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Short communication

Describing temporal change in adult female *Lepeophtheirus salmonis* abundance on Scottish farmed Atlantic salmon at the national and regional levels

L.M. Hall*, A.G. Murray

Marine Scotland Science, Aberdeen, AB11 9DB, UK

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ABSTRACT

Patterns of change over time for adult female *Lepeophtheirus salmonis* abundance on Scottish farmed Atlantic salmon, *Salmo salar*, from December 2010 to September 2017 inclusive at the national level and four constituent regions are described. The analysis comprises a Generalized Additive Model on summary statistics published by the Scottish Salmon Producers' Organisation. Irregular within-year oscillations were detected at the national level and for three regions. Non-linear longer-term changes at the national level and for two regions were also detected with no apparent overall increase occurring over the period. The results from this analysis are compared to those from a previous analysis utilising a linear model on a subset of the data. We conclude that the GAM provides an improved description of the temporal changes of this parasite.

1. Introduction

Atlantic salmon, *Salmo salar* L., farming is an important part of the Scottish economy (Marine Scotland, 2014, Munro and Wallace, 2017). Marine production is affected by multiple pathogens (Soares et al., 2011) with the problem of sea louse (family Caligidae) infestations longstanding (Rae, 1979), endemic (Revie et al., 2002a) and costly (Pike and Wadsworth, 1999). Indeed, louse infestations have been posited as a potential constraint to increased production in Norway (Jansen et al., 2012) and within Scotland the identification of technologies to control the parasite are regarded as a priority 'knowledge need' (Jones et al., 2015). There is also evidence of a spread of lice between Scottish farmed and wild salmonids (e.g. Middlemas et al., 2013) with concerns of a potential impact on wild salmonid populations (e.g. Butler, 2002; Susdorf et al., 2018). Government therefore overseas industry monitoring of louse abundance as a part of its regulatory function (Scotland, 2007, 2013) and intervenes when this is elevated.

Two species of sea louse are of concern on farmed Scottish marine Atlantic salmon. These are *Lepeophtheirus salmonis* (Krøyer) and *Caligus elongatus* Nordmann (Rae, 1979). *Lepeophtheirus salmonis* is, in general, more abundant on farmed Scottish Atlantic salmon than *C. elongatus* (Revie et al., 2002a; Revie et al., 2002b), regarded as being more injurious (Pike and Wadsworth, 1999), and are emphasised for monitoring and control purposes (CoGP, 2015).

The Scottish Salmon Producers' Organisation (SSPO) has collated farmed Atlantic salmon sea louse counts from December 2010 and publishes summary statistics for adult female L. *salmonis*. A previous analysis of temporal variation for a three year subset of these data to December 2013 using a simple parametric linear model (Searle, 1971) has been published (Murray, 2016). The ability of such models to describe complex temporal change is limited however, in part because they require the user to make explicit assumptions regarding the possible form of the functional dependence. Rather it is likely that a non-parametric approach in which the data provide the form of functional dependence based on flexible smoothers within a Generalized Additive Model (GAM) framework (Hastie and Tibshirani, 1986; Wood, 2017) would be more satisfactory. The availability of additional summary statistics to September 2017 justifies the application of GAM to refine the previous analysis.

2. Materials and methods

2.1. Description of source data

Stocked marine salmon aquaculture production sites, hereafter referred to as 'sites', in Scotland are required to record a weekly count of sea lice on their fish when possible (Scotland, 2008). The minimum suggested sampling strategy, as described by the Code of Good Practice

Abbreviations: CI, confidence interval; GAM, Generalized Additive Model; *p*, *p*-value; SSPO, Scottish Salmon Producers' Organisation; ≤, no greater than; >, greater than

* Corresponding author.
E-mail address: malcolm.hall@gov.scot (L.M. Hall).

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for Scottish Finfish Aquaculture (CoGP, 2015), involves counting the number of chalimus, 'mobile' and adult female L. *salmonis* and identifiable *C. elongatus* on 25 fish from each site. The 25 fish should comprise five randomly selected individuals from five randomly selected pens, both without replacement, for sites with five or more pens, or proportionally more fish per pen from sites of fewer than five pens (CoGP, 2015). Alternative sampling strategies generating reproducible benchmarked results are permitted.

The SSPO collates weekly sea louse counts from members and publishes a weighted time period mean of adult female L. *salmonis* counts on sites for each of several areas; no other louse count statistics are made available. Weights for the mean are the number of fish on contributing sites. The areas and time periods comprise either six mutually exclusive reporting regions over one to four months from December 2010 to December 2012 inclusive, or 30 mutually exclusive reporting areas on a monthly basis thereafter. These SSPO weighted means are hereafter described as 'averages' and the time periods on which they are based as 'monitoring-periods'. The six reporting regions are east Shetland, west Shetland, Orkney, the western isles, and the north and south of the Scottish mainland with the 30 reporting areas constituent to these. For this report, as for the previous analysis (Murray, 2016), the reporting regions of east Shetland, west Shetland and Orkney or their constituent reporting areas were aggregated into a single northern isles region. A map of these regions and reporting areas is available (Murray, 2016). The adult female L. *salmonis* averages for reporting regions to December 2012 have been listed (Murray, 2016) and the subsequent statistics for reporting areas, currently available at http://scottishsalmon.co.uk/publications (accessed 30 November 2017), are plotted (Fig. 1). Additional data including quarterly statistics of reporting area licensed capacity as a proportion of active Scottish production, hereafter referred to as "proportional active capacity", are available from January 2013.

