BACKGROUND

In collaboration with colleagues at universities and research institutes in St Andrews, elsewhere in the UK and overseas I have, over the past 15 years, published 10 journal articles, 1 book chapter and 1 major grey literature report relating to sea lice and their effects on host fish physiology and survivorship. Our research has primarily been funded by the Natural Environment Research Council and the European Union, but the most recent journal article (Paper 12) in Proceedings of the Royal Society B had no support from any external bodies other than the host institutions of the six co-authors.

In view of the recent interest in Paper 12 – and its relevance to Part 1 of the Aquaculture and Fisheries (Scotland) Bill – I would wish here to provide a summary of how and why we came to undertake the work and publish the results in Papers 11 and 12 in the peer-reviewed literature.

Paper 11

This work comprised part of a large international collaboration (“Sustainable Management of Interactions between Aquaculture and Wild Salmonid fish” – SUMBAWS – funded by European Union FP5; Contract number Q5RS-2002-00730) between Scotland, Ireland, Netherlands and Norway over the period 2002-2005. St Andrews was the lead Partner and Dr Neil Hazon the Project Co-ordinator.

Paper 11 reported on the eight experimental releases of hatchery-reared salmon smolts undertaken as part of SUMBAWS in three river systems in Ireland over the period 2003-2005. For each release, approximately half the smolts were untreated controls and half were treated with the in-feed parasiticide, emamectin benzoate (SLICE) prior to release. SLICE is an effective treatment against sea louse infestation that is routinely applied in the salmon aquaculture industry. Its efficacy is limited to perhaps 1-2 months so any protection offered to the experimental smolts was restricted to the early marine migration of the juvenile fish. It is known (Paper 2) that wild salmon continue to cross-infect one another at sea throughout their marine migration and that adults returning after 2 years at sea carry, on average, higher infestations than those returning after just 1 year.

All experimental fish were internally tagged and externally marked to indicate the presence of a tag should the adult fish be recaptured on return to freshwater one or two years later. In total, 74,234 smolts were released and 472 tagged adult fish were recaptured one year later and 21 two years later. The overall result from the analysis of the tag recaptures, using Fisher's Combined Probabilities test, was that there was a highly significant increased likelihood of survival to return for smolts receiving the treatment. The probability of obtaining this overall result by chance was much less than one in a thousand (P <0.001). A probability of 5 in 100 (P = 0.05) is conventionally taken as the critical level in ascribing significance to an experimental outcome. The conclusion drawn from this study was that protection of smolts over the earliest weeks of their marine migration had a highly significant effect on survival to adulthood, and that sea lice comprise a significant source of mortality
to free-ranging salmon. From estimates in the paper of the proportion of smolts that returned as adults, "protected" smolts were, on average, 1.8 times more likely to return than unprotected (control) smolts.

**Paper 12**

*Paper 12* was published in November 2012. Just prior to, and immediately following, the publication of *Paper 11*, two other papers (Jackson, D. *et al.* [2011] *Aquaculture*, **320**: 159-163, and Jackson, D. *et al.* [2011] *Aquaculture*, **319**: 37-40) were published elsewhere. Those papers reported the results and conclusions of similar experiments (also in Ireland) but undertaken by a different research group. The conclusion of both those papers was that "the salmon louse (was) a minor component of the overall marine mortality in the stocks studied". We had raised some concerns about the first Jackson paper in the Discussion section of our *Paper 11*, but following the second Jackson paper a group of us (Finstad, Gargan, Krkošek, Revie, Skilbrei, Todd) found that we all had concerns not only over the data that they analysed, and the statistical methods applied in analyzing those data, but also the validity of the conclusions that had been drawn in both. In view of this, we chose to compile all the available published literature (including both Jackson papers) on experimental releases of chemically treated and control groups of salmon smolts and to subject these to a detailed meta-analysis. Meta-analysis is a widely used approach to synthesizing and combining data from disparate sources, and has proved to be a powerful tool for identifying the pattern (or patterns) and strengths ('effect sizes') of significant outcomes. The available experimental data on releases of treated salmon smolts were extensive both in time (1996-2006) and geographic range (Ireland, Norway), and involved very large sample sizes totalling >280,000 fish. All releases were undertaken in rivers adjacent to areas subject to aquaculture.

