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Pollution from fish farm effluents increases in-river mortality of adult Atlantic salmon prior to spawning

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Abstract

Fish farm effluents released in rivers are point sources of pollution which perturb lotic ecosystems. They are known to have an impact on the production of Atlantic salmon (*Salmo salar*) juveniles. They may have an effect on Atlantic salmon adults before spawning as well. This hypothesis was assessed on the R. Scorff (Brittany, France), a small coastal stream on which a major trout farm is located. A previous study allowed to identify the zone impacted by the fish farm pollution. Using radio-tracking data before the spawning season, the (non-fishing) mortality of salmon adults which entered this zone was compared with that of fish who stayed downstream, where the influence of the source of pollution is considered to be negligible. The Bayesian treatment of a generalized linear model revealed that pollution from fish farm effluents caused a significant increase in the pre-spawning mortality of salmon adults. Consequences of this result on the renewal of Atlantic salmon populations are briefly discussed.

Keywords: Atlantic salmon, adult, pollution, mortality, fish farm

Introduction

In rivers, fish farm effluents are point sources of pollution which can perturb the ecosystem downstream from the site of release (Kendra, 1991). On the River Scorff (Brittany, France), Prévost (1999) showed that population densities of Atlantic salmon (*Salmo salar*) parr were significantly lower on a stretch extending several kilometres downstream from the effluent output of two major rainbow trout (*Oncorhynchus mykiss*) farms. De Oliveira et al. (2000, 2001) further quantified the losses of juvenile salmon production due to those point sources of pollution.

But the impact of aquaculture pollution in rivers on Atlantic salmon may not be restricted to juveniles. Adults residing in freshwater for several months prior to spawning may be affected as well. To date, this issue has received little (if any) attention. A radio-tracking study of adult salmon conducted on the R. Scorff in 2001 and 2002 allowed a comparison of the survival of fish known to have been exposed to effluents from a trout farm with those which were not exposed. In this paper, I present the results of this comparison, conducted by means of the Bayesian treatment of a generalized linear model.

Material and methods

Study site

The R. Scorff is a small coastal stream (mainstem length: 75 km, mean flow: ~ 5 m^3/s, drainage area: 480 km^2) of Southern Brittany which flows directly into the sea (Fig. 1). It holds an Atlantic salmon population in the order of several hundred anadromous adults which have access to 47 km of mainstem river. A major rainbow trout farm is located 28 km from the head of tide. Although not precisely quantified, the annual production of this facility is evaluated at several hundred tonnes. The ecological effects of the pollution it generates have been documented by various studies (Bourget-Rivoallan, 1982; Bez, 1990; Daniel and Haury, 1995; Claude, 1996). Prévost (1999) showed that the production of salmon juvenile was significantly reduced over a stretch extending 5 km downstream.

Fish radio-tracking

A study on the riverine migration behaviour of anadromous salmon adults was undertaken in the Scorff in 2001 and 2002. Fish were caught at the Moulin des Princes trapping station located at the head of tide (Fig. 1). They were anaesthetised, weighed (g), measured (fork length, mm), and a few scales were removed for ageing. A radio-transmitter (supplied by Advanced Telemetry System Inc., USA) was inserted into their stomach following the protocol described by Chanseau et al. (1999). The transmitters were cylindrical (length: 60 mm, diameter: 20 mm) and weighed 22.5 g in air. They had a "mortality option" consisting in the doubling of their signal frequency if they remained immobile for 10 hours. Fish injured or apparently weak were discarded and radio-tags were distributed so as to cover the various components of the run, i.e. spring, summer and autumn fish. Fish were allowed to recover after handling into a tank directly connected to the river. They could swim out freely through a short conduit opening upstream from the trapping facility. Fish were localised within the river mostly by means of mobile receivers fitted with a loop antenna. The zone used by salmon adults (i.e. the mainstem from the trapping station to 47 km upstream, Fig. 1) was scanned at least once a week. A fixed receiver with a recorder was also installed in 2001 immediately upstream of the fish farm.

Data selection

The issue of interest is the marginal effect of the trout farm pollution on the survival of salmon adults before spawning. The survival of anadromous salmon after spawning is very low. Salmon reproduction in the R. Scorff never starts before the last week of November. In order to separate pre-spawning mortalities from natural post-spawning death, the fate of the radio-tagged individuals was considered up to November 15.

