FAST-TRACKING FARMED KING SALMON CLIMATE CHANGE ADAPTATION

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SUMMARY

The thermal tolerance of pedigree Chinook salmon (*Oncorhynchus tshawytscha)* was tested in two tank-based challenges: (a) High temperature (HT) at 23.5 °C and (b) Temperature and Oxygen (TO) at 21.0 °C with low dissolved oxygen (DO), using commercial breeding programme fish. Fish were measured at the start and end of both challenges and survival was monitored. Survival and days to death in both the HT and TO treatments were moderately heritable. Low genetic correlations between these traits at the different challenge conditions indicate they are separate traits. The results demonstrate the significant potential to breed for improved thermal tolerance in all-female farmed Chinook salmon.

INTRODUCTION

Climate change is altering Aotearoa New Zealand's marine environment at an unprecedented rate with major changes severely impacting farming and natural systems. Farmed Chinook salmon are negatively impacted when temperatures exceed 17.0-18.0 °C for prolonged periods and marine heatwaves have resulted in reduced survival. An important climate resilience trait is thermal tolerance, and we explored the potential to improve this trait in pedigree Chinook salmon by investigating survival, time to death and growth at two temperatures: (a) 23.5 °C (HT) and (b) 21.0 °C with lower DO (TO). We report genetic parameters for these experimental challenges.

MATERIALS AND METHODS

A total of 2,609 individually tagged all-female pedigree Chinook salmon from the 2023-year class were obtained from a commercial salmon breeding programme. The tagged salmon were transferred to Cawthron's Finfish Research Centre (FRC) in June 2024, 13 months post-fertilisation, and acclimated to seawater. A timeline of the trial is shown in Figure 1. Weight (g) (WT) prior to the challenge tests (WT1) and after exposure to HT (WT2) and TO (WT3) were measured. Specific growth rates (SGR) (percent change in weight per unit of time) from pre- to post-challenge under the HT (SGRHT) and TO treatments (SGRTO) were also calculated. Further details of the rearing systems, husbandry and phenotypes can be found in Elvy *et al*. (2022) and Scholtens *et al*. (2023).

For the challenges 2,609 fish were randomly distributed across 9 x 8000 L tanks, 289-290 fish per tank. Four tanks of fish were challenged at 23.5 °C (DO 6.0 to 8.0 mg/L) and 5 tanks were challenged at 21.0 °C with lower DO (3.5-4.5 mg/L). In all tanks, the temperature was increased by 0.5 °C per day from 15.0 °C until the target temperature was reached. Lower DO levels were achieved by reducing the amount of oxygen added to the tanks over 7 days. Mortalities and time of death were recorded regularly. The end-point for HT was 60 % mortality. For TO the end-point was after 73 to 77 days under the challenge conditions.

Statistical analysis. Thermal tolerance was evaluated based on survival and growth. Survival traits were defined in two different ways - binary and continuous. Binary test survival (BS) after exposure to either HT (BSHT) or TO (BSTO) was coded as 1 for survivors and 0 for dead. The continuous survival trait was measured as the number of days to death (DTD) at HT (DTDHT) and

TO (DTDTO). To accommodate censoring of survivors in the challenges, DTD traits were transformed after giving survivors a DTD beyond the maximum in the mortalities (Gianola and Norton 1981). All analyses were run using R 4.3.3. Descriptive statistics were obtained using the 'psych' package. Specific growth rate was calculated as $(\ln(Wt_y) - \ln(Wt_x))/\text{days}) \times 100$ where x and y represent pre- and post-challenge weights, respectively (Scholtens *et al*. 2023).

