scotland (Aquatic Animal Health (Scotland) Regulations, 2009) include the visual inspection of production sites (hereafter referred to as sites) for clinical signs of BKD and diagnostic testing for *R. salmoninarum* to confirm suspected outbreaks. The current disease management policy (hereafter referred to as a policy), which exceeds this minimum, is intended to limit the spread of *R. salmoninarum* and includes movement restrictions on infected sites, the visual inspection of sites in recent epidemiological contact with confirmed disease, and the requirement to eradicate *R. salmoninarum* from a site before movement restrictions are lifted. Marine Atlantic salmon sites also carry out site-level fallowing of not less than 4 weeks between production cycles (pc) usually synchronously with neighbouring sites (Code of Good Practice Management Group, 2010). Previous policies, such as that in place between 2004 and 2010, have additionally included active surveillance for *R. salmoninarum* (Munro, 2007) although this is unlikely to have significantly contributed to detection rates (Hall et al., in press).

Existing and previous policies have failed to eradicate BKD from Scottish aquaculture although, for Atlantic salmon, it is likely that they helped to keep it at a low prevalence (Murray et al., 2012b). It was therefore decided to evaluate whether the current policy is beneficial relative to alternative hypothetical policies and whether it can be modified to further reduce and ideally eradicate BKD. The policies are likely to be associated with different costs and it is in terms of cost-effectiveness, rather than epidemiological-effectiveness, that the policies are assessed.

2. Materials and methods

An influence diagram (Howard and Matheson, 1984) illustrating the conceptual model underlying the analysis is presented in Fig. 1. The

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Abbreviations: BKD, Bacterial kidney disease; D, sites with BKD; HOG, head-on-gutted; EBIT, operational earnings before interest and tax kg^{-1} HOG; GBP, Great Britain pounds; IHN, Infectious haematopoietic necrosis; ISA, Infectious salmon anaemia; K, sites with a known asymptomatic infection of *R. salmoninarum*; M, mean harvest mass; NOK, Norwegian kroner; P, price of HOG Atlantic salmon kg^{-1}; pc, production cycle; PI, percentile interval; U, sites with an undetected asymptomatic infection of *R. salmoninarum*; UK, United Kingdom; T, number of days following the start of each pc; VHS, Viral haemorrhagic septicaemia; Y, calendar year.

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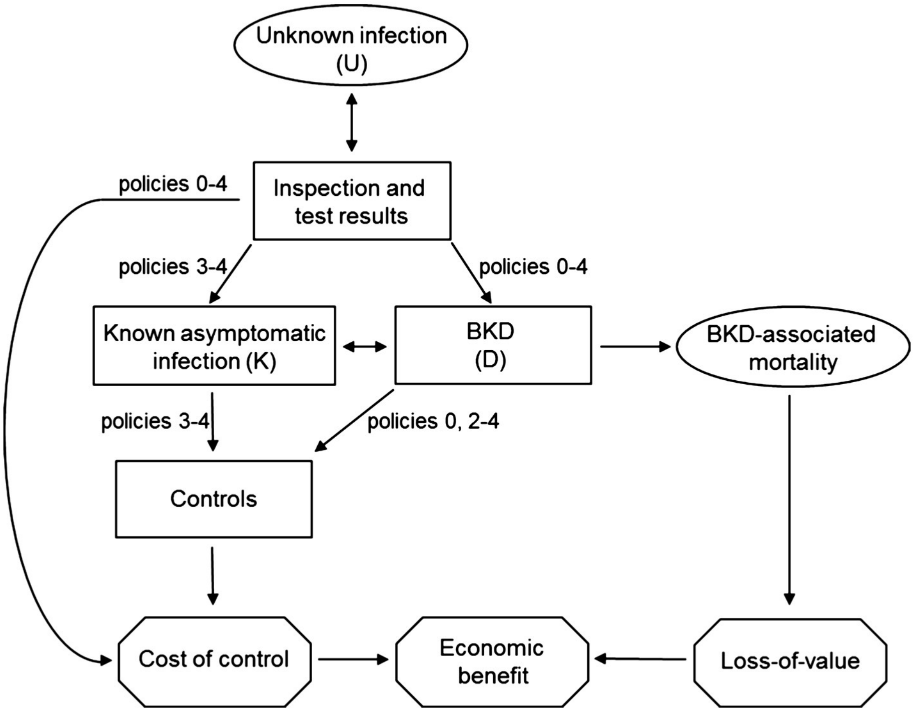

