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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

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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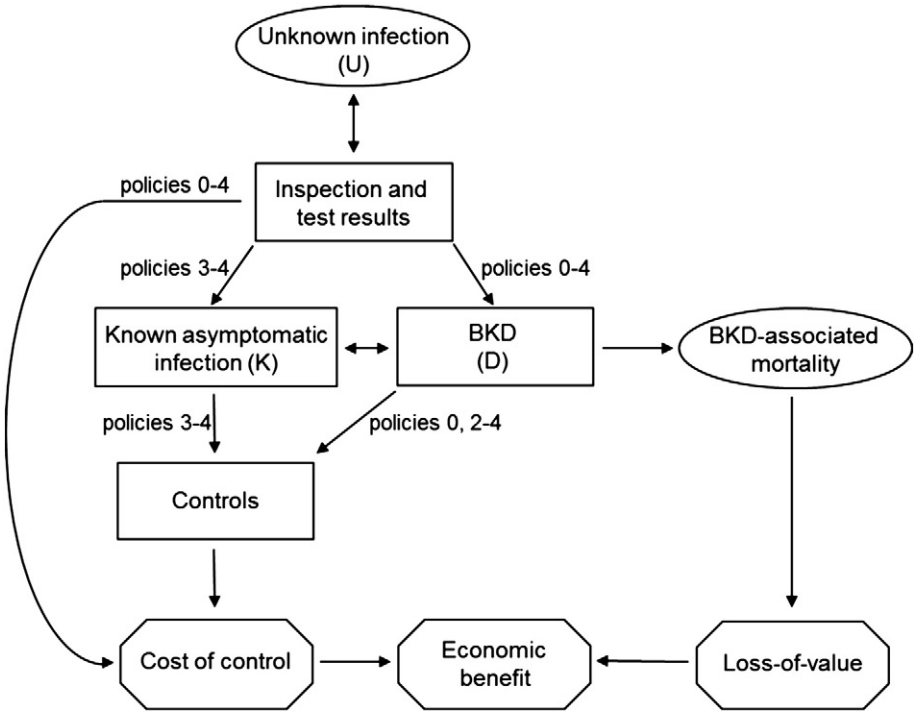

Fig. 1. Influence diagram of conceptual model for each policy. Ovals represent uncertainty nodes, rectangles decision nodes and octagons value nodes. Bracketed characters (U, K, D) are the epidemiological site infection-status assignments and numbers (0–4) the policies. The net economic benefit was calculated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

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 (≥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 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.