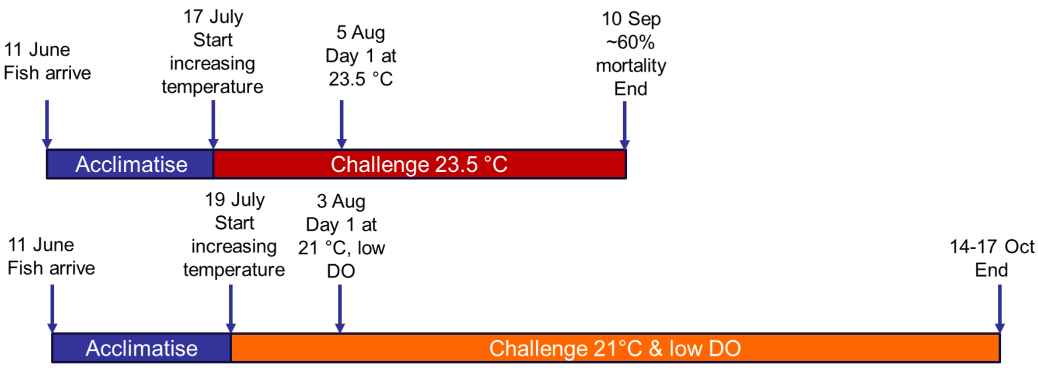

Figure 1. Timeline of the two challenge treatments

Genetic parameter estimation. Estimates of variance and covariance components for WT, SGR, DTD, and BS were obtained using the Restricted Maximum Likelihood (RML) procedure in ASReml version 3 (Gilmour *et al*. 2009). Continuous traits (WT, SGR and DTD) were analysed fitting a mixed linear animal model (LM); $y_{ij} = \mu + f_i + a_j + e_{ij}$, where y_{ij} is the phenotype observed; μ is the overall mean; f_i is the fixed effect of tank (tank history); a_j is the additive genetic effect for the j^{th} individual and e_{ij} was random residual. The additive genetic effect was assumed to be $a_i \sim N(0, \mathbf{G}\sigma_a^2)$, and residuals assumed to be $e_{ij} \sim N(0, \mathbf{I}\,\sigma_e^2)$, where **G** is the genomic relationship matrix, calculated using the GBS data while taking read depth into account (the KGD method) (Dodds et al., 2015); and **I** is an identity matrix. The phenotypic variance was the sum of genetic (σ_a^2) and residual (σ_e^2) variances. For the binary traits (BSHT and BSTO), a generalized linear mixed model using a binomial distribution with a logit function was used. Narrow-sense heritability (h^2) was estimated for each trait as the proportion of genetic variance with respect to the total variance, except for BSHT and BSTO, where the residual variance was fixed at $\pi^2/3$.

Genetic and phenotypic correlations were estimated using bivariate animal models with the same components as the univariates, it was assumed that genetic effects were distributed as $\sim N\left(\begin{bmatrix}0\\0\end{bmatrix}, G\otimes\begin{bmatrix}\sigma_{a_i}^2 & \sigma_{a_{ij}}\\ \sigma_{a_{ji}} & \sigma_{a_j}^2\end{bmatrix}\right)$, where $\begin{bmatrix}\sigma_{a_i}^2 & \sigma_{a_{ij}}\\ \sigma_{a_{ji}} & \sigma_{a_j}^2\end{bmatrix}$ is the additive genetic variance-covariance structure and the residual effects were distributed as $\sim N\left(\begin{bmatrix}0\\0\end{bmatrix}, I\otimes\begin{bmatrix}\sigma_{e_i}^2 & \sigma_{e_{ij}}\\ \sigma_{e_{ji}} & \sigma_{e_j}^2\end{bmatrix}\right)$, where $\begin{bmatrix}\sigma_{e_i}^2 & \sigma_{e_{ij}}\\ \sigma_{e_{ji}} & \sigma_{e_j}^2\end{bmatrix}$ is the residual variance-covariance structure.

RESULTS AND DISCUSSION

Fish phenotypic results. Descriptive statistics for growth and survival traits at multiple timepoints are presented in Table 1. As the temperature increased above 19.0 °C the feed response in all tanks decreased and most fish stopped feeding at 23.5 °C. This is reflected in the negative mean SGR over the HT challenge period. The TO fish had a mean SGR of 0.43. Mean SGR under optimal trial conditions (17.0 °C) was 0.84 for fish of similar size in a different trial (Scholtens *et al*., 2023).

Table 1. Descriptive statistics of growth and survival traits in Chinook salmon

Trait	N	Mean	SD	Min	Max
WT1	2,609	468.87	119.10	194.20	882.70
WT2	414	431.36	151.14	166.00	823.00
WT3	1,250	787.49	287.61	172.60	1760.00
SGRHT	414	-0.02	0.29	-0.83	0.67
SGRTO	1,273	0.43	0.30	-0.42	1.08
DTDHT	718	21.28	7.75	2.0	37.0
DTDTO	145	59.17	11.97	19.0	75.0
BSHT	1,134	0.37	0.48	0	1
BSTO	1,419	0.90	0.30	0	1

WT = weight (g); SGR = SGR between weight assessments pre- (WT1) and post-challenge (WT2 or WT3); DTD = days to death for mortalities only and BS = binary survival.