Fig. 1. Influence diagram of conceptual model for each policy. Ovals represent uncertainty nodes, rectangles decision nodes and octagons value nodes. Bracketed characters (U, K, D) are the epidemiological site infection-status assignments and numbers (0–4) the policies. The net economic benefit was calculated as the difference between the economic benefit of a hypothetical policy (1–4) and the reference policy (0).

term 'BKD' is used hereafter to denote clinical disease caused by *R. salmoninarum* and 'infection' the presence of viable *R. salmoninarum* with or without associated clinical symptoms.

Four hypothetical but practicable policies were developed. These range from a minimally stringent policy of detecting BKD with no subsequent controls to a maximally stringent policy of detecting infection at low prevalence with subsequent control. The hypothetical policies comprise, in order of increasing stringency, the detection of BKD and no control (policy 1); the detection and control of BKD (2) and the detection and control of infection at moderate or low prevalence (3 and 4 respectively). The current policy of detecting BKD and controlling infection (0) is used as a reference to which the hypothetical policies are compared. The policies are summarised in Table 1 with further details available in the supplementary information.

A previously published (Murray et al., 2011) epidemiological susceptible–infected model was used to provide steady-state predictions of the proportion of marine sites in production experiencing an undetected or known asymptomatic infection (denoted U and K respectively) or BKD (D) at a point in time for each policy. Calculations were performed using code given by Murray et al. (2011, 2012a) and the parameter values are presented in Table 2. The model is deterministic and variation to outputs was introduced by carrying out 1000 simulations parameterised using different initial values of U (Table 2). Additional variation was introduced for each simulation by estimating the number of K- and D-sites per 100 sites in production from binomial distributions using the proportions of K- or D-sites predicted by the model. Subsequent modelling assumes that once infected with *R. salmoninarum* a site will remain so until the pathogen is eradicated at the end of the pc.

Table 1
Summary of policies.

Measure[a]	Policy[b]			
	0	1	2	3–4
a. Intelligence-led inspection for BKD	✓	✓	✓	✓
b. Systematic inspection for BKD	✓	✓	✓	✓
c. Confirmatory testing for suspected BKD	✓	✓	✓	✓
d. Systematic testing for infection				✓
e. Temporary imposition of movement restrictions	✓		✓	✓
f. Confirmation of movement restrictions	✓		✓	✓
g. Contact tracing	✓		✓	✓
h. Inspection for post clinical disease status	✓			✓
i. Removal of confirmed movement restrictions	✓		✓	✓

[a] Site-level fallowing between pc is included for all policies as a standard practice of Atlantic salmon production.

[b] 0 = reference comprising detection of BKD and control of infection, 1 = detection of BKD and no control; 2 = detection and control of BKD; 3 = detection and control of infection at moderate prevalence; and 4 = detection and control of infection at low prevalence.

Resource wastage due to mortality from BKD is assumed to be the only cause of on-site losses of value (Fig. 1). Mortalities ascribed to BKD (hereafter referred to as BKD-associated mortalities) in a Scottish commercial Atlantic salmon production database (Kilburn et al., 2012) were enumerated for the seven recorded marine pc affected by BKD between 2003 and 2007. The affected pc were on different sites and were characterised by a median harvest-weight biomass of 2316 tonnes (with 95 percentile interval (PI) of 658 and 2496 tonnes). All seven sites were operating under official controls for *R. salmoninarum* and positive culture and/or enzyme-linked immunosorbent assay results for the pathogen had been obtained by the regulatory authority during the pc for six of these. Experimental data indicate high diagnostic specificities ($\geq$99.9%) for both tests (Hall et al., in press) although the diagnostic sensitivities are likely to be suboptimal. The identification of BKD as the cause of mortalities was made following clinical evaluation by site managers and, for larger events, investigations by veterinarians. Other mortalities on the sites were ascribed within the database to suspected Infectious pancreatic necrosis and Pancreas disease with confirmations by the regulatory authority of the presence of *Infectious pancreatic necrosis virus*, *Costia* spp., *Vibrio* spp. and *Pasteurella* spp. on at least some of the sites. The capitalised harvest weight of each BKD-associated mortality at the nearest subsequent presumptive harvest at 12, 18 or 24 months following the start of the pc was estimated using a linear model (Searle, 1971) of the association between the mean harvest

Table 2
Parameter values for epidemiological model.