We undertook three complementary analyses of the composite data, ranging from the standard computation of odds ratios (to estimate effect size), to simple paired *t*-tests and mathematical modelling of marine survival. All analyses converged on the same conclusion: that treatment had a highly significant effect on the survivorship of salmon smolts to return as mature adults. The overall odds ratio of 1.29 was shown by the mathematical modelling to correspond to an estimated loss of 39% of adult salmon recruitment. The 95% confidence interval around that mean estimate of 39% was 18-55%. Thus, when assessing the total mortality of salmon over their marine migration, the ultimate consequence was that more than one third of return adults were being lost if they had not been treated.

In *Paper 12* we made no attempt to estimate per cent survivorship of all the experimental releases but, as far as was possible, retained our analytical focus on comparisons of the numbers of tags actually retrieved. The generation of per cent survivorship estimates for populations or experimental groups is complicated, and necessitates various assumptions regarding tagged fish which survived but which were not caught or retrieved. Notwithstanding those qualifications, it is apparent that the conclusion drawn by Jackson *et al.* in their two papers (that sea lice mortality is a minor component of overall mortality) is based upon their estimates of a difference of perhaps 1 or 2% in the ultimate survival to return of treated and un-treated smolts, and that marine mortality increased markedly over the time period of their experiments. The latter can be explained by several factors relating to the experimental fish themselves and quite distinct from any purported changes in
overall marine mortality regime. Moreover, focusing on an absolute difference of 1-2% obscures the most important implications of these research findings. For example, if sea lice reduce adult recruitment (to re-enter the river) from 6% to 4% then this 2% reduction is equivalent to a one third (33%) increase in overall total marine mortality and a one third decrease in adult recruitment. To place this in hypothetical numerical terms, if, for a given river stock, numbers returning fell from 6,000 to 4,000 adults then that reduction would be viewed as being of concern to a river manager.

But here there are consequences beyond the simply numerical for the management and conservation of wild salmon populations. Because of their typical fidelity to return to their natal river, salmon stocks characteristically show marked genetic differentiation. Some of that genetic variation is considered to be adaptive. Salmon populations often have very low effective population sizes and the actual numbers of breeding adults can be very low in small river systems. Thus, if a stock is reduced from 60,000 to 40,000 that number alone may be of concern, but will likely have relatively little genetic effect at the population level. But a reduction from 60 to 40 adults in a small river may engender critically important population genetic effects as a result of the perhaps irreversible loss of genetic diversity in that stock.

We believe that the analyses and conclusions reported in Paper 12 are comprehensive and robust. We would suggest that there is a crucial importance to focusing on pair-wise comparisons in analysing experimental data such as these, and that the focus should not be directed towards absolute percentages but to relative proportions (or percentages), when assessing the overall total mortality effects influencing successful adult salmon return and which is attributable to sea lice. We maintain in Paper 12 that sea lice are a highly important source of mortality to free-ranging salmon. The data from all the experiments showed the same directionality of effect and a consistently significant outcome. But the nature of these experiments is such that one cannot unequivocally attribute a source to parasites infecting the experimental fish. However, given that the treatment was effective for only the first 1-2 months at sea, and that almost all rivers for which the analysed releases were undertaken were close to salmon aquaculture, the likelihood has to be high that salmon farms contributed to those infestations as the smolts emigrated through coastal waters. In our 2009 WWF report we urged a strongly precautionary approach in assessing the risk to wild and free-ranging fish posed by sea lice on farmed salmon: "...we believe that the weight of evidence is that sea lice of farm origin can present, in some locations and for some host species populations, a significant threat. Hence, a concerted precautionary approach both to sea lice control throughout the aquaculture industry and to the management of farm interactions with wild salmonids is expedient" (Paper 9). The salmon aquaculture industry has long placed high priority on the control of parasites on their captive salmon but the minimization of interactions between wild and farmed stocks remains a challenge.
References


   
   Electronic Supplementary Material pertaining to the published article at (http://rspb.royalsocietypublishing.org/content/suppl/2012/11/01/rspb.2012.2359.DC1/rspb20122359supp1.pdf)