Understanding the effects of environmental variability on the run timing of juvenile Atlantic salmon (*Salmo salar* L.) migrating from upland tributaries

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Introduction and Aims

- Atlantic salmon (*S. salar* L.) migrate from tributary streams as autumn parr and spring smolts.
- Strong seasonal patterns in the timing of migration (run-time) vary within and between catchments.
- Within-site, between-year run-time variability has been related to environmental controls (EC) including river temperature and discharge.
- Recent studies suggest long-term temporal trends in run-timing.
- Unclear to what extent any temporal trends can be explained by temporal trends in EC.
- **This study aims to: 1) describe inter-annual variability in juvenile migration and relationships to EC; 2) assess evidence for long-term trends in run-timing and EC; 3) determine whether trends in run timing (start, middle and end of the migration), can be explained by inter-annual variability in EC.**

Study Site and Methods

- Juvenile emigrants monitored at two permanent fish traps in Scottish Highlands (Fig. 1) by Marine Scotland Science.
- Girnock Burn: ~32 km^2, 1966 – present
  Baddoch Burn: ~23 km^2, 1988 – present
- Start, middle, end of run characterised as day of year (DoY) where 15 (RT15), 50 (RT50), and 85-%ile (RT85) of run has migrated, respectively.
- For both sites, mean daily water temperature (T, °C) was modelled from air temperature and discharge following Jackson et al., (2018) (Fig. 2).

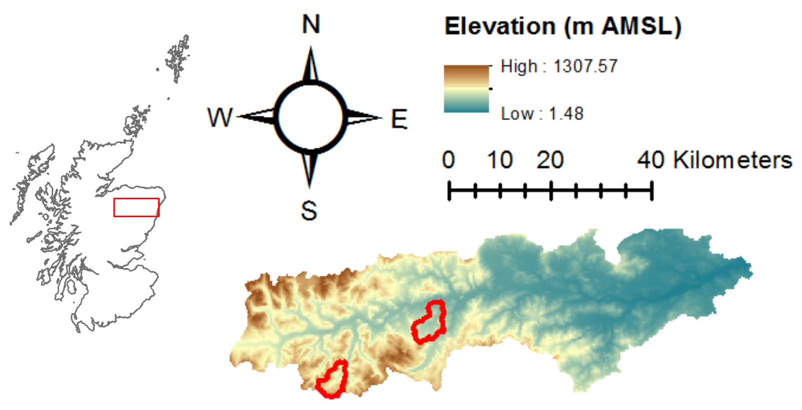

Figure 1: Inset shows location of Dee catchment. Location of Girnock and Baddoch Burn monitoring sites on Deeside. Baddoch Burn at higher elevation and further from sea than Girnock.

- Mean daily discharge (Q, m^3 s^{-1}) time series for Baddoch modelled based on statistical relationship with neighbouring catchment to fill missing data for historical time period (Fig. 3).

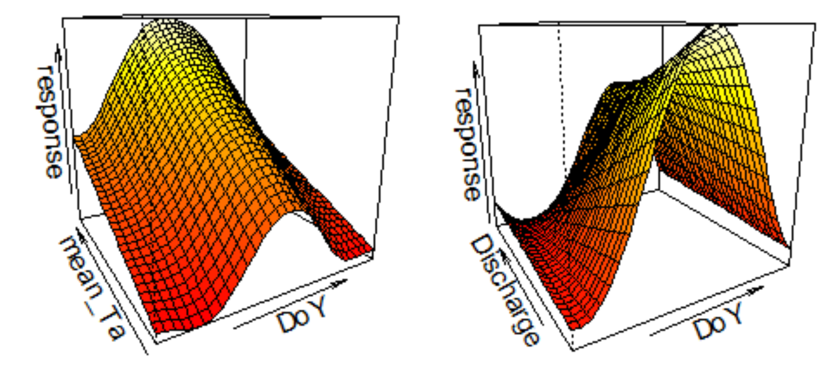

Figure 2: Mean daily water temperature modelled as a linear function of air temperature (left) and discharge (right) where slope and intercept were allowed to vary with DoY.