Only fish for which survival or death could be ascertained by November 15 were retained for analysis. A fish was considered dead if recovered dead, if its transmitter was recovered along the river bank with fish remains, or if it was located within the hole of a potential predator or scavenger. A fish was considered alive at November 15 if located within the river at least once after this date and its transmitter was sending a normal frequency signal. Fish which died within a week after tagging, most likely due to handling, or which were caught by angling, were excluded as they brought no information about the issue of interest (i.e. the marginal effect of pollution on survival). All fish "lost" (i.e. never located again prior to November 15), or whose transmitter was sending a double frequency signal (mortality option) but was not recovered or was recovered without evidence of death, were also excluded. The fate of these fish was uncertain: they might be dead, alive, outside the R. Scorff, caught by an angler or having regurgitated their transmitter (Smith et al., 1998; Keefer et al., 2004). Among these "uncertain" fish, those having left the R. Scorff or been caught by angling did not bring any information about the issue of interest and should have been discarded anyway. The others, which were within the R. Scorff, alive or dead but not angled, were assumed to correspond to missing at random data. It means the lack of information for these fish is not linked to their entry into the polluted zone and their mortality. This is a reasonable default hypothesis, although it cannot be formally checked with the data.

The issue of interest is addressed by contrasting the fate (dead/alive) of individuals having entered the zone impacted by the trout farm effluents (treatment) with those having remained outside (and downstream) from this zone (control). The polluted zone corresponds to the five kilometres downstream from the fish culture facility over which a significant reduction in the salmon juvenile abundance was evidenced (Prévost, 1999). Among the fish retained for analysis, those whose presence within the polluted zone could be ascertained before November 15 – by having been located there at least once or by having been recorded at the fixed station above the trout farm - were considered within the treatment group.

The data set used consists of 52 fish having returned to the R. Scorff in 2001 (43 fish) and 2002 (9 fish) (Table 1). They had spent two winters at sea (2SW, 15 fish) or one winter at sea (lSW or grilse, 37 fish). The date of entry into freshwater and of tagging ranged from March 3 to June 21 for the 2SW fish and May 29 to October 26 for the grilse. Eleven individuals entered the polluted zone below the fish farm. Of the 13 fish which died prior to November 15, 5 had previously entered the polluted zone. The experimental design underlying this data set is obviously unbalanced and non-orthogonal. However, as usual with ecological field data, it was mostly imposed by nature and could not be fully controlled.

Mortality model

Pre-spawning mortality of an anadromous adult is assumed to be a Bernouilli process:

$$f_i \sim Bern(m_i) \qquad (1)$$

m_i is the mortality probability of salmon i (i = 1 to 52), whose fate f_i is equal to 1 if it died or 0 if it survived.

The issue of interest is to assess the effect of the entry into the polluted zone on the m_i's. Previous information gathered on the R. Scorff indicates that mortality differs between 2SW and 1SW fish and varies annually. We use a logit linear formulation to account for the effect of these three factors:

$$\text{logit}(m_i) = b_0 + b_y\, y_i + b_a\, a_i + b_p\, p_i \qquad (2)$$

y_i, a_i, and p_i are binary variables indicating the year (0 → 2001, 1→ 2002), the sea age (0 → 1SW, 1→ 2SW), and the entry into the polluted zone (0 → no entry, 1→ entry), respectively. b_0, b_y, b_a *and* b_p are the model parameters. Given the relative paucity of data available and the lack of balance and orthogonality of the experimental design, interaction effects could not be estimated properly. Hence, none were introduced in the model.

The intensity of the effect of the entry into the polluted zone can be seen as a mortality multiplier, denoted $m^p_{\psi,\alpha}$ for a fish of year ψ and sea age α. Under the model set at equation (2):

$$m^p_{\psi,\alpha} = \frac{\text{logit}^{-1}(b_0 + b_y I_\psi + b_a I_\alpha + b_p)}{\text{logit}^{-1}(b_0 + b_y I_\psi + b_a I_\alpha)} \qquad (3)$$

where :
$I_\psi = 0$ for $\psi = 2001$ and $I_\psi = 1$ for $\psi = 2002$,
$I_\alpha = 0$ for $\alpha = 1SW$ and $I_\alpha = 1$ for $\alpha = 2SW$

$\text{logit}^{-1}(b_0 + b_y I_\psi + b_a I_\alpha + b_p)$ is the probability of mortality of a fish of year ψ and of sea age α having entered the polluted zone, whereas $\text{logit}^{-1}(b_0 + b_y I_\psi + b_a I_\alpha)$ is the probability of mortality of a fish of the same year and sea age but not having entered the polluted zone.