Challenge results. Mortalities occurred once the temperature reached 23.5 °C and HT was terminated at close to 60% cumulative mortality after 37 days. The TO cumulative mortality reached only 10.18 % after 73-77 days. The heritabilities (h^2) for the temperature tolerance traits BS and DTD at both temperatures were moderate (Table 2) but not as high as in some reports (Benfey *et al*. 2024; Perry *et al*. 2005).

Table 2. Estimates of variance components for growth and survival traits in Chinook salmon

Trait	$h^2 \pm$ SE	$\sigma_e^2 \pm$ SE	$\sigma_a^2 \pm$ SE
WT1	0.37±0.03	8270.21±295.90	4824.24±459.88
WT2	0.43±0.08	13619.97±1691.73	10408.32±2525.65
WT3	0.34±0.04	53988.63±2884.67	27557.13±4003.27
SGRHT	0.37±0.09	0.01±0.01	0.01±0.01
SGRTO	0.21±0.04	0.01±0.01	0.01±0.20
DTDHT	0.29±0.06	0.70±0.06	0.28±0.07
DTDTO	0.38±0.20	0.59±0.18	0.36±0.20
BSHT	0.23±0.04	3.29	0.96±0.20
BSTO	0.25±0.05	3.29	1.08±0.30

SE = standard error; h^2 = heritability; $\sigma_e^2 =$ error/residual variance; $\sigma_a^2 =$ additive genetic variance; WT = weight; SGR = SGR between weight assessments pre and post-challenge; DTD = days to death and BS = binary survival.

Weight and SGR heritabilities were moderate to high in both challenges. Pre-challenge weight (WT1) was positively correlated with survival in TO but negatively correlated with survival in HT (Table 3). The genetic correlations between the survival traits in HT and TO were all low and negative, indicating they are different traits. Although WT1 was negatively correlated with survival at 23.5 °C, the SGR during this challenge was positively correlated with survival (0.254±0.150). Similarly, the SGR during the 21.0 °C challenge was also positively correlated with DTDTO and BSTO (0.512±0.134 and 0.576±0.131) respectively, indicating that animals with good growth genetics also tended to survive longer. Further bivariate analysis will consider latent threshold models with the binary traits.

Table 3. Estimates of genetic (below diagonal) and phenotypic (above diagonal) correlations ± (standard errors) for growth and survival traits in Chinook salmon

	WT1	WT2	WT3	SGRHT	SGRTO	DTDHT	DTDTO	BSHT	BSTO
WT1		**0.916** (0.012)	0.775 (0.013)	0.505 (0.055)	0.314 (0.032)	-0.308 (0.037)	0.269 (0.030)	-0.274 (0.036)	0.288 (0.030)
WT2	**0.909** (0.027)			0.788 (0.041)		0.533 (0.069)		0.432 (0.079)	
WT3	**0.900** (0.022)	0.688 (0.120)			0.797 (0.014)		0.330 (0.043)		0.200 (0.047)
SGRHT	0.421 (0.107)	0.764 (0.077)	0.355 (0.143)			0.218 (0.089)		0.205 (0.089)	
SGRTO	0.490 (0.081)	0.600 (0.150)	**0.806** (0.043)	0.492 (0.170)			0.066 (0.046)		0.097 (0.046)
DTDHT	-0.165 (0.082)	0.490 (0.110)	-0.155 (0.105)	0.254 (0.150)	-0.171 (0.121)				
DTDTO	0.488 (0.092)	0.464 (0.163)	0.588 (0.098)	0.192 (0.187)	0.512 (0.134)	-0.168 (0.128)		0.778 (0.016)	**0.974** (0.002)
BSHT	-0.279 (0.089)	0.167 (0.152)	-0.250 (0.112)	0.062 (0.172)	-0.236 (0.129)	**0.957** (0.021)	-0.181 (0.142)		
BSTO	0.549 (0.090)	0.525 (0.164)	0.582 (0.107)	0.256 (0.189)	0.576 (0.131)	-0.217 (0.130)	**0.988** (0.006)	-0.239 (0.144)	

Key:
>0.8
0.60-7.9
0.40-5.9

CONCLUSION

The results indicate that selecting for improved thermal tolerance in Chinook salmon is possible but the design of the tank-based challenge has to be carefully considered as survival and SGR at 21.0 °C with low DO and at 23.5 °C are different traits.

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