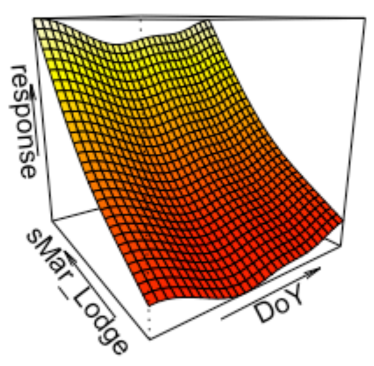

Figure 3: Mean daily discharge at Baddoch was modelled as a linear function of discharge at Mar Lodge, where the intercept and slope of this relationships was allowed to vary with DoY.

- Agglomerative polythetic clustering analysis was performed to group years with similar emigrant run-timing characteristics. Groups were compared to groups of years determined through clustering of EC characteristics. See Table 1 for summary characteristics.

Discharge/Temperature	Smolt run
Median duration Q > 1.0 (m^3 s^{-1})	RT15
Median duration Q > 0.5 (m^3 s^{-1})	RT50
Cumulative Q (DoY 1-151)	RT85
CV_Q (-)	Duration (DoY 1-DoYq85)
Pulse count T > 12 (days)	Maximum proportion
Maximum T (°C)	CV_proportion (-)
Cumulative T (DoY 1-151)	
CV_T (-)	

Table 1: Variables included in the clustering, shown for smolt migration only. CV = Coefficient of Variation. DoYq indicates values for DoY where a percentile 'q' of run is reached. Maximum proportion is the maximum observed proportion on a single day of the run for each year. Variables were selected from initial list, whereby variables with a correlation > 0.7 were excluded, providing a list of uncorrelated variables describing variability in discharge, temperature, and smolt run.

- EC covariates based on cumulative metrics for temperature and discharge calculated for sites and parts of the run.
- Regression model used to investigate trends in RT15, RT50, and RT85.
- Step up, step down model selection using Bayesian Information Criterion (BIC).
- Model terms allowed to be smooth or linear.
- Starting model of general form, with site allowed to interact with all covariates:

$$RT_{quantile} \sim Site * (Year + CumulativeT + CV\_T + CumulativeQ + CV\_Q)$$

Reference
Jackson et al., 2018. *Sci Total Environ.* DOI: https://doi.org/10.1016/j.scitotenv.2017.09.010

Results

Characterisation of run and EC

- Only Girnock spring run data shown as example.
- Heatmaps (and cluster analysis) indicate no clear association between migration runs with different characteristics and EC regimes (Fig. 4a-b).
- Years with early RT15 tend to also have extended duration and vice versa (Fig. 4a); years with late RT50 and RT85 tend to have low max_Proportion and CV_proportion and vice versa (Fig. 4a).

