Climate change may affect growth and life history in Atlantic salmon juveniles over the last 30 years

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Introduction

• Context

Atlantic salmon stocks (*Salmo salar*) are declining worldwide. The species is sensitive to direct impacts of human activities (*e.g.* exploitation) and to indirect impacts (e.g. habitat loss or degradation, climate change). It is on the red list of endangered species in Europe.

In France, 80% of the French salmon rivers are found in the Armorican Massif (Brittany and Lower Normandy, AM in the following). This region has a mosaic of small stocks supported by many short rivers. Salmon populations in the AM support a recreational rod-and-line fishery (> 50% of the total annual catches in France). A mandatory declaration of catches was introduced in 1987.

• Intra-population variation in the reproductive life span

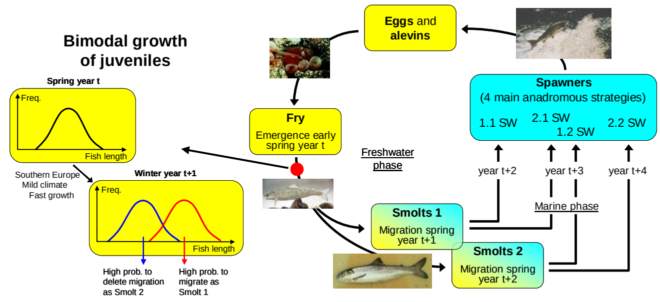
A. Salmon populations in the AM are characterized by an intra-population variation in the reproductive life span. Almost all juveniles smoltify after 1 or 2 years spent in freshwater (Smolt 1 or Smolt 2, under the control of bimodal growth of juveniles). Almost all returning adults are 1 or 2 sea-winter fish (1SW or 2SW). The equilibrium between these 4 anadromous reproductive strategies conditions the mean generation time and the population dynamics. Maintaining the intra-population variability in the reproductive life span is fundamental to face the inter-annual variations of environmental conditions.

• Question and Objectives

Available data suggest a decline in the mean generation time during the last 30 years, that may be due to : 1) A decline in the mean sea-age (not investigated here) ; 2) A decline in the Mean Age at Smoltification (MAS) (the proportion of Smolt 1 per cohort).

The aim of the study was : 1) To characterize the variations (medium-long term trend and inter-annual variations) of the MAS of A. salmon in the AM over the last 30 years ; 2) To investigate the mechanisms leading to the observed variations, in particular the influence of temperature and the enrichment of nutrients upon the juvenile growth.

Simplified A. salmon life cycle

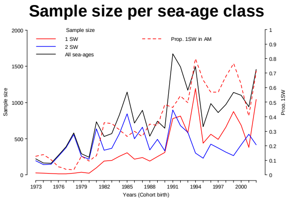


Salmon data

• Sampling of returning adults : Survey of the rod-and-line fishery

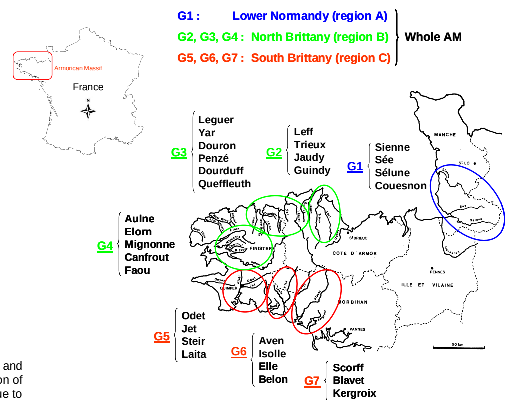
Adults fish are sampled during their spawning migration in 30 rivers in the AM. *Main sampling method* : Survey of the rod-and-line fishery (a valuable method for large sample sizes). Voluntary declaration of capture from 1972 to 1986, and mandatory declaration since 1987. *Complementary sampling* : Scientific traps (Sélune R., Aulne R., Scorff R.). *Sample size* : >25000 fish over the whole 1972-2005 period.

Sample size per sea-age class



Sample size is equilibrated between regions A,B and C (not shown) and increases during the period (1987 – date of the mandatory declaration of catches). The proportion of 1SW fish in catches increases, partly due to a selective fishery with an increasing effort on 1SW.

• 30 rivers sampled in the Armorican Massif

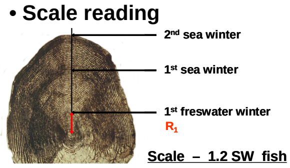


• Available information on each captured fish

- Date, place (river) of capture
- Size, weight
- Scale reading : river-age (Sm1 or Sm2 or more), sea-age (1SW or 2SW or more), spawning mark (multi-spawners)

➔ **Estimation of the birth date.**

• Scale reading



• Prop. of Sm1 per cohort and per geographical strata

$$PSm1(t) = \frac{n_{1.1\,SW}(t+2) + n_{1.2\,SW}(t+3)}{n_{1.1\,SW}(t+2) + n_{1.2\,SW}(t+3) + n_{2.1\,SW}(t+3) + n_{2.2\,SW}(t+4)}$$

Year of cohort birth — Year of 1st spawning

• Focus on the Scorff R. : Back-calculated size of pre-smolts and δC^{13} stable isotopes analysis

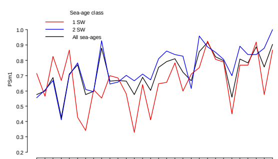
The hypothesis that the temporal changes in MAS results from modifications in juveniles growth conditions was investigated at the scale of the Scorff R.. **1)** 720 adults were captured in the Scorff R. between 1972 and 2005. R_1 (radius at the circuli of the 1st freshwater winter) was estimated from scale reading. The fish length L_1 at the 1st winter was back-calculated from the linear relation $L_1 = f(R_1)$ established from juveniles captured by electrofishing. **2)** δC^{13} stable isotopes analysis on archived scales of juveniles were performed to test for a local enrichment of the food chain.