Policy	Parameter[a,b]			
	β_k	β_d	q	Initial U
0	0	4.0×10^{-2}	0	Random values[c]
1	2.0×10^{-1}	2.4×10^{-1}	0	
2	2.0×10^{-1}	4.0×10^{-2}	0	
3	0	4.0×10^{-2}	2.0×10^{-3}	
4	0	4.0×10^{-2}	2.0×10^{-2}	

[a] Values for unlisted model parameters have been given previously (Murray et al., 2011).

[b] β_k = transmission coefficient from a K site, β_d = transmission coefficient from a D site, q = rate of detection of U sites during active surveillance. Initial U = initial proportion of U sites prior to the adoption of the hypothetical policy (defined by U* in Murray et al., 2011).

[c] The difference between the observed average proportion of K + D sites (7×10^{-3}) (Murray et al., 2011) and randomly generated values from Beta(4,436) corresponding to the estimated prevalence of infected Atlantic salmon sites (Hall et al., in press); this difference was subject to a minimum value of 1×10^{-4}.

mass (M) and the number of days following the start of each pc (T). The model, M = 1.963 + 0.003 T, was obtained using harvest data from the production database and assumes that the sum of the normally distributed errors is zero. Predicted harvest masses were converted to head-on-gutted (HOG) masses by assuming that the latter is 90% of the former (Marine Harvest, 2013) yielding predicted HOG harvest masses of 2.8, 3.3 and 3.8 kg at 12, 18 and 24 months respectively from the start of the pc. A log-normal distribution of lnN (10.3,2.7) describes the sums of the capitalised HOG biomass of BKD-associated mortalities on sites. Random sampling from this distribution provided stochastic variation for the capitalised biomass lost to BKD on each D-site during a pc.

The value of the capitalised mortality biomass was estimated using operational Earnings Before Interest and Tax kg^{-1} of HOG Atlantic salmon (hereafter referred to as EBIT). A summary of these, together with HOG price kg^{-1} and production cost kg^{-1}, is available from 1993 to 2012 inclusive for Norwegian Atlantic salmon production (Marine Harvest, 2013). Inspection of the EBIT suggests an overall decrease of both price and costs of production over this time with annual changes in EBIT primarily associated with annual fluctuations in price. The association of EBIT with calendar year (Y) and price (P), converted from Norwegian Kroner (NOK) to Great Britain Pounds (GBP) at the average spot daily exchange rate for 2012 (9.22 NOK GBP^{-1}), was evaluated through a linear model (Searle, 1971) assuming normally distributed errors and including an interaction between Y and P. The resulting predictive equation for EBIT in 2012 was −3.14 + 1.28 P. Diagnostic plots of the model (not shown) indicate a satisfactory fit and the intercept, which represents the production cost kg^{-1}, is similar to indicative values for the aquaculture company to which the mortality data pertains (Marine Harvest, 2013). Random sampling of the observed price over the previous 10 years from the uniform distribution U(2.39, 4.01) generates a distribution of predicted EBIT characterised by a median of 0.93 GBP and a 95 PI of −0.04 and 1.93 GBP which is used to estimate the loss-of-value of BKD-associated mortality. An additional 0.01 GBP kg^{-1} was added to the loss-of-value to cover the additional extraordinary cost of collecting and disposing of BKD-associated mortalities. The on-site loss-of-value associated with a policy is, therefore, the product of the sum of the randomly sampled capitalised biomasses of BKD-associated mortalities on the D-sites and the predicted EBIT including the extraordinary cost of mortality. The difference in loss-of-value between each hypothetical policy and the reference policy is, therefore, the loss-of-value due to the adoption of that hypothetical policy.

