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MEMORANDUM

TO: John Palmer, Environmental Protection Agency

Michele DeHart

FROM: Michele DeHart, Fish Passage Center

DATE: May 8, 2018

SUBJECT: Fall Chinook Survival between Bonneville and McNary Dams, and the Relationship between Water Temperature, Travel Velocity, and Arrival Timing

The Fish Passage Center (FPC) received a request from the Environmental Protection Agency (EPA) for an analysis. The main objective of this request was to compare the passage time (or travel time) and survival for fall Chinook adults from Bonneville to The Dalles dam when river temperature were below 20°C, between 20 and 21 °C, and above 21 °C. Also, the requester would like the results to include the percentage of the annual fall Chinook run that occurred when temperatures were in the three specified ranges. We have completed the request and the main findings were as follows:

- Adult fall Chinook that encountered water temperatures below 20°C had a higher mean survival compared to fish that encountered temperatures between 20 and 21°C, and above 21°C.
- The mean survival for the adult fall Chinook that migrated in-river as juveniles was higher than the transported fish, across all three temperature ranges.
- Adult fall Chinook had a steady mean travel velocity between 18 to approximately 20°C, but the mean velocity slowed when they encountered temperatures greater than approximately 20°C.
- Adult fall Chinook traveled more rapidly when they arrived at Bonneville dam later in the season, accounting for water temperature and river flow.
- Adult fall Chinook had lower travel velocities in higher flow and/or if they were transported as juveniles.

Background

The Fish Passage Center has developed an upstream migration success analysis for Snake River summer Chinook, sockeye, and steelhead as a part of the Comparative Survival Study (CSS; McCann et al., 2017). Our adult upstream migration success study focused on the relationship between survival and water temperature between Bonneville and McNary dams. Overall, we confirmed the past findings that adult salmon and steelhead had a lower survival if they encountered higher water temperatures. Our results also indicated that adult salmon and steelhead exhibited a lower temperature tolerance and had longer travel time if they were transported as juveniles.

Because the EPA request had similar objectives to our CSS adult upstream migration success study, and Bonneville-McNary reach included the Dalles dam, we justified that the methodology for our CSS analysis could be applied for this analysis. Further, the results of this analysis could complement the CSS to provide a more comprehensive understanding of survival-temperature relationship in the Columbia River. Mainly, for this analysis, we examined the relationships between water temperature and 1) travel time/velocity, 2) arrival timing, and 3) survival.

Methods

We included PIT-tagged adult fall Chinook that were detected at Bonneville dam during return years 2003 to 2017. For each fish in the data set, we included its detection history at Bonneville, McNary, Ice Harbor, and Lower Granite dams. We also matched each fish with McNary tailrace temperature (°C) and McNary total flow volume (Kcfs) at the time of its detection/arrival at Bonneville, along with juvenile migration history (transported or not). We utilized water temperature information at McNary tailrace because temperature collection at Bonneville stopped around September 1st each year. We only included known fall Chinook (i.e. PTAGIS species codes of 13H and 13W) from the Snake River and adults that spent at least two years at sea. In other words, we did not include jacks nor fish with unknown origins. We did not distinguish between hatchery and wild fish, nor did we attempt to quantify the seasonal or annual changes in harvest in the fisheries between Bonneville and McNary dams.

Fish Travel Time/Velocity

For the travel time-temperature relationship, we first calculated the travel time in days between Bonneville and McNary dams for all fish that were detected at McNary (i.e. fish that made it successfully from Bonneville to McNary dams). Past analyses suggested that the distribution of fish travel time was often right skewed and required transformation to better approximate normality of the residuals and reduce heteroscedasticity (Chapter 3 in McCann et al., 2017; FPC, 2018). We also noticed that transforming travel time into velocity (by dividing distance between Bonneville and McNary dams, 236 km, by travel time) would often yield a centered, bell-shaped distribution and still allow a straight forward interpretation of the results.

We began to develop a regression model to assess the relationship between fish travel velocity (FTV) and its biological and environmental conditions, particularly Julian date of Bonneville detection, flow volume at McNary, McNary tailrace temperature, and juvenile transport history of individual fish. We included adult upstream migration year as a random effect to account for year to year variations in overall travel velocity. We compared models with different combinations of explanatory variables, including quadratic terms, and selected a best fitting model based on Akaike Information Criterion (AIC; Akaike, 1973). To improve model fit, we standardized all continuous variables. We fitted all models using `lmer()` function in the *lme4* package (Bates et al. 2015) in R.