Results

1. Time trends in PSm1(t)

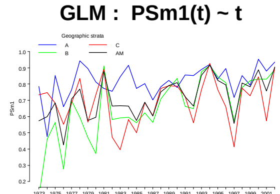
The time trend is estimated from logistic regression (*glm*) PSm1(t) ~ t. Residuals of *glm's* were analyzed for *i)* patterns of synchronization between geographical strata ; *ii)* correlation with environmental factors.

Psm1(t) per sea-age class

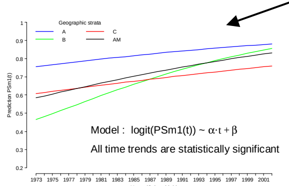


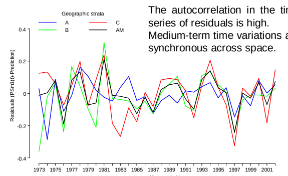
⇒ The increase in PSm1 is similar for both 1SW and 2SW sea-age classes. It is not an artifact due to the shift in sea-age classes in catches / returns

GLM : PSm1(t) ~ t



Trends — Residuals





The autocorrelation in the time series of residuals is high. Medium-term time variations are synchronous across space.

For all geographical strata, the time variation in the PSm1(t) combines a long-term increasing trend over the period 1973-2002 (year of cohort birth) with medium-term fluctuations that are synchronous across the geographical strata.

⇒ A significant reduction in the Mean Age at Smoltification.

⇒ Similar patterns of time series across space strongly suggest the influence of environmental forcing variables.

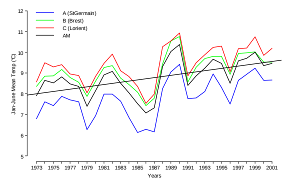
2. Environmental data

Annual mean Air temperature (T°C) were computed for the period : January-June (fry emergence and early growth of juveniles) (*Source* : Météo France).

Annual and Winter North Atlantic Oscillation Index (*Source* : www.cgd.ucar.edu/cas/jhurell).

Time trends (and residuals) were estimated from linear model Env(t) ~ t.

Temperature



⇒ For all geographical strata, the time variation in the Mean Air Temperature (January - June) combines a long-term increasing trend over the period 1973-2001 with medium-term fluctuations that are synchronous across the geographical strata.

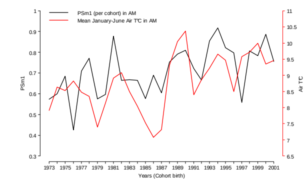
⇒ No correlation was found with NAO Index series.

3. Correlation of PSm1 with environmental variables

Correlations were computed between time series of residuals after filtering linear trends (time series of residuals are stationary).

Statistical tests were adjusted for autocorrelation (*Pyper and Peterman 1998. Comparison of methods to account for autocorrelation in correlation analysis in fish data. Can J. Fish Aquat Sci., 55: 2127-2140*).

Correlation Psm1 - Temperature



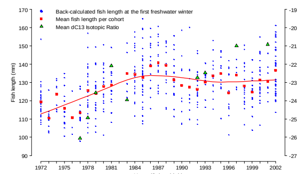
⇒ Both series have a significant increasing time trend

⇒ Linear correlation between series of residuals (PSm1 and T°C, after removing the linear trend) is positive and highly significant (R^2 = 0.55, p-value = 0.006 accounting for a reduction of the df from N=29 to N*=18 due to the high level of autocorrelation in the series).

4. Focus on the Scorff R. : Back-calculated lenght of pre-smolts and δC^{13} stable isotopes analysis

⇒ A significant trend in the back-calculated length of fish at the first freshwater winter before smoltification as Smolt 1 (+1.5cm over the study period).

⇒ Stable isotopes analysis on archived scales of juveniles revealed that δC^{13} significantly increases over the study period



Conclusion

- In the Armorican Massif, the time variation in PSm1 combines a long-term increasing trend over the period 1973-2002 (year of cohort birth) with medium-term fluctuations that are synchronous across the geographical strata.
- Results showed a significant reduction in the Mean Age at Smoltification. Similar patterns of time series across space strongly suggest the influence of environmental forcing variables. Correlation analyses at the regional scale of the AM showed that the time series of PSm1 is positively correlated with the Temperature during the first freshwater winter-to-spring growth period for 0+ juveniles.
- At the local scale of the Scorff R., back-calculation of juvenile size revealed that the length of one-year juveniles significantly increased over the period. Stable isotopes analysis on archived scales of juveniles showed that δC^{13}-ratio in scales increased.
- Results suggest that the decrease in the Mean Age at Smoltification may be due to changes in juveniles growth performance, in response to warming (climate change) and/or to change in primary production level (local nutrients enrichment) in the rivers. Hence, this could be an evidence of the impact of global warming and eutrophication on A. salmon life history traits and population dynamics.
- However, the decrease in MAS could also be a response to other factors. In particular, selective fishing on late maturing fishes may be responsible for a decrease in the mean age at sexual maturity.
- Many different forces are likely to push towards a reduction of 1) the mean reproductive life span ; 2) the intra-population variability of life histories. This could greatly impact the capacity of populations to resist to inter-annual variations of environmental conditions.