Costs required to regulate the policies (Fig. 1) comprise expenditure on inspections, diagnostic tests and the placement and removal of movement restrictions by the regulatory authority in GBP and the loss-in-value of fish destructively sampled during systematic testing for infection during the pc. Expenditure was estimated for each policy at 2012 values on a site^{-1} basis using information from representatives of the Fish Health Inspectorate and the Scottish National Reference Laboratory for Fish Mollusc and Crustacean Diseases (both a part of Marine Scotland Science and acting as the regulatory authority) and include the full economic cost of staff-time, laboratory consumables, travel and subsistence (Table 3). The relevant expenditure site^{-1} was multiplied by either 100 (for expenditure applying to all sites) or by the number of D- and K-sites as appropriate for each policy.

The economic model estimated the direct net economic benefit of each hypothetical policy (1–4) relative to the reference policy (0) as the sum of the loss-of-value and the expenditure on policy measures for 100 active sites over the course of their pc (Fig. 1). Results across simulations were summarised using the median and 95 PI and the percentile associated with the break-even value of the hypothetical policy relative to the reference policy also estimated.

All calculations were performed within a single script integrating the epidemiological and economic models under the R statistical environment version 2.15.2 (R Core Team, 2012) and using the supplemental R package MASS version 7.3-22 (Venables and Ripley, 2002).

3. Results

The epidemiological consequences of the hypothetical policies relative to the reference policy are presented in Table 4. There is an increased proportion of infected and BKD-affected sites for policies less stringent (1 and 2) than the reference (0). In contrast more stringent policies (3 and 4) are associated with a decreased proportion of infected and BKD-affected sites.

Cumulative BKD-associated mortalities for the seven marine pc are presented in Fig. 2. There is substantial variation in BKD-associated mortality on different sites with cumulative values at the end of pc characterised by a median of 2% and ranging from <1% to 23%. BKD-associated mortalities commenced between day 163 and 586 following the initial stocking of the pc and in general continued towards the end of the pc.

The economic consequences of the hypothetical policies relative to the reference policy are presented in Table 5. The median direct net-benefit of all hypothetical policies compared to the reference policy are negative indicating that, on average, the reference policy is more cost-effective. There are a minority of occasions, however, when the direct net-benefit of hypothetical policies exceed that of the reference policy indicating that there are specific circumstances under which hypothetical policies may be more cost-effective. Such specific circumstances include, for example, the occurrence of a

Table 3
Parameter values for economic model.

Item[a]	Policy[b]	Value (GBP)	Sites
EBIT	All	0.93 (−0.04 to 1.93)	D
Collection and disposal of mortalities kg^{-1}	All	0.01	D
Intelligence-led inspection for BKD occasion^{-1}	All	485	D
Systematic inspection for BKD pc^{-1}	0,1,2	56	All
	3	64	All
	4	116	All
Testing to confirm BKD occasion^{-1}	All	437	D
Systematic testing for infection pc^{-1}	3	757	All
	4	6676	All
Temporary imposition of movement restrictions occasion^{-1}	0,2	73	D
	3,4	73	D,K
Confirmation of movement restrictions occasion^{-1}	0,2	61	D
	3,4	61	D,K
Contact tracing occasion^{-1}	0,2	2122	D
	3,4	2122	D,K
Removal of confirmed movement restrictions occasion^{-1}	0,2	606	D
	3,4	606	D,K

[a] Inspection for post clinical disease status omitted because marine sites avoid moving stock from pc which have experienced BKD.

[b] Cost regarded as 0 GBP if item is not listed.

Table 4
Epidemiological consequences of hypothetical policies relative to reference.

Policy	Median % infected sites (95 PI)		Median % D-sites (95 PI)	
1	−78.0[a]	(−88.4 to −33.5)	−33.3	(−43.6 to −5.9)
2	−64.2	(−80.1 to −20.2)	−27.4	(−39.5 to −3.6)
3	0.4	(−0.1 to 0.9)	0.2	(0 to 0.2)
4	0.9	(0.1 to 2.0)	0.4	(0 to 0.4)

[a] Negative values represent an increase in the proportion of infected sites relative to the reference policy and are detrimental.