Bayesian treatment

The Bayesian treatment of this model amounts to deriving the posterior probability distribution of the unknown model parameters, denoted $p(B|D)$, B being the full set of coefficients (b_0, b_y, b_a, b_p) and D the mortality data of radio-tracked fish (Table 1). The parameter of ultimate interest is b_p. It accounts for the effect of the entry into the zone perturbed by the trout farm on the mortality of salmon adults. The *a posteriori* probability that b_p is positive, denoted $P(b_p>0|D)$, evaluates the odds that the entry into the polluted stretch increases mortality given the data. This probability is obtained by the following integral:

$$P(b_p > 0|D) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{0} p(B/D)\,db_0\,db_y\,db_a\,db_p \qquad (4)$$

Integrating the joint posterior of B over the full range of variation of b_0, b_y, and b_a amounts to treating these unknowns as nuisance parameters. The intensity of the effect of the entry into the polluted zone was assessed by considering the marginal posterior probability distributions of the $m^p_{\psi,\alpha}$'s which are functions of the original parameter vector B.

Bayesian analysis requires assigning prior probability distributions to all the free unknowns of the model. We chose the default option of using little informative and independent priors for each component of the parameter vector B. Normal priors with mean 0 and large variance (10^6) were used.

Posterior inferences were conducted by MCMC sampling techniques using the Winbugs software (Spiegelhalter et al., 2003). Convergence towards the target distribution was assessed by means of the Gelman-Rubin statistic as modified by Brooks and Gelman (1998), a tool included in Winbugs. Three chains with contrasted starting points were used.

Convergence was reached after 1000 iterations for all the model parameters. Sampling was carried on for 10000 additional iterations and all inferences were derived from the resulting 30000 draws.

Results

The posterior probability that the entry into the zone polluted by the trout farm increases the risk of riverine mortality of salmon adults is very high: $P(b_p>0|D) = 0.984$. Pre-spawning mortality was also dependent on (Table 2):

- sea age, 2SW fish having a significantly higher mortality probability than their 1SW counterparts;
- the year, with a poorer survival in 2001 compared to 2002.

The intensity of the effect of the trout farm pollution was potentially very high (Figure 2); the median of the posterior distribution of the $m^{p}_{\psi,\alpha}$'s varies between 1.956 and 7.08 according to the combination of year and sea age considered. This means that in the best case (1SW fish in 2002), there is a 50% chance that the mortality probability of individuals having entered the polluted zone is at least double that of fish which have not been exposed to that zone.

Discussion

The ecological impact of freshwater fish culture on rivers has been largely documented (e.g. Daniel and Haury, 1995; Doughty and McPhail, 1995; Boaventura et al., 1997; Selong and Helfrich, 1998; Lalumera et al., 2004). Pollution from fish farm effluents alters various components of lotic ecosystems, including fish (Prévost, 1999; Oberdorff and Porcher, 1994). This paper demonstrates that the riverine pre-spawning mortality of anadromous Atlantic salmon adults is increased by the pollution from a fish farm. Even when substantial, fish mortalities are easily overlooked in the field. Anadromous adults of Atlantic salmon are big fish and the R. Scorff is a small river, regularly frequented by anglers and its salmon population is subject to a continuous scientific monitoring programme. Despite these favourable conditions, among the 13 salmon adults which were confirmed dead in the present study, only one was detected without the help of its radio-transmitter.

Riverine mortality of adults before reproduction impacts on population renewal. The decrease in survival for adults due to fish farms is potentially high but has to be appraised on a case by case basis. Of course it shall depend on both the type and the intensity of the pollution, but also on the location of the fish farm along the river. It would be of particular concern when a facility is located on the lower reaches. Indeed, in such a case the entire population of adults has to get into the polluted zone and thus would be exposed to a factor which could increase mortality. This applies to Brittany, where salmon populations are found in many relatively small coastal streams (the R. Scorff being of average size), which are also used for intensive aquaculture of trout. The largest farms are installed on the lower to medium reaches of the main branches of the river networks in order to have an adequate water supply for the operation. The concern is reinforced by recent information from the R. Scorff (Prévost, unpublished data) indicating that in recent years, the Atlantic salmon population did not or hardly replaced generations.

