The following supplement accompanies the article

Effects of solar ultraviolet radiation exposure on early ocean survival and fry-to-smolt growth of juvenile salmon

Michael C. Melnychuk[1,4,]*, Carl J. Walters[1], Villy Christensen[1], Max L. Bothwell[2], David W. Welch[3]

[1]Department of Zoology and Fisheries Centre, University of British Columbia, Vancouver, British Columbia V6T 1Z4, Canada
[2]National Water Research Institute, Environment Canada, Pacific Biological Station, Nanaimo, British Columbia V9T 6N7, Canada
[3]Kintama Research Services, Nanaimo, British Columbia V9S 3B3, Canada

[4]*Present address:* School of Aquatic & Fishery Sciences, University of Washington, Seattle, Washington 98195-5020, USA

*Email: mmel@uw.edu

Marine Ecology Progress Series 457:251–264 (2012)

Supplement. This supplementary material mainly consists of detailed methods and results of mark-recapture models applied to smolt detection data. Models are described for each of the 2 populations. General migration pattern results are also presented. In addition, Fig. S1 shows the transmittance spectra of the UV shading material used above hatchery tanks, and Fig. S2 shows the relationship between absorbance of UVB radiation by pigments in the epithelial mucus of caudal fin samples and the area of the fin sample for the different treatment groups.

Mark-recapture model construction

Variants of the Cormack-Jolly-