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A simple model of the role of area management in the control of sea lice

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ABSTRACT

Sea lice are parasites whose treatment is a major cost on farming salmon, and sea lice from salmon farms can significantly increase lice numbers on wild salmonids in their vicinity. Effective sea lice control is thus an important consideration for sustainable salmon aquaculture. Sea lice have free-living planktonic larvae that are transported by currents and for this reason co-ordination of farm activities within management area (MAs) is increasingly used to control lice. Here we develop a simple model of co-ordinated management and resultant frequency of treatment required to maintain control of lice numbers in order to assess the benefits of using MAs. The model consists of a circle of salmon farms nodes that exchange larva lice with their neighbours on both sides. The farms are grouped into MAs, whose sizes are based on those of Disease Management Areas currently operating in Scotland. Transmission across MA boundaries is reduced, but is not generally stopped completely. Using this model, co-ordinated management within MAs is shown to reduce the number of treatments required to keep lice burdens under control. Co-ordinated fallowing is always effective at reducing treatment requirements, however the benefits of co-ordinated treatment depend on hydrodynamic mixing regimes and the efficacy of medicines used. Benefits of co-ordinated management apply even when MA boundaries are epidemiologically ineffective, but strong boundaries can greatly increase MA benefits. There are thus robust clear benefits of the use of MAs and so simple modelling supports their use as a general policy. However, specific benefits in a particular area depend on the specific local environment which requires the use of more sophisticated hydrodynamic and population modelling to evaluate.

1. Introduction

Atlantic Salmon (*Salmo salar*) production has expanded to become a major economic activity in cool temperate coastal waters such as those of Scotland where production exceeds 179,000 t (Munro and Wallace, 2015) and is estimated to contribute some £1.4BN to the wider economy (Alexander et al., 2014). Because of the importance of finfish aquaculture, Scottish Government supports the industry led targets of sustainably increasing production to 210,000 t by 2020 (Scottish Government, 2015). Limitations caused by disease and environmental concerns have emerged to restrict production and these must be overcome for production to increase.

Sea lice, copepodic ectoparasites of fish, are one such disease agent which is limiting the sustainable expansion of salmonid aquaculture. The most important species that affect salmon are *Lepeophtheirus salmonis* in the northern hemisphere and *Caligus rogercressyi* in Chile. Other Caligus species also infest farmed salmon, but are considered to cause less serious problems. Sea lice also infect wild salmonids and infection on these wild fish can be enhanced from farmed sources (Middlemas et al., 2012). Although salmon lice may cause relatively little direct mortality on farmed fish (Soares et al., 2011) they have been estimated to cost €305M globally to control (Costello, 2009). A large amount of this cost is through the use of antiparasite medicines, whose frequency of use has increased (Murray, 2016) as a consequence of reduction in efficacy (Aaen et al., 2015). Environmental residues can result from excessive use, and these could potentially be toxic (Mayor et al., 2008). Therefore efficient use of these medicines is required as required as a part of a greater integrated pest management strategy (Kogan, 1998).

Larval sea lice disperse through hydrodynamic transport (Amundrud and Murray, 2009) which can result in farms interacting over distances of kilometres (Salama et al., 2016) both with other farms (Adams et al., 2012) and with wild salmonids

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(Middlemas et al., 2012). For this reason, area management is often used to control lice on farmed salmon whereby groups of farms in a local area are managed according to a local plan or agreement. For example, farm management areas (MA) in Scotland (CoGP, 2014) which is required to be described as part of statutory requirements (Aquaculture and Fisheries Act (Scotland) 2013) and disease management areas used in control of notifiable disease (MSS, 2015). Similarly, local barrios are used in Chile (Kristoffersen et al., 2013) and area management in Canada (DFO, 2011).

There has been considerable effort applied to modelling of sea lice in studies relating to: dispersal (e.g. Amundrud and Murray, 2009; Adams et al., 2012; Salama and Rabe, 2013; Adams et al., 2015), aspects of population modelling (e.g. Revie et al., 2005; Gettinby et al., 2011, McEwan et al., 2015), and statistical modelling such as of factors influencing lice treatment rates (Revie et al., 2003; Murray and Hall, 2014). However, there is no specific modelling analysis of the benefits of using area management strategies for lice control beyond recent modelling of interacting pairs of farms (Peacock et al., in press). There has been no theoretical basis for assessing if area management is effective, and for identifying the role of key factors influencing the extent of any benefit.

Therefore, we take a modelling approach that has been used to assess area management of emerging infectious diseases in Scottish farmed salmon (Werkman et al., 2011) and adapt it to describe lice dynamics in order to inform area management of sea lice parasitism on farmed salmonids. The model is used to assess the effect of subdivision of the population of salmon farms into area based sub-populations and, within these areas, the benefits of synchronisation of fallowing and treatment regimes relative to asynchronous regimes. These effects are investigated for different hydrodynamic dispersal regimes and hence exchange between farms.