Fall Chinook Arrival Timing

For the arrival timing-temperature relationship, we summarized the percentage of the annual fall Chinook run that occurred when water temperatures were in the following three specified ranges: between 20-21°C, below 20°C, and above 21°C. We also graphically summarized each year the arrival time of all fish in our data set along with the water temperature they encountered at McNary tailrace.

Fall Chinook Survival

To estimate the survival-temperature relationship, we used a Cormack-Jolly-Seber (CJS) model with individual covariates. We employed a Bayesian framework for our CJS models because it allowed immense flexibility to fit complex models. We followed the procedures in the CSS adult upstream migration success section (Chapter 8; McCann et al., 2017) to explore the data and identify suitable survival-temperature models. The response variable of the CJS model was a three-digit detection history at Bonneville, McNary, and above McNary (i.e. detection at Ice Harbor and Lower Granite combined into a single event). By having a three-digit detection history, we were able to estimate the detection and survival of adult fall Chinook to McNary. The individual fixed effects (explanatory variables) for survival between Bonneville and McNary dams were Julian date of Bonneville detection, flow volume at McNary, juvenile transport history of individual fish, and the three specified ranges of McNary tailrace temperature during detection (between 20-21°C, below 20°C, and above 21°C). The model also included random adult migration year effects.

After obtaining the results for the CJS model, we assessed the differences in survivals for adult fall Chinook that encountered each of the three specified temperature ranges. First, we summarized the marginal posterior distributions of the mean survivals for below 20°C, between 20 and 21°C, and above 21°C. Then we directly compared the survivals and summarized the distributions of differences. We also compared the mean survivals between groups with different juvenile transport histories, with all temperature ranges combined. The details of the CJS model and calculations can be found in Appendix A.

Results

Fish Travel Time/Velocity

The best fitting model included fixed effects explanatory variables McNary tailrace temperature, square of temperature, Julian date of Bonneville detection, square of Julian date, flow volume at McNary, and juvenile transport history of individual fish and random upstream migration year effects (Table 1, Model 2). The model was specified as follows:

$$FTV_i = \beta_0 + \beta_{Temp} \cdot Temperature_i + \beta_{Temp^2} \cdot Temperature_i^2 + \beta_{Jday} \cdot JulianDate_i + \beta_{Jday^2} \cdot JulianDate_i^2 + \beta_{Flow} \cdot Flow_i + \beta_{MigHis} \cdot Transport_i + \gamma_{yr[i]} + \epsilon_i,$$

where i is individual PIT-tagged fish, yr represents migration years 2003 to 2017, $Transport_i$ is an indicator variable, $\epsilon_i \sim N(0, \sigma^2)$, and $\gamma_{yr} \sim N(0, \sigma_{yr}^2)$.

Table 1: Comparison between fish travel velocity models with different explanatory variables. All models include random year effects.

	Variables	DF	AIC	Residual SE
Full	All variables and their quadratic terms	10	90969	10.6
Model 2	Without flow^2	9	90967	10.6
Model 3	Without flow^2 and Julian^2	8	90973	10.6
Model 4	Without flow^2, Julian^2, and temperature^2	7	91035	10.6

Our model showed the coefficients for β_{temp^2} and β_{Jday^2} being negative, indicating a concave down relationship for either water temperature or Julian date with fish travel velocity. To take a closer look, adult fall Chinook had a steady travel velocity between 18 to approximately 20°C, but the velocity slowed when they encountered temperature greater than approximately 20°C. Adult fall Chinook traveled more rapidly when they arrived at Bonneville dam later in date. And travel velocity ceased to increase around the end of September (Figure 1). Relationship between travel velocity and flow volume was mostly linear, and it showed that adult fall Chinook traveled less rapidly in higher flow. Also, adult fall Chinook traveled less rapidly if they were transported as juveniles.

Variance inflation factor showed low values for all variables (except for the quadratic terms) and indicated no serious concerns for multicollinearity. The *t* values for all parameter estimates were greater than two, indicating a strong support for the results (Table 2).

