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Effect of winter harshness on Atlantic salmon (*Salmo salar* L.) egg to fry (0+) and fry to parr (1+) over-winter mortality

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Although winter mortality has long been regarded as a major factor affecting salmonid production in cold-region rivers, only few studies have explored the impact of winter harshness on salmonid mortality. In this study, we conducted an analysis of juvenile Atlantic salmon egg to fry (0+) and fry to parr (1+) over-winter mortality in relation to various hydro-climatic variables. We analysed the egg and fish abundances data collected between 1983 and 1992 on the Trinité River (Québec, Canada) by the Société de la Faune et des Parcs du Québec (FAPAQ, Québec). The results indicate that egg to fry over-winter mortality was high (min 83%, max 93%) but inversely related to winter coldness as defined by the cumulated freezing degree-days between October 1st and January 31st ($r^2 = 0,81$, $p < 0,001$) and positively related to winter low discharge as defined by the ratio of November to February mean discharges ($r^2 = 0,80$, $p < 0,001$). Fry to parr overwinter mortality ranged from 42% to 73% between years and was inversely related to winter coldness (cumulated freezing-degree days in January and February) ($r^2 = 0,91$, $p < 0,0001$) and positively related to conditions conducive to frazil and anchor ice formation in early winter (number of days in November with mean air temperature below –10^{o}C) ($r^2 = 0,77$, $p < 0,01$). These results are discussed in relation with other similar studies conducted on the Indian River, New Foundland (Chadwick, 1982) and Catamaran Brook, New Brunswick (Cunjak and Therrien, 1998).

1. Introduction

Although winter mortality has long been regarded as a major factor affecting salmonid survival in cold-region rivers (Reimers, 1957; Needham and Jones, 1959; Power *et al.*, 1993; Cunjak, 1996), only few studies have explored the impact of winter harshness on juvenile Atlantic salmon (*Salmo salar* L.) inter-stage mortality. In this paper, we assessed the effect of winter harshness on Atlantic salmon egg to fry (0+) and fry to parr (1+) over-winter mortality on the Trinité River. In particular, the potential impact of discharge, air temperature and ice events was explored.

2. Methodology

2.1 Study site

The Trinité River (49˚25' N; 67˚18' W) is located on the north shore of the St-Lawrence River (Québec, Canada) and drains an area of 562 km^2 over granitic rocks of the Canadian Shield. The main stem of the river is 80 km long but only the first 70 km is available to salmon. The Trinité River basin is characterized by a boreal climate (Anonymous, 2005) with average monthly air temperatures below 0°C from November to April (Environment Canada, station 7042749). The coldest months are generally January and February with mean monthly temperatures near -15°C. The river is generally covered by ice from mid-November to late April.

2.2 Abundance and inter-stage mortality

Inter-stage mortality was estimated from egg, fry and parr abundances calculated by the Société de la Faune et des Parcs du Québec (FAPAQ, Government of Québec) between 1983 and 1992. Egg deposition was estimated from the weight and abundance of spawners captured at a fish ladder near the river mouth (Caron and Fournier, 1994; Caron *et al.*, 2004). Spawners count and weight were multiplied by a fecundity factor (grils: 2 430 eggs kg^{-1}; multi-sea-winter: 1 535 eggs kg^{-1}) and then summed up to estimate the annual egg production on the river (Caron *et al.*, 2004). No correction for predation, egg loss from retention in the female body cavity and non-fertilization during spawning was applied to the estimated egg abundance.

Electrofishing data collected by the FAPAQ between 1984 and 1992 were used to estimate the annual abundance of fry (0+) and parr (1+). From photo interpretation, the Trinité river was classified into four habitat units: pool, riffle, rapid and run (Clavet, 1982). Average juvenile density was estimated for each habitat unit from stratified electrofishing data and total abundance within each habitat unit was computed by multiplying juvenile density by the area of the respective habitat. Parr older than 1+ were excluded of the analysis because migration starts at that age (Caron *et al.*, 2004) and migration data could not be reliably matched with abundance data. Thus only fry (0+) and parr (1+) abundance data were used in the present analysis.

Egg to fry (0+) mortality M_E (%) was derived from the estimated total egg deposition (E) at year t and fry abundance (F) at year t+1 [$M_E = (E_t - F_{t+1}/E_t)*100$]. Similarly, fry (0+) to parr (1+) mortality (M_F) was estimated from fry abundance at year t and parr abundance (P) at year t+1 [$M_F = (F_t - P_{t+1}/F_t)*100$].