2.2. Data preparation

For clarity the term 'abundance' refers to the analysed calculated national or regional adult female L. *salmonis* weighted means, 'average' to published SSPO adult female L. *salmonis* summary means from which abundances were calculated, and 'count' to unknown weekly site adult female L. *salmonis* enumerations upon which the SSPO averages were calculated.

National (viz. Scotland) and regional abundances were calculated as a weighted mean of the SSPO averages with weighting provided by reporting area proportional active capacities. Louse averages, and consequently abundances, for the multiple month monitoring-periods before 2013 were assigned to the midpoint of their monitoring-period. Proportional active capacities are not available before 2013 and weights for these abundances were approximated using means of aggregated reporting area proportional active capacities over 2013. The analysed data therefore comprises adult female L. *salmonis* abundances ascribed to specific calendar months from December 2010 to September 2017 for either Scotland or for each of four constituent regions. Reporting areas that were fallow had no active production, therefore no lice, and do not contribute to national or regional abundances at that time.

2.3. Statistical analysis

The primary purpose of the statistical analysis was to infer longer-term temporal changes in adult female L. *salmonis* abundance at the national and regional levels. This was achieved by fitting non-parametric smoothers to abundance over time using GAM at the national and regional levels. The model comprised:

$$\log(E[y_{ij}]) = \beta_0 + f_1(x_i) + f_2(x_j) + f_3(x_i x_j)$$

where $E[y_{ij}] =$ expectation (E) of adult female L. *salmonis* abundance (y_{ij}) during calendar month i and monitoring-period j at the national or regional levels assuming a Gamma error distribution (y_{ij} range from 0.09 to 8.96); β_0 = fixed effect intercept; f_1 = function for within-year oscillations comprising a penalised cyclic cubic regression spline over calendar months i (1 to 12); f_2 = function for longer-term changes comprising a penalised cubic regression spline for monitoring-periods j (1 to 82); f_3 = function for interaction between within-year oscillation (f_1) and longer-term changes (f_2) comprising a penalised cubic regression tensor product interaction. A potential association between consecutive monitoring-period abundances was incorporated into the model as a continuous autoregressive correlation of residuals which serves to protect against over-fitting longer-term changes. Models were fitted by penalized quasi-likelihood with smoothing parameters fitted as variances. Ninety-five percent confidence intervals (CI) of predicted values were calculated from estimates of the standard error around the splines. The presence of within-year oscillations (f_1), longer-term changes (f_2) and interaction (f_3) were inferred using a Wald-type test. Additionally within-year oscillations were categorised as being regular or irregular depending on the statistical significance of the interaction (f_3). Statistical significance was defined as a p-value (p) of no greater than ($\leq$) 0.05. Analyses were performed within the R statistical environment version 3.3.3 (R Core Team, 2017) utilising the supplementary R package mgcv version 1.8–17. The reader is referred to Wood (2017) for further details of GAM and the mgcv package.

Analysis results are presented graphically (Figs. 2 and 3). A first graph shows "observed" and "expected" adult female L. *salmonis* abundances over time. 'Observed' values are the abundances to which the model was fitted (y_{ij}), and 'expected' values are the modelled expectations ($E[y_{ij}]$). The first graph includes both the within-year oscillation (f_1) and longer-term changes (f_2). A second graph shows relative expected adult female L. *salmonis* abundance over time for longer-term changes only (f_2). The relative values are standardised to the median national abundance during October and show longer-term changes corrected for within-year oscillations.

3. Results

Observed and expected national adult female L. *salmonis* abundances over time are presented (Fig. 2a). Temporal variation comprises a statistically significant irregular ($p \leq 0.001$) within-year oscillation ($p \leq 0.001$) and statistically significant longer-term changes ($p \leq 0.001$). Overall the within-year oscillation has minima and maxima around April and October respectively, although the pattern from the middle of 2016 is substantially different. The longer-term changes, standardised for the within-year oscillation, are complex (Fig. 2b). There is a first longer-term increase from a relative abundance of 0.7 (95% CI 0.4–1.2) at the beginning of the time series (December 2010) to 1.7 (1.3–2.3) around March 2012 followed by a subsequent decrease to 0.6 (0.5–0.7) during June 2013. A second longer-term change comprises an increase to a relative abundance of 1.4 (1.1–1.8) during December 2015 followed by a subsequent decrease to 0.5 (0.4–0.8) at the end of the time series (September 2017). The longer-term change can be summarised as comprising two cycles.

Observed and expected regional adult female L. *salmonis* abundances over time are presented (Fig. 3a, c, e and g). Statistically significant irregular ($p \leq 0.039$) within-year oscillations ($p \leq 0.034$) are detected for the northern isles, north mainland and western isles. The within-year oscillation for south mainland is not categorised as statistically significant ($p = 0.077$). Minimum within-year abundances for each region occurred during March to May and maxima during September to November inclusive. The longer-term changes, standardised for within-year oscillations, differ between regions. Statistically significant ($p \leq 0.001$) longer-term changes for the northern isles (Fig. 3b) are not dissimilar to those observed at the national level. In contrast longer-term changes for both the north mainland (Fig. 3d) and south