Atlantic salmon is a well studied species both from an ecological perspective in the wild and from a fish health perspective in aquaculture. Freshwater fish farming activities may have a significant influence on the renewal of wild fish populations and Atlantic salmon is an interesting species to look deeper into this issue. For instance, in the present case, it is the combination of the migratory behaviour of the adults and their large size which allowed the use of radio-tags to track individually marked fish and to contrast them relative to their exposure to the fish farm effluents. The ultimate mechanism(s) by which survival of salmon adults is affected is(are) not known. A combination of immuno-depression due to contaminated water and sediments below fish farms (Rice et al., 1996; Arkoosh et al., 1998a) with a higher exposure to pathogens or parasites originating from fish farms (McVicar, 1997) is a plausible explanation which could be investigated further (Arkoosh et al., 1998b). Atlantic salmon can be affected by fish farming in freshwater not only at the adult stage but also during the juvenile recruitment process (Prévost, 1999). The ultimate consequences (fish losses) are quantifiable (De Oliveira et al., 2001; this paper) and therefore could be integrated into comprehensive modelling approaches such as life cycle models (Rivot et al., in press) or individual based models (Rose, 2000).

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Table 1: Summary of the mortality data of the radio-tagged salmon adults from the R. Scorff.

			Fate		
Year	Sea age	Pollution	alive	dead	Total
2001	1SW	no	24	4	28
		yes	2	1	3
	2SW	no	6	4	10
		yes	0	2	2
2002	1SW	no	2	0	2
		yes	3	1	4
	2SW	no	1	0	1
		yes	1	1	2
Total			39	13	52

Table 2: Summary statistics of the posterior distribution of the model parameters based on a 30000 MCMC sample.

Parameter	mean	Std. dev.	5^{th} percentile	median	95^{th} percentile
b_p	2.218	1.103	0.5083	2.168	4.095
b_0	-2.038	0.5575	-3.008	-2.002	-1.183
b_a	1.693	0.7691	0.4466	1.684	2.97
b_y	-1.908	1.339	-4.224	-1.825	0.1305