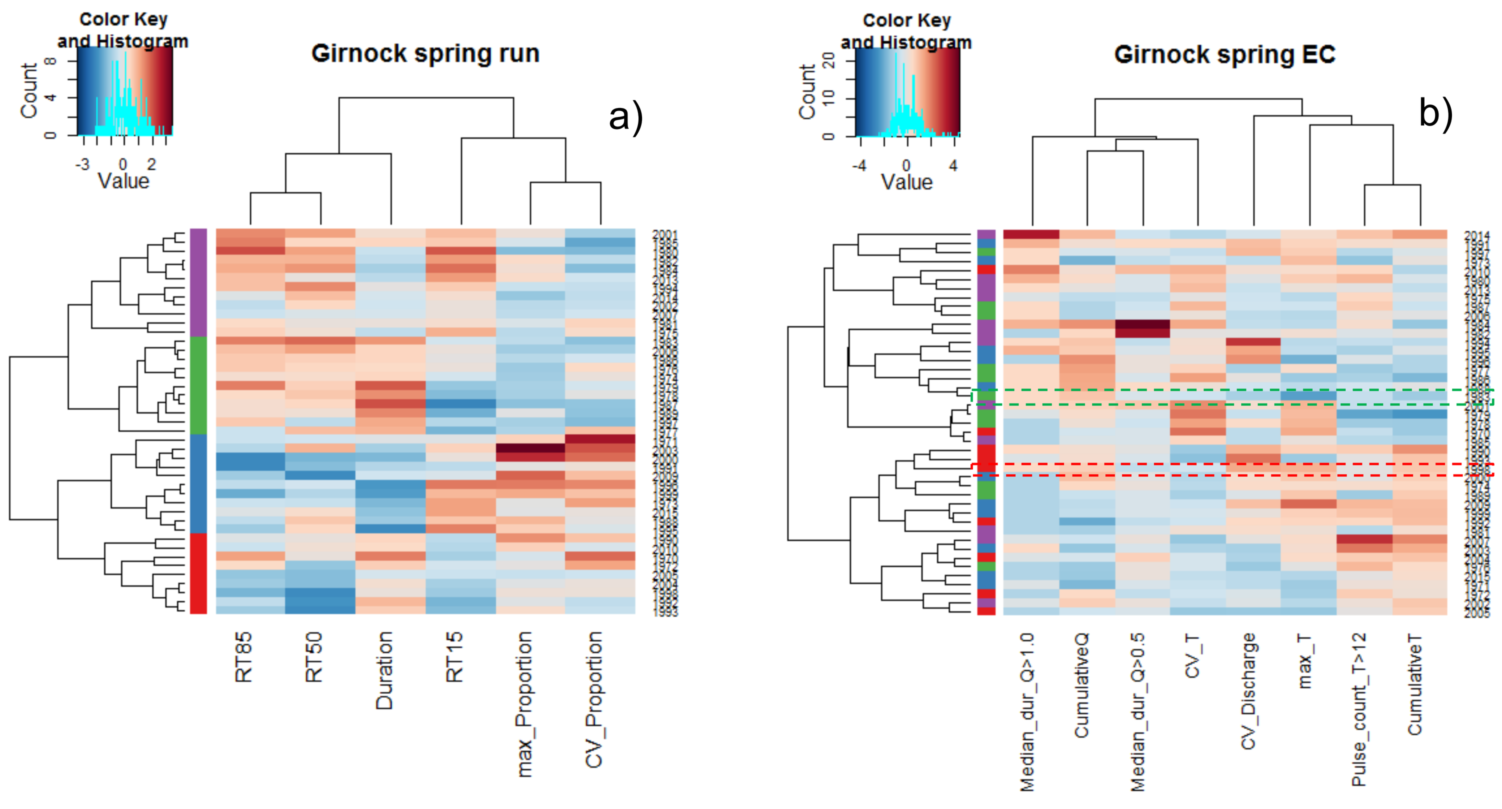

Figure 4: Heatmap and clustering of the smolt run (left panel) and EC regime (right panel), for the Girnock Burn. Warm colours indicate high values (e.g., reds for RT50 indicate late start of the run). Colour bar on the left indicates the clustering of years for the run-timing characteristics, which is also mapped onto the left hand side of the EC clustering.

- Warmer years with variable Q associated with early RT50 (red box Fig. 4 and bold red line Fig. 5).
- Cooler years with less variable Q associated with late RT50 (green box Fig. 4 and bold green line Fig. 5).

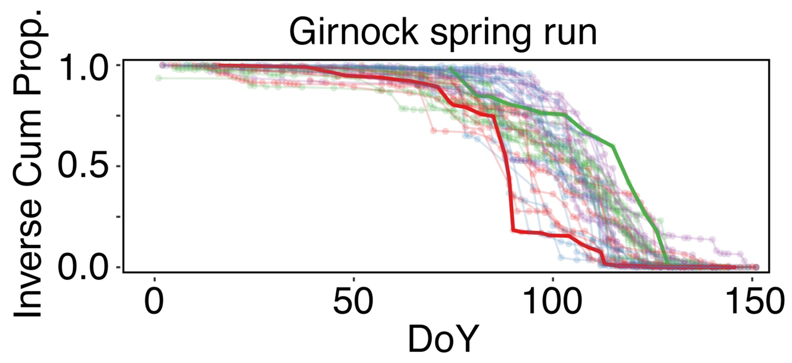

Figure 5: Smolt migration duration curves for the Girnock Burn, coloured according to run clustering from Fig. 4.