2.3 Hydro-climatic variables

A first group of variables was derived from air temperature data. These variables consisted of cumulated freezing degree-day indices (FDD) calculated i) monthly from October to April (FDD_O to FDD_A), ii) bimonthly to describe the freeze-up period (FDD_{ND}), the main winter period (FDD_{JF}) and the break-up period (FDD_{MA}), iii) by cumulating freezing degree-days from October 1st to the end of each month (FDD_{O-N} to FDD_{O-A}) (Table 1). Cumulated freezing degree-days indices have been shown in the past to provide reliable estimations of river ice growth (Ashton, 1986; Hirayama *et al.*, 2002). In addition, since frazil and anchor ice events have been shown to generally occur when air temperature is below -10°C (Hirayama *et al.*, 1997), variables compiling the number of days with mean daily temperature below -10°C in November ($Inf\text{-}10_N$) and December ($Inf\text{-}10_D$) were created to assess the potential role of such events on egg and juvenile overwinter mortality (Table 1).

The second group of variables was derived from water discharge data. These variables consisted of mean monthly discharges ($Flow_N$ to $Flow_A$), mean winter discharge (Mean Winter) and of the peak discharge during the break-up period (Peak flow) (Table 1). Discharge ratios between the autumn and winter periods ($Flow_{N/F}$, $Flow_{N/J}$ and $Flow_{O/F}$) were calculated in order to evaluate the variations of flow level between these periods. Finally, the freeze-up date was included in the analysis (Freeze-up date) (Table 1).

Table 1 Independent variables used in the analysis and sorted by category. FDD: Freezing degree-day, subscripts O, N, D, J, F, M and A denote respectively October, November, December, January, February, Mars and April.

Temperature Cumulated freezing degree-day				**Discharge**			**Ice**
Monthly	Bimonthly	Period starting Oct 1st	Frazil and anchor ice	Monthly	Ratio	Peak Flow	Cover
FDD_O	FDD_{ND}	FDD_{O-N}	$Inf\text{-}10_N$	$Flow_N$	$Flow_{N/F}$	Peak flow	Freeze-up date
FDD_N	FDD_{JF}	FDD_{O-D}	$Inf\text{-}10_D$	$Flow_D$	$Flow_{N/J}$		
FDD_D	FDD_{MA}	FDD_{O-J}		$Flow_J$	$Flow_{O/F}$		
FDD_J		FDD_{O-F}		$Flow_F$			
FDD_F		FDD_{O-M}		$Flow_M$			
FDD_M		FDD_{O-A}		$Flow_A$			
FDD_A				Mean Winter			

2.4 Data analysis

A total of 30 environmental hydro-climatic variables (Table 1) were analysed using simple and multiple regression analysis in order to determine their potential effects on egg to fry (0+) and fry to parr (1+) over-winter mortality. The Bonferroni technique for limiting the overall experimentwise error rate was applied as a precautionary principle.

3. Results

3.1 Egg and juvenile abundance

From 1983 to 1991, estimation of annual egg deposition on the Trinité River ranged from 2·19 million to 4·17 million eggs (mean = 2·62 million). From 1984 to 1992, annual fry abundance ranged from 196 679 to 386 215 individuals (mean = 292 798) and annual parr abundance from 76 772 to 203 639 individuals (mean = 130 889).

3.2 Egg to fry mortality

The results indicate that egg to fry over-winter mortality was high (min 83%, max 93%) but inversely related to winter coldness as defined by $FDD_{O\text{-}J}$ (cumulated freezing degree-days between October 1st and January 31st) ($r^2 = 0{,}81$, $p < 0{,}01$) and positively related to winter low discharge as defined by $Flow_{N/F}$ (ratio of November to February mean discharges) ($r^2 = 0{,}80$, $p < 0{,}01$). When combined in a multiple regression analysis, these two variables explained 92% (adj. r^2) of the inter-annual variations of egg to fry mortality ($p < 0{,}05$). These two predictors were not significantly cross-correlated and thus considered valid predictors of mortality ($r = -0.31$, $p > 0{,}05$).

3.3 Fry to parr mortality

Fry to parr overwinter mortality ranged from 42% to 73% between years and was inversely related to coldness of the main winter period as defined by FDD_{JF} (cumulated freezing-degree days in January and February) ($r^2 = 0{,}91$, $p < 0{,}0001$) and positively related to conditions conducive to frazil and anchor ice formation in early winter $Inf\text{-}10_N$ (number of days in November with mean air temperature below -10^oC) ($r^2 = 0{,}77$, $p < 0{,}009$). When combined together in a multiple regression analysis, these two variables explained 97% (adj. r^2) of the inter-annual variations of fry to parr mortality. These two predictors were not significantly cross-correlated and thus considered valid predictors of mortality ($r = 0.21$, $p > 0{,}05$).