2. Methods

A simple model of interaction of lice infection on salmon farms is developed and coded in R version 2.15.0 (R core team, 2012). This simple model is used to identify the behaviours of a system that are not dependent on details of local conditions and local interactions (Murray, 2001) and hence identify robust system responses to management. Other effects of management strategies will indeed depend on details of interactions between farms, and more complex modelling is required to assess the specific optimal strategies for such effects (Salama and Rabe, 2013). However, the robust benefits identified from simple modelling are precisely those which can be used to derive and support standardised sea lice control policies that are likely to be effective in most areas.

2.1. Basic structure of the model

The basic structure of the model is formed of nodes arranged in a ring to represent farms distributed along a coast (Fig. 1); there are 251 nodes as this is the observed number of farms (MSS, 2015). The use of a ring follows the standard Watts-Strogatz model (Watts and Stogatz, 1998) used for simulating spread of pathogens between nodes without introducing arbitrary boundary conditions and is similar to a structure used by Werkman et al. (2011) to model infectious disease spread in aquaculture. The ring avoids the need to consider boundary conditions, since all nodes have neighbours on both sides and pathogens can spread in both directions. The simple ring structure model assumes farms interact most strongly with neighbouring farms in the ring, which generally (but not always) will be their geographically closest neighbours. The ring structure makes exchange 1 dimensional, we are neglecting the 2-D structure of the coastal environment to simplify the model.

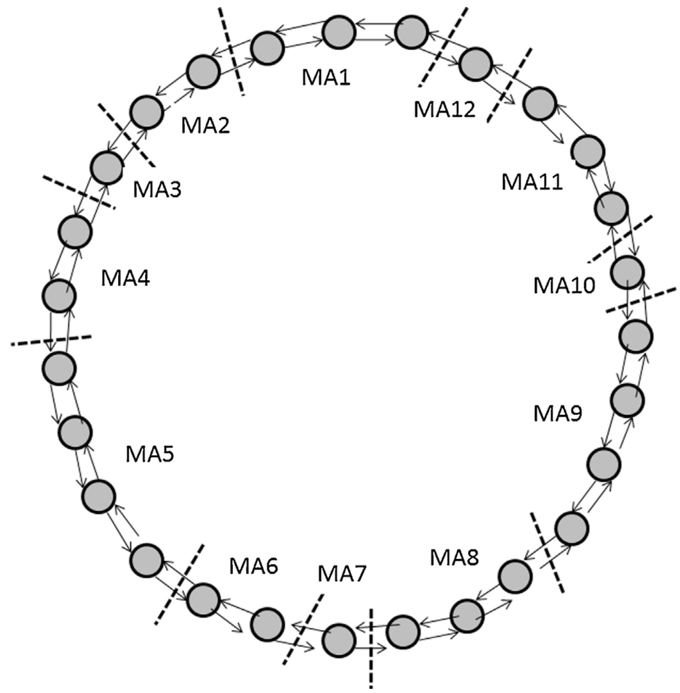

Fig. 1. Ring of farms that interact with neighbours and are divided into 12 MAs.

Strength of interactions between pairs of farms depends on both seaway distances between farms and local current strengths and on the adult lice population on the source farm. Essentially this is similar to the contact probability as a function of distance derived from more sophisticated statistical space time modelling (e.g. Aldrin et al., 2013), but we simplify this by assuming equal spacing of farms and excluding more distant contacts which contribute relatively little to infection pressure (Salama et al., 2016) for this simple model. These farms hold salmon on them, which can become infected with lice from environmental background sources, from re-infection from the farm itself, or with larval lice spread from neighbours.

The farms are grouped into management areas (MSS, 2015) with a reduced probability of infection transmission between neighbours if they are in different management areas because of physical separation between areas. In this paper we use disease management areas (MSS, 2015) as used for official disease control programmes, rather than industry farm management areas (CoGP, 2014). This is because the number of farms within DMAs can be obtained from the official maps of DMA, which is not the case for FMAs. The use of DMAs also makes this analysis consistent with earlier work (Werkman et al., 2011), although DMA boundaries are updated here to account for changes since the earlier analysis. As this is a simple model the DMAs are representative and used to illustrate the concept of area management, with real DMAs having interactions that are complex and variable, both internally and with neighbouring management areas.

Each simulated farm holds a population of salmon that are held on the site for an 18 month period after which the site is emptied for harvest, fallowed and repopulated; this approach was used by Werkman et al. (2011). Fallowing at the site level has been shown to be an effective means of reducing lice infestation (Bron et al., 2006) and is now ubiquitous on Scottish sites engaged in salmon production for harvest. When salmon initially are put onto a marine farm that has been fallowed they are free of lice since these parasites are exclusively marine, with rapid mortality in freshwater (Bricknell et al., 2006), and salmon are sourced from freshwater smolt production sites. Once on these farms the fish can become infested