Run time modelling

- Best model for RT15 was null model indicating no environmental controls
- Final model for RT50 was:

$$RT50 \sim CumulativeT + CumulativeQ + CV\_Q + Site$$

- RT50 is earlier in years where accumulated temperature is higher (Fig. 6a).
- RT50 is later in years where accumulated Q is greater (Fig. 6b).
- RT50 is earlier in years where Q is more variable (Fig. 6c).
- RT50 is later in the Girnock than the higher altitude Baddoch (Fig. 6d).

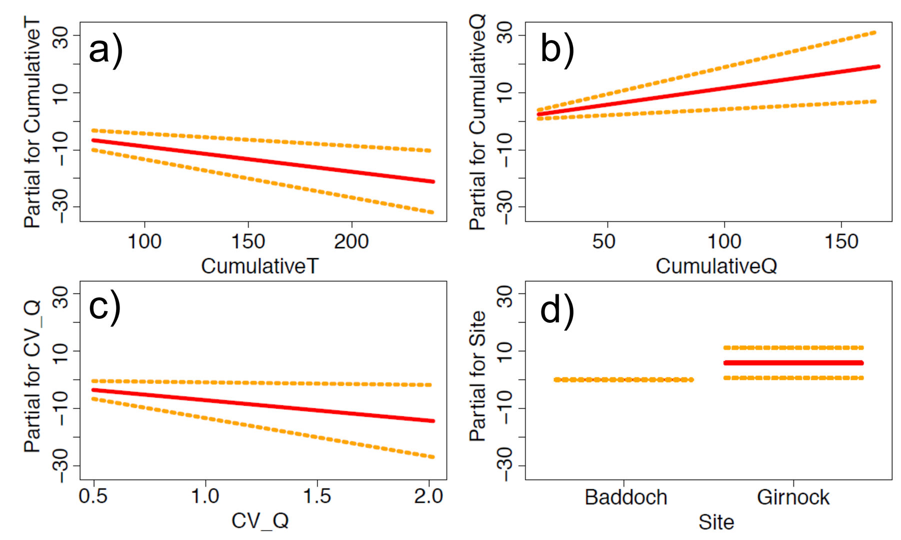

Figure 6: Partial effect plots for the final model for RT50. Red lines indicate the scaled effect, orange lines indicate the standard error.

- Final model for RT85 was:

$$RT85 \sim CumulativeT$$

- The RT85 is earlier in years where cumulative temperature was greater.

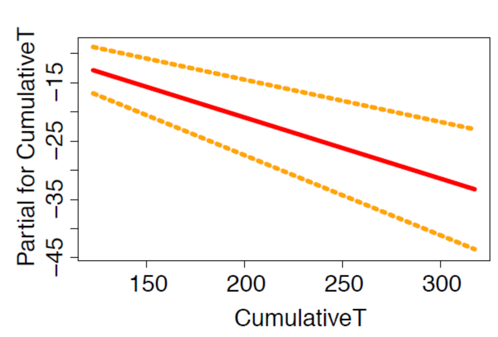

Figure 7: Partial effect plots for the final model for RT85. Red line indicates the scaled effect, orange lines indicate the standard error.

Conclusions

- Effects of EC on migration are complex, but general shape of migration curve influenced by temperature and discharge.
- Start of smolt run unaffected by EC.
- Temperature has a strong influence on middle and end of the run.
- This has implications for smolt migration in a warming climate: higher temperatures lead to earlier end of run and compressed migration.

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