4. Discussion

4.1 Egg to fry mortality

The results of the analysis of the Trinité River data demonstrate the existence of a strong and significant negative relationship between inter-annual egg to fry mortality and winter coldness. These results are different from those obtained by Chadwick (1982) on the Indian River (New Foundland, Canada) and by Cunjak and Therrien (1998) on Catamaran Brook (New Brunswick, Canada) who both observed a generally positive trend between egg to fry mortality and winter coldness. We suggest that these disparities could possibly be explained by differences in winter coldness between these rivers. On the Trinité river, a cold winter ($FDD_{O\text{-}J} \approx$ 1 000-1100°C-d) will lead to the rapid formation of a complete ice cover, thereby reducing the frequency and importance of frazil ice events. Conversely, a mild winter on this river ($FDD_{O\text{-}J} \approx$ 700-800 °C-d) will leave some portions of the river open (usually fast flowing water) during part of the winter season, thereby favouring the occurrence of frazil and anchor ice events. The habitat conditions selected by salmonid for spawning are known to be favourable to anchor ice formation (Beltaos *et al.*, 1993) and the eggs are particularly vulnerable to these winter conditions due to their immobility. As a results of anchor ice formation, eggs may freeze into the substrate (McNeil, 1966; Reiser and Weshe, 1979; Walsh and Calkins, 1986) or suffer from the restriction of the intragravel flow causing a depletion in dissolved oxygen within the substrate and limiting the elimination of metabolic waste (Stuart, 1953; Bakkala, 1970; Walsh and Calkins, 1986; Calkins, 1989; Power *et al.*, 1993; Cunjak *et al.*, 1998; Beltaos, 2000). This could explain the observed negative relationship between egg to fry mortality and coldness on the Trinité River.

On Indian River and Catamaran Brook, winters are generally milder than on the Trinité River. Thus, a mild winter ($FDD_{O\text{-}J} \approx 250$°C-d) on these rivers will generate small amounts of surface ice and, since few cold spells will occur, there will be a reduced number of detrimental frazil and anchor ice events on incubating eggs. However, very cold winters on the Indian River and Catamaran Brook ($FDD_{O\text{-}J} \approx 700$°C-d) are more similar to mild winters on the Trinité River ($FDD_{O\text{-}J} \approx$ 700-800 °C-d), where frazil and anchor ice events are susceptible to have a negative effect on the survival of the eggs.

Analysis of the Trinité River data also showed a significant positive relationship with winter low discharge as defined by the ratio of November to February mean discharges ($r^2 = 0{,}80$, $p < 0{,}001$). A similar relationship has also been observed by Chadwick (1982) on the Indian River and is explained by the fact when the spawning period coincides with high water levels, females tend to position their redds higher in elevation on the spawning riffles, thereby making the incubating eggs more likely to be dewatered during extreme winter low flows. Such large flow variations between spawning and winter low flows have also been reported to cause freezing of the eggs within the substrate (Walsh and Calkins, 1986).

4.2 Fry to parr mortality

Our analysis of fry to parr mortality on the Trinity River showed a strong significant inverse relationship with winter coldness and a positive relationship with air temperature conditions conducive to frazil and anchor ice events in early winter. These results differ from those obtained in Normandy (France) by Baglinière *et al.*, (1993) and in Newfoundland (Canada) by Chadwick (1982) who both observed that fry to parr mortality was greater during cold winters. We also here suggest that on the Trinité River, cold winters lead to the rapid formation of a complete and stable ice cover that offers protection to juvenile salmonid by reducing the frequency of frazil and anchor ice events. Early winter is a stressful period of acclimatization to a changing environment (Cunjak and Therrien, 1998) and is critical for juvenile trout survival especially during their first winter (Smith and Griffith, 1994). Modification of their habitat by frazil and anchor ice might force the juveniles to move and find a new shelter (Brown and Mackay, 1995b; Brown, 1999) using critical energy reserves (Walsh and Calkins, 1986). Additionally, Beltaos *et al.* (1993) have noted that frazil ice can directly harm or kill salmons by plugging their gills.

The highest mortality rates for the Trinité River were observed during the mildest winters. From field observations, Chisholm *et al.* (1987) proposed that the harshest winter conditions are encountered at mid-elevation where surface ice cover is incomplete and anchor ice frequently observed. These observations are confirmed by Brown (1999) who observed that conditions with multiple and recurring freezing-thawing cycles leading to anchor ice events are hazardous for trout. If conditions with unstable ice conditions are detrimental to salmon and trout, a complete and stable ice cover might be beneficial to the salmonids. Indeed, Calkins (1989) observed that there is no direct evidence that surface ice cover limits fry and parr habitat and Power *et al.* (1993) suggested that the ice cover may provide protection against predation from birds and mammals Furthermore, the ice cover may play a positive role on the energy budget of Atlantic salmon by raising food consumption (Finstad *et al.*, 2004; Parrish *et al.*, 2005) and decreasing resting metabolic rates (Crawshaw, 1984; Finstad *et al.*, 2004), thereby decreasing energy losses during this critical period.

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