Table 5
Direct net-benefits of hypothetical policies relative to reference[a].

Policy	Direct net-benefit[b] (95 PI)		Break-even percentile[c]	Net control costs (95 PI)	
1	−1732[d]	(−9908 to 42)	4%	−29	(−45 to −3)
2	−1417	(−8200 to 0)	2%	−85	(−136 to −7)
3	−85	(−253 to 128)	6%	−87	(−101 to −73)
4	−749	(−895 to −564)	1%	−764	(−865 to −668)

[a] Over the course of the pc of 100 active production sites in 000s GBP benchmarked to 2012.

[b] Includes on-site mortality and control costs.

[c] Proportion of simulations at which direct net-benefit of hypothetical policy exceeds reference policy.

[d] Negative values represent an increased cost of BKD relative to the reference policy and are detrimental.

negative EBIT for policies 1 and 2. Median net control costs, a component of the direct net-benefit, are negative for all hypothetical policies.

4. Discussion

The cost-effectiveness of animal disease management policies has been a concern of government for some years (e.g. Great Britain, 2004). Previous work (Moran and Fofana, 2007) undertaken within an UK aquaculture context investigated the cost-effectiveness of controls for the salmonid diseases Infectious salmon anaemia (ISA), Viral haemorrhagic septicaemia (VHS) and Infectious haematopoietic necrosis (IHN). It was concluded that the public funding of control for ISA and VHS, both of which have occurred and subsequently eradicated in territories of the UK, represent an acceptable rate of return. In contrast the cost-effectiveness of surveillance for IHN, which has not occurred in the UK, is more marginal. The present report extends this previous work by investigating the cost-effectiveness of policies for BKD within Atlantic salmon aquaculture, a disease first observed in wild representatives of this species in Scotland during 1930 (Smith, 1964). Over the long-term, the reduction in costs of removing disease controls (policy 1) would almost certainly be exceeded by the costs of resource wastage from mortality and confirming BKD-affected sites. Indeed the low ratio between the cost of controls and direct net-benefit (29:1732, Table 5) indicate that the same conclusion is applicable to a policy, not formally modelled within this investigation, of changing existing national legislation (Aquatic Animal Health (Scotland) Regulations, 2009) to delist the disease. In summary the results suggest that policies incorporating measures which control for BKD in Atlantic salmon production have the potential to be cost effective and that the reference policy currently in place is beneficial.

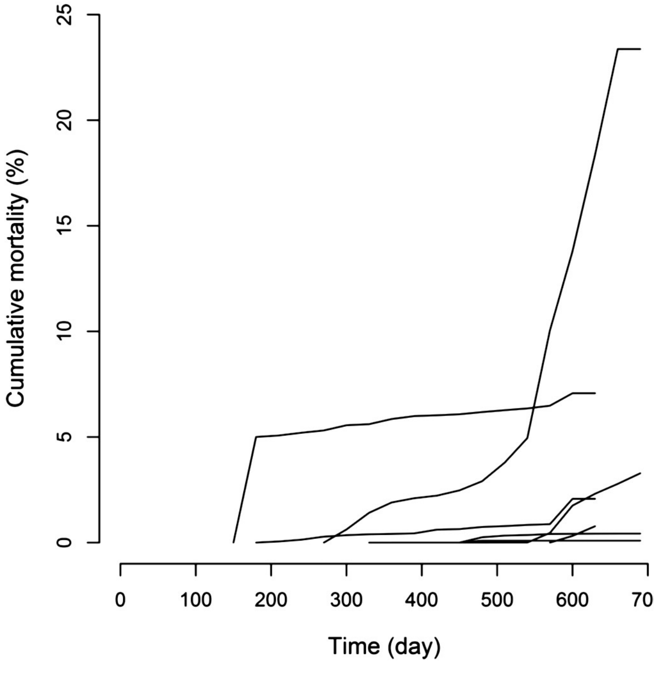

Fig. 2. Cumulative BKD-associated mortality as a percentage of the number of harvested individuals (including BKD mortalities) for seven pc. Time is the number of days following the initial stocking of the pc.