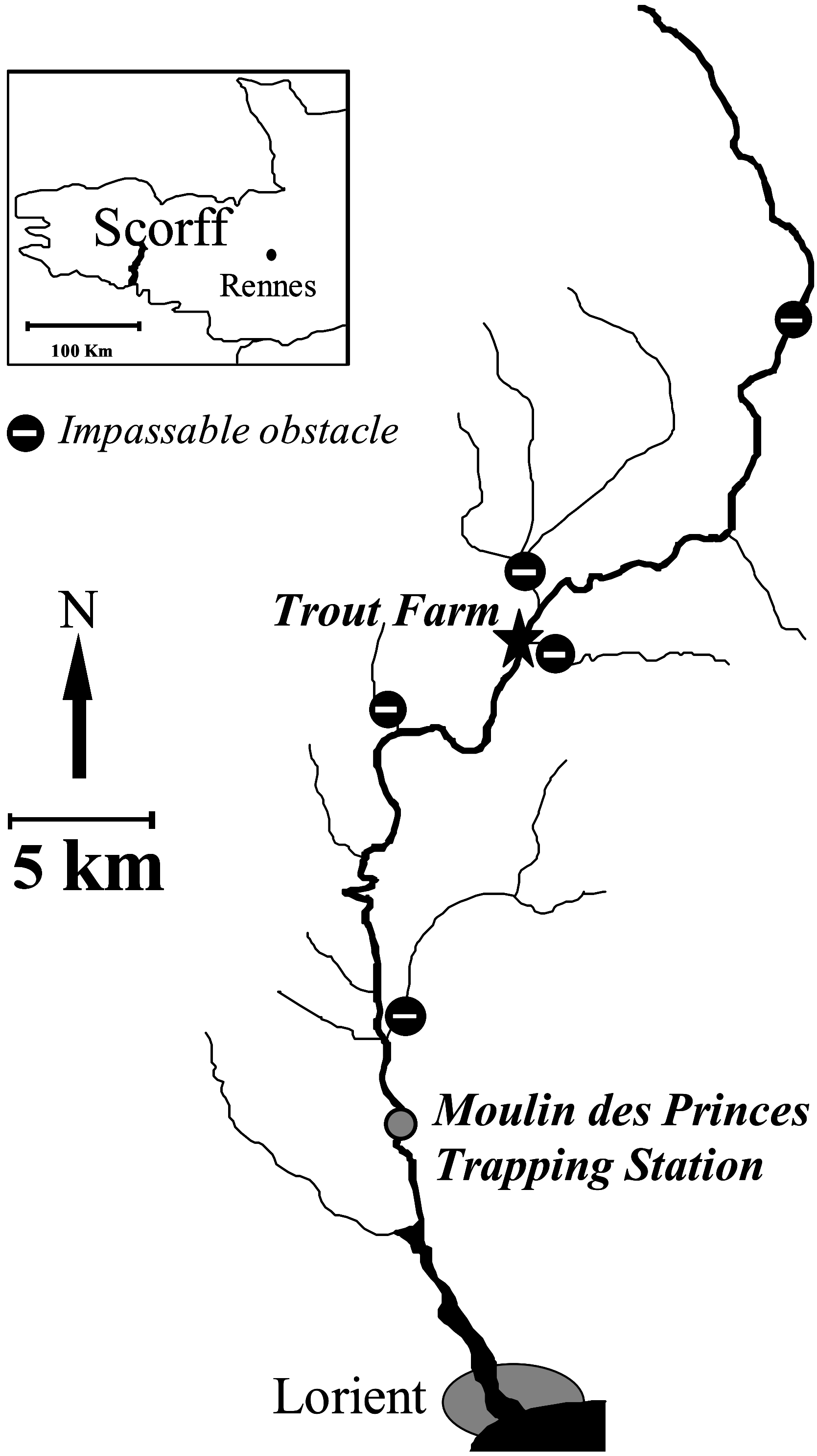

Figure 1: The R. Scorff.

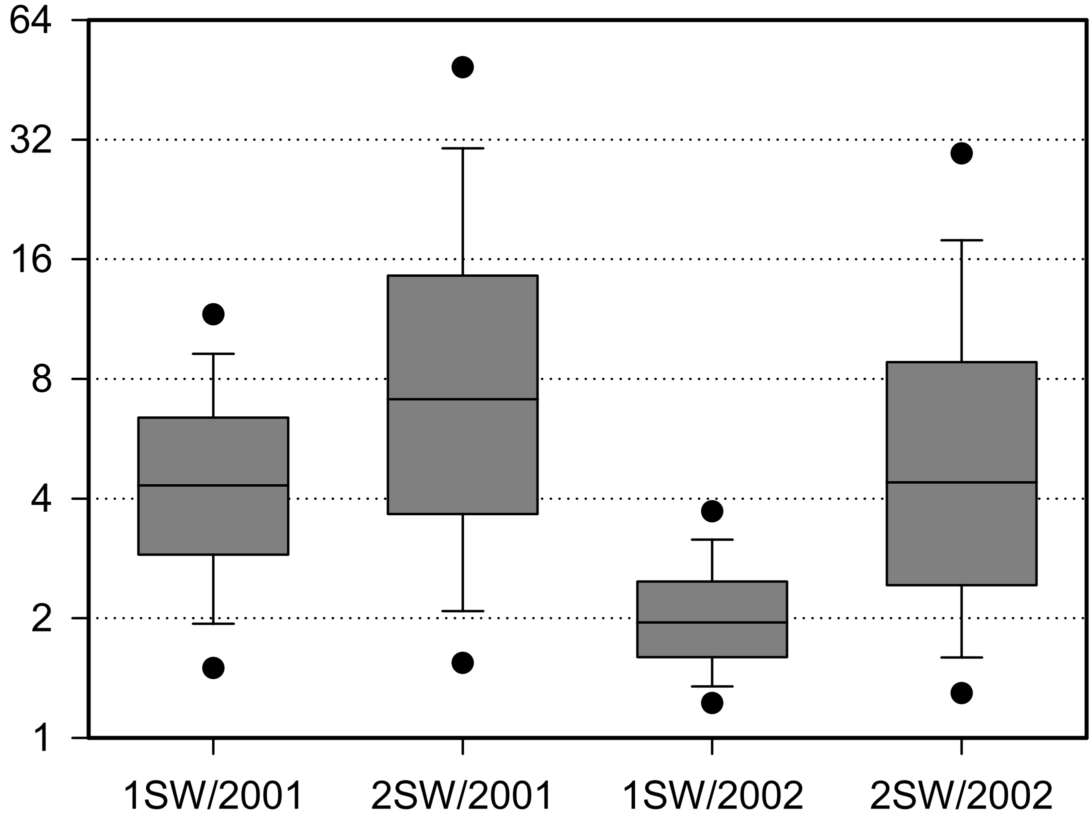

Figure 2: Box plots of the posterior distributions of the mortality multipliers $m^{p}_{\psi,\alpha}$. The 5th, 10th, 25th, 50th, 75th, 90th, 95th percentiles are displayed. A log scale is used for the Y-axis.