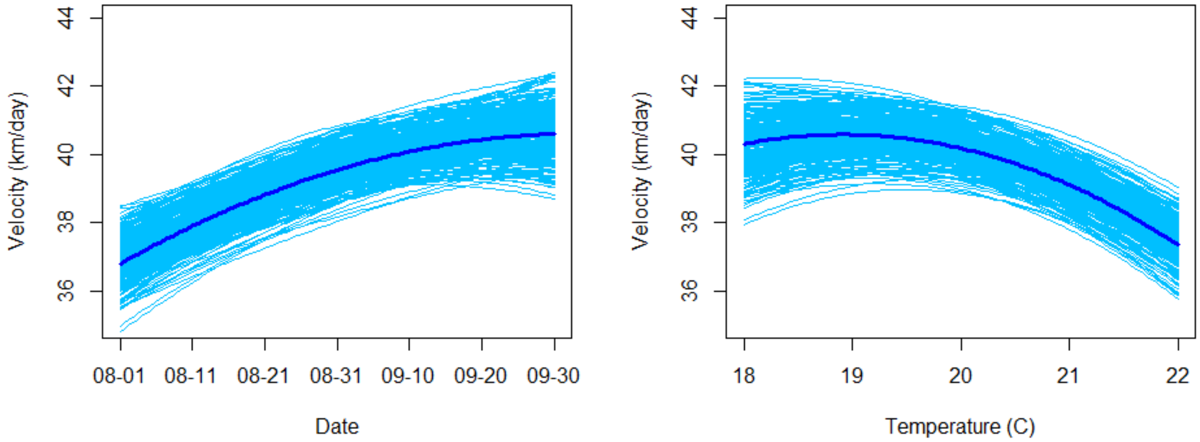

Figure 1: Left plot shows the estimated relationship between fish travel velocity and arrival date. Right plot shows the estimated relationship between fish travel velocity and water temperature. Light blue lines represent model uncertainties. The estimated relationships are shown for only in-river fish. The ranges of arrival dates and temperatures correspond to the middle 95% of our data.

Table 2: Coefficient estimates for the fish travel velocity model.

	Estimate	Std. Error	t value
(Intercept)	39.62	0.501	79.07
Transport	-3.101	0.238	-13.01
Temperature	13.05	2.835	4.602
Temperature^2	-13.86	2.78	-4.987
Julian Day	6.336	2.688	2.357
Julian Day^2	-5.565	2.73	-2.039
Flow	-0.736	0.169	-4.361

Fall Chinook Arrival Timing

Summaries of adult fall Chinook arrival timing, as it related to the three temperature ranges of interest were provided in Table 3 and Figure 2.

Table 3: The portions of PIT-tagged adult fall Chinook detected at Bonneville dam under each of the three specified ranges (below 20°C, between 20 and 21°C, and above 21°C) and their respective annual Bonneville to McNary conversions.

	Below 20°C	20 to 21°C	Above 21°C	MCN Conversion
2003	0.566	0.09	0.344	0.844
2004	0.584	0.368	0.048	0.776
2005	0.389	0.491	0.12	0.657
2006	0.125	0.768	0.107	0.571
2007	0.173	0.808	0.019	0.808
2008	0.398	0.444	0.159	0.691
2009	0.036	0.425	0.539	0.63
2010	0.754	0.203	0.043	0.7
2011	0.389	0.588	0.024	0.59
2012	0.904	0.096	0	0.773
2013	0.021	0.024	0.955	0.653
2014	0.364	0.341	0.295	0.679
2015	0.538	0.253	0.209	0.672
2016	0.206	0.3	0.494	0.606
2017	0.136	0.328	0.536	0.616

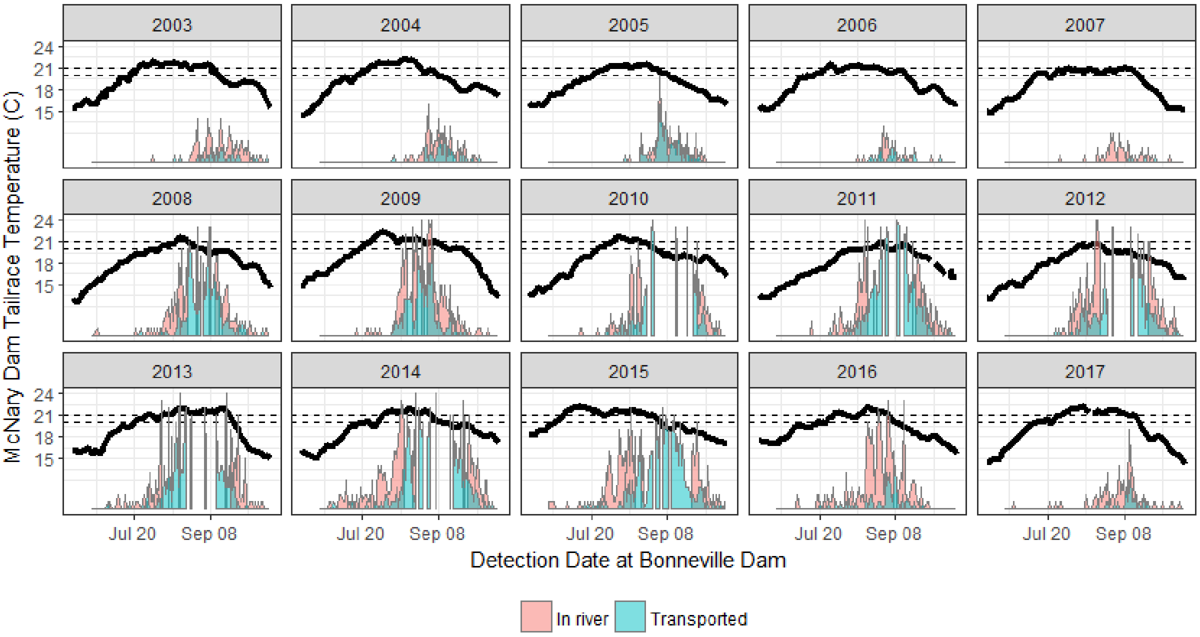

Figure 2: Black lines indicate the McNary tailrace temperature corresponding to the adult fall Chinook arrival dates at Bonneville dam. Below the temperature lines are the distributions of arrival for in-river and transported fish. Dash lines indicate temperatures 20 and 21°C.

Fall Chinook Survival

For adult fall Chinook that migrated in-river as juveniles, the estimated mean survival was 0.736 for fish that encountered temperature below 20°C (95% CRI= 0.695 to 0.778; Figure 3), 0.702 for temperature between 20 to 21°C (95% CRI= 0.658 to 0.748), and 0.682 for temperature above 21°C (95% CRI= 0.635 to 0.73). For adult fall Chinook that were transported as juveniles, the estimated mean survival was 0.669 for fish that encountered temperature below 20°C (95% CRI= 0.621 to 0.718), 0.631 for temperature between 20 to 21°C (95% CRI= 0.581 to 0.684), and 0.609 for temperature above 21°C (95% CRI= 0.557 to 0.664).

The mean survival for in-river adult fall Chinook that encountered temperature below 20°C was 0.034 greater than the ones that encountered temperature between 20 and 21°C (95% CRI= 0.015 to 0.053). The mean survival for adult fall Chinook that encountered temperature below 20°C was 0.054 greater than the ones that encountered temperature above 21°C (95% CRI= 0.028 to 0.08). For fall Chinook that were transported as juveniles, the differences in mean survivals between temperature ranges were similar to the in-river group.

The estimated mean survival for the transported fish was 0.071 lower than the in-river fish (95% CRI= 0.054 to 0.089), with all temperature ranges combined. Figure 3 compared the survivals between juvenile transport histories and separated by temperature range.

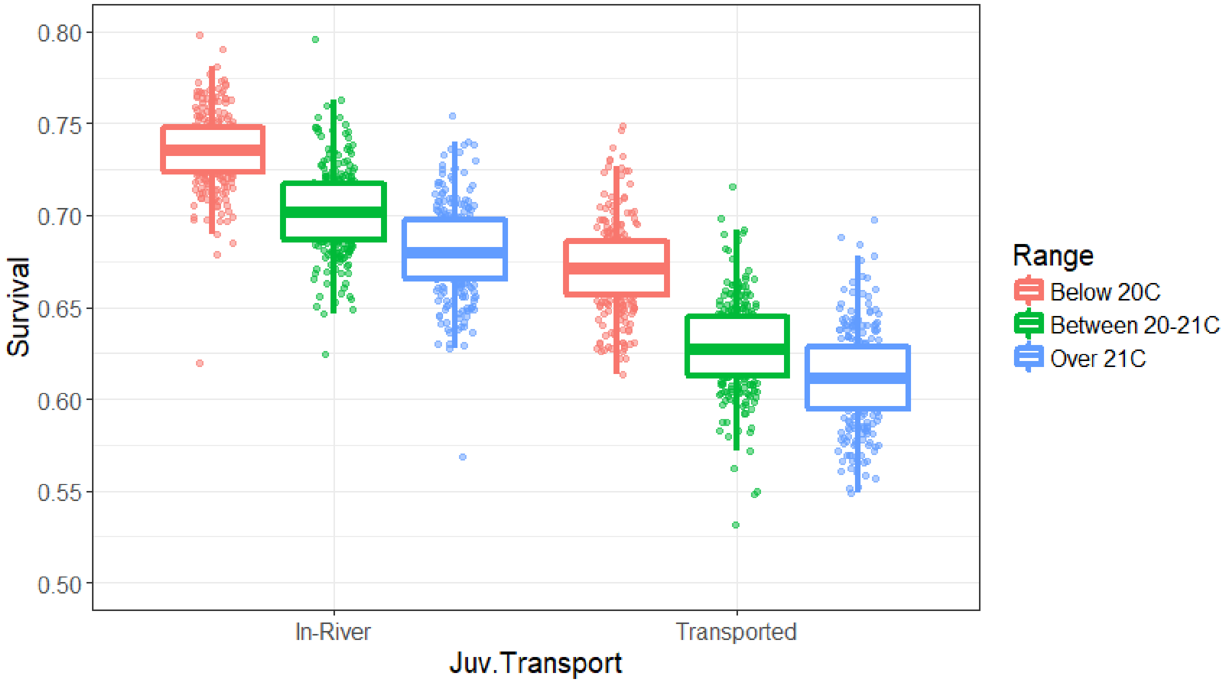

Figure 3: Boxplots compare the marginal posterior distributions of survivals for in-river and transported fall Chinook, categorized by temperature ranges.

Conclusion

The results from this analysis for the Snake River adult fall Chinook were consistent with our findings in the CSS adult upstream migration success section (chapter 8; McCann et al., 2017). We found that adult fall Chinook had a lower survival if they encountered water temperatures greater than 20°C and/or if they were transported as juveniles. Moreover, the results indicated that adult fall Chinook traveled less rapidly once they encountered water temperatures greater than 20°C. It is worth noting the similarity in patterns between temperature-survival and temperature-travel velocity relationships for adult fall Chinook.

Reference

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Appendix A

Fall Chinook Survival

To estimate the survival-temperature relationship, we used a CJS model with individual covariates in the Bayesian framework. The model was specified as follows:

$z_{i,t}|z_{i,t-1} \sim Bernoulli(z_{i,t-1} \cdot \phi_{i,t-1})$, where $z_{i,t}$ defined the true state of individual i at occasion t ($t = 1,2,3$), and $z_{i,1} = 1$ defined that all fish were to be alive when first detected at Bonneville.

$y_{i,t}|z_{i,t} \sim Bernoulli(z_{i,t} \cdot p_t)$, where $p_t \overset{iid}{\sim} Unif(0,1)$. p_t were the detection probabilities at McNary (t= 2) and the upper dams (t= 3).

To incorporate the individual covariates and random year effects, we modeled the survival from Bonneville to McNary dam ($\phi_{i,1}$) using a logit link function:

$logit(\phi_{i,1}) = \beta_0 + \beta_{Jday} \cdot JulianDate_i + \beta_{Flow} \cdot Flow_i + \beta_{Trans} \cdot Transport_i + \beta_{<20} \cdot Below20_i + \beta_{>21} \cdot Above21_i + \gamma_{year[i]}$.

Because survival (ϕ_2) and detection (p_2) upstream of McNary dam were confounded in the CJS model, we set $p_2 = 1$ and let ϕ_2 represent $\phi_2 \cdot p_2$ in our model. Further, we learned from previous studies that adult survivals were generally quite high at all reaches between Bonneville and Lower Granite dams (Chapter 8; McCann et al., 2017), so we assigned ϕ_2, or $\phi_{i,2} \cdot p_2$ in our model, a prior distribution between 0.5 and 1: $\phi_{i,2} \sim Unif(0.5,1)$. We also assigned $p_1 \sim Unif(0.5,1)$ under the same reasoning. We followed the recommendations by Gelman et al. (2008) and Broms et al. (2016) for choosing prior distributions for other parameters:

$\beta_0 \sim Cauchy(0,10)$,
$\beta_{Jday}, \beta_{Flow}, \beta_{Trans}, \beta_{<20}, and \beta_{>21} \overset{iid}{\sim} Cauchy(0,2.5)$,

$\gamma_{year[i]} \sim N(0, \sigma_{year}^2), year = 2003, \ldots, 2017$,
and $\sigma_{year} \sim half - Cauchy(0,2.25)$.

To facilitate better model convergence during estimation process, we standardized all continuous variables. We fitted the CJS model in program JAGS through an R environment (*jagsUI*; Kellner, 2016). The sampling included four chains of 40,000 iterations, with burn-in of 20,000 each. To reduce output file size, we only kept every fourth draw of our MCMC sampling (thinning of 4), which yielded a total of 20,000 sample draws from the joint posterior distribution.

Gelman's diagnostics showed that all parameters had $\hat{R}$'s close to 1 and adequate effect sizes (Table 4). Traceplots showed well mixing for all parameters (Figure 4). Diagnostics indicated no major concerns overall for model convergence.

To obtain the marginal posterior distribution of mean survival for below 20°C, we summed up each posterior draw for β_0 and $\beta_{<20}$ and take the inverse logit of the sum ($logit^{-1}(\beta_0 + \beta_{<20})$). For the mean survivals between 20 and 21°C and above 21°C, we followed the same procedures and calculated the following: $logit^{-1}(\beta_0)$ and $logit^{-1}(\beta_0 + \beta_{>21})$, respectively. We also compared the mean survivals between groups with different juvenile transport histories, with all temperature combined. To obtain the marginal posterior distributions for the difference between in-river and transported fish, we subtracted the posterior draw of survival for the transported fish from the posterior draw of in-river fish: $logit^{-1}(\beta_0) - logit^{-1}(\beta_0 + \beta_{Trans})$.

Table 4: Estimates from the CJS model for fall Chinook.

	Mean	SD	95% CRI	$\hat{R}$	Eff size
(Intercept)	0.86	0.11	(0.654, 1.087)	1.005	596
Arrival Date	0.259	0.028	(0.204, 0.313)	1	5416
Flow	0.194	0.029	(0.138, 0.252)	1	4758
Transported	-0.323	0.038	(-0.397, -0.248)	1	20000
Below 20C	0.169	0.047	(0.076, 0.261)	1	7509
Above 21C	-0.092	0.057	(-0.203, 0.018)	1	6643
Year 2003	0.69	0.246	(0.248, 1.213)	1.001	5483
Year 2004	0.251	0.199	(-0.123, 0.655)	1.001	3948
Year 2005	-0.027	0.17	(-0.361, 0.31)	1.001	2024
Year 2006	-0.255	0.231	(-0.731, 0.18)	1	16260
Year 2007	0.301	0.256	(-0.165, 0.847)	1	20000
Year 2008	0.047	0.126	(-0.208, 0.285)	1.003	961
Year 2009	0.064	0.134	(-0.2, 0.322)	1.003	902
Year 2010	0.052	0.114	(-0.182, 0.267)	1.004	795
Year 2011	-0.602	0.121	(-0.854, -0.379)	1.003	963
Year 2012	0.106	0.121	(-0.141, 0.335)	1.003	820
Year 2013	-0.021	0.116	(-0.256, 0.2)	1.003	951
Year 2014	-0.038	0.111	(-0.265, 0.171)	1.004	702
Year 2015	-0.094	0.116	(-0.331, 0.122)	1.003	929
Year 2016	-0.19	0.144	(-0.486, 0.088)	1.002	1377
Year 2017	-0.238	0.187	(-0.608, 0.122)	1.001	2084

Detection (McN)	0.997	0	(0.996, 0.998)	1	20000
$\phi_2 \cdot p_2$	0.97	0.002	(0.966, 0.973)	1	20000
σ_{year}	0.35	0.098	(0.199, 0.58)	1	13006
Deviance	10273	128.3	(10022.146, 10529.732)	1	7802

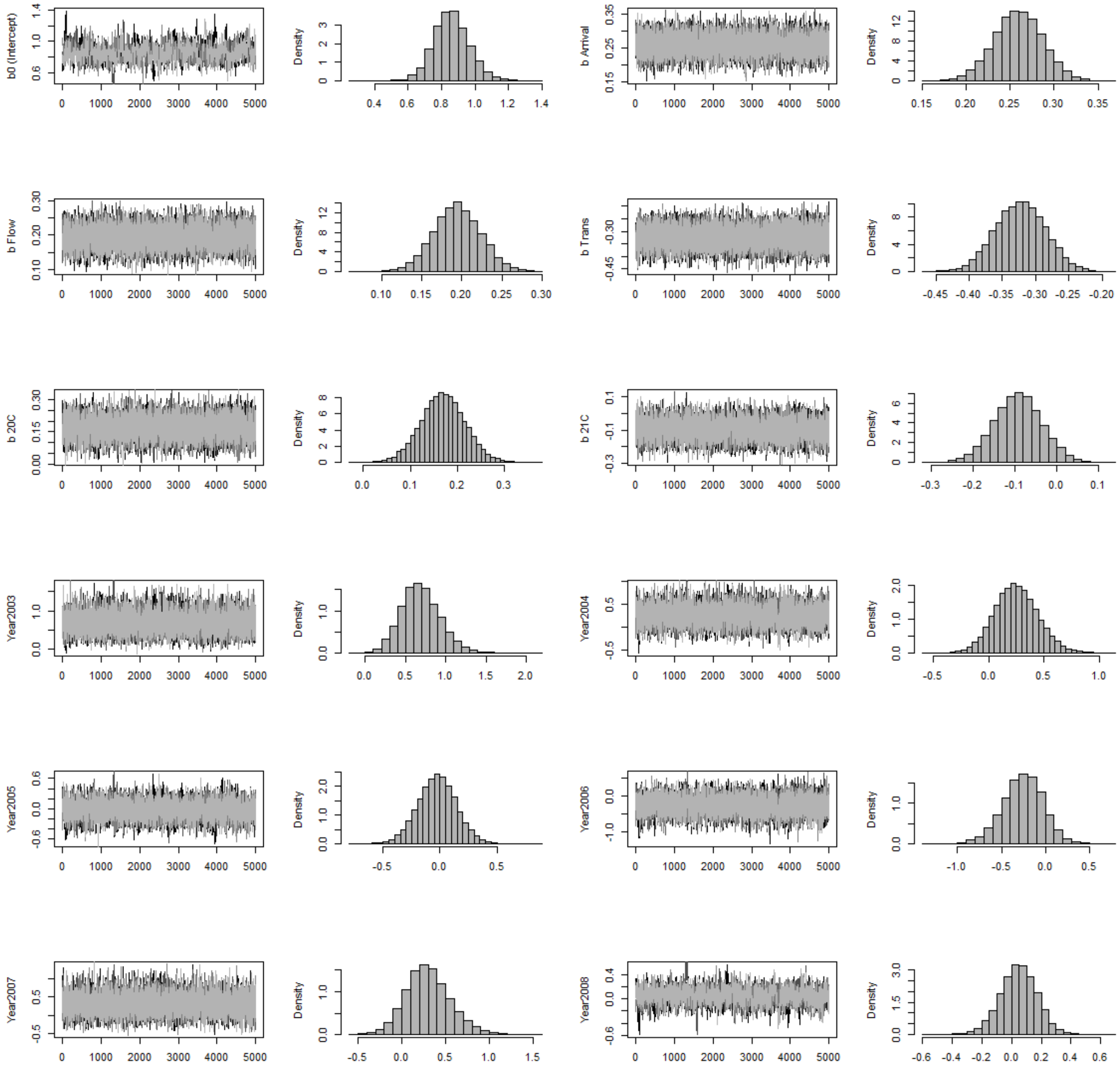

Figure 4: Traceplots of MCMC samplings and the posterior distribution of parameters.