Although the reference policy for BKD is beneficial it is not necessarily optimal. This study has therefore compared the cost-effectiveness of the reference policy with other hypothetical policies which incorporate procedures controlling for BKD. One of these policies is less stringent (policy 2) than the reference and two are more stringent (3 and 4). The net economic benefit of all these hypothetical policies is less than the reference (Table 5) except for a minority of occasions (≤6%) even though the more stringent policies are epidemiologically more beneficial (Table 4). Such a result is consistent with a loss–expenditure frontier of diminishing reductions in output losses associated with BKD with increased control expenditure (McInerney et al., 1992) and suggests that the reference policy is closer to the optimal disease control strategy than the hypothetical alternatives investigated.

The economic model used for this analysis is a simplification of an approach which partitions direct costs associated with a disease into those attributable to prevention, resource wastage and treatment (Bennett et al., 1999). There are no licensed preventive or treatment medicines for BKD in the UK. The biological consequences of BKD on Atlantic salmon production are known to include mortality (Murray et al., 2012b). While the cause of mortality ascribed to each individual in the production database is not definitive the company diagnostic procedures are such that it is unlikely that substantial numbers of mortalities would be ascribed to BKD without veterinary confirmation; it is reassuring that mortality ascribed to BKD for the pc unsupported by a positive *R. salmoninarum* test result by the regulatory authority (although the site was still operating under official controls for the pathogen) was the lowest of the affected sites and if the diagnosis of BKD mortalities was incorrect would not substantially affect the resulting statistical distribution. Reductions in growth rate or flesh-quality as a consequence of BKD in an Atlantic salmon production context have not been reported and are, therefore, unlikely to contribute significantly to resource wastage. Treatment practices comprise the collection and disposal of BKD-affected fish as a part of a routine daily inspection which should be carried out whether the disease is present or not (Code of Good Practice Management Group, 2010). The potential for extraordinary on-site costs other than those associated with BKD mortalities is, therefore, limited. Resource wastage is modelled from the capitalised mortality ascribed to BKD using EBIT an approach which avoids the need for a detailed breakdown of the costs of production. The EBIT used in this report originate from Norway and although one to three cases of BKD occur annually (Johansen, 2013) the effect of these on the values will be negligible given the scale of production. Inspection of a sample of annual business reports indicates that the Norwegian values of EBIT are comparable with Scottish operations. These simplifications facilitate the inclusion of variation in parameter estimates. In summary, while some bias in median estimates cannot be discounted, the inclusion of variation into parameters ensures that the results of this investigation can be regarded as being ‘vaguely right’ rather than ‘exactly wrong’.

This report has described the control of BKD for Atlantic salmon aquaculture. Atlantic salmon represent 97% of the biomass from aquaculture production in Scotland (Marine Scotland Science, 2013) with other salmonid species, rainbow trout (*Oncorhynchus mykiss*), brown trout (*Salmo trutta*) and Arctic char (*Salvelinus alpinus*) which are also susceptible to BKD (Belding and Merrill, 1935; Souter et al., 1987), representing a very large majority of the remaining production (Marine Scotland Science, 2013). It was not possible to incorporate these other sectors into this analysis because comparable mortality data is unavailable. The different sectors are not independent however, with the potential for disease transmission between species on an occasional basis occurring through a small number of sites stocking mixed species, hydrodynamic dispersion of *R. salmoninarum* from an infected site to nearby sites of different species, infection from wild and/or escaped fish and other anthropogenic causes as reviewed by Murray et al. (2012b). Recent genetic (Matejusova et al., 2013) and modelling (Murray, 2013) results are consistent with the idea that at least a proportion of outbreaks on Atlantic salmon sites originate from outside the Scottish Atlantic salmon aquaculture sector per se. These additional sources of infection indicate that the eradication of BKD from Atlantic salmon is impractical and so support the conclusion that the adoption of more stringent policies for this sector is unlikely to be economically beneficial.

In summary, this report concludes that the control of BKD is cost-effective, and that a policy of limiting the spread of *R. salmoninarum* through the detection of BKD-affected sites, imposition of movement restrictions on such sites, and requirement to eradicate *R. salmoninarum* before movement restrictions are lifted is more cost-effective than alternative hypothetical policies of either increased or reduced stringency.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.aquaculture.2014.07.023.

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