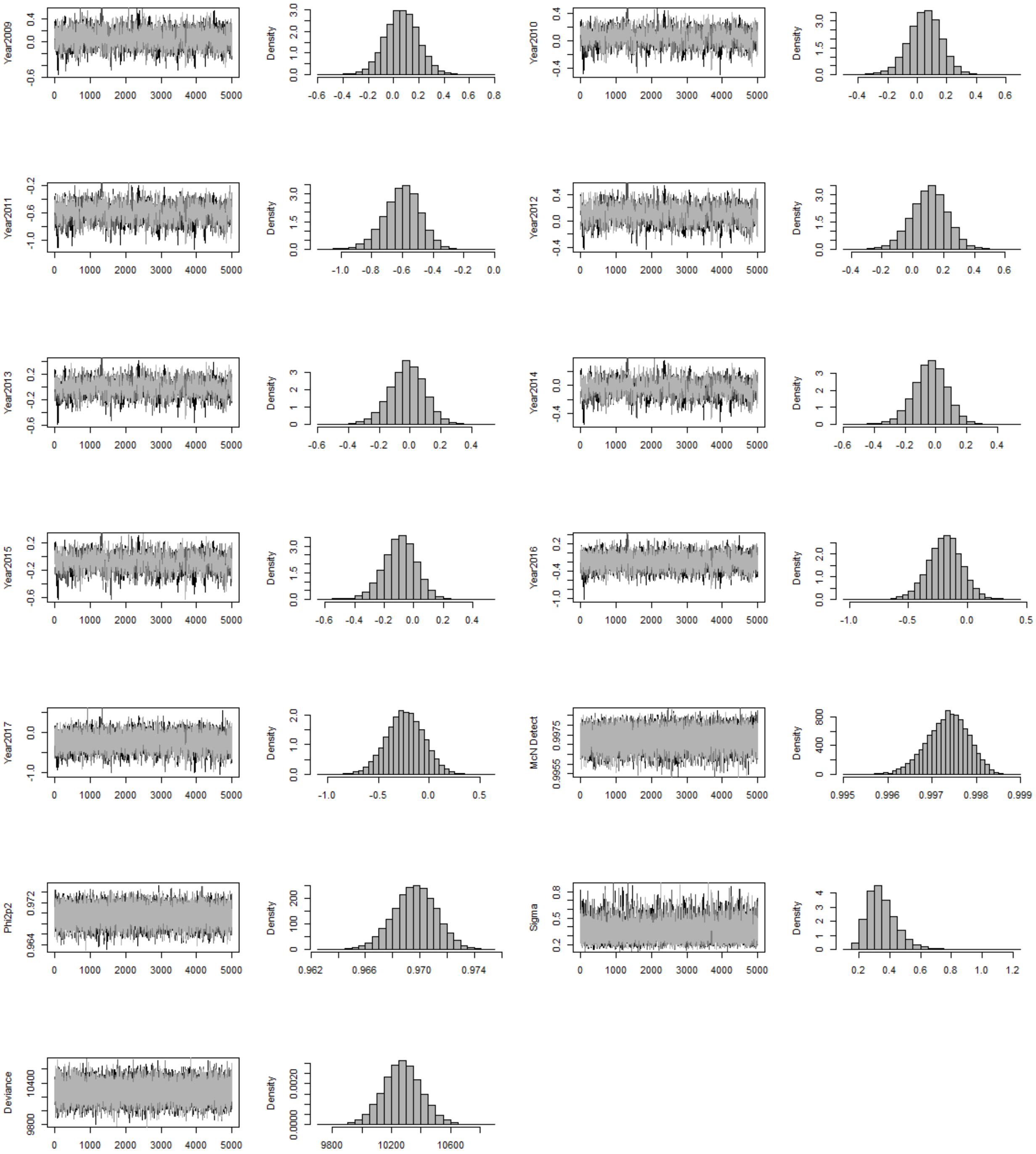

Figure 4 (continued): Traceplots of MCMC samplings and the posterior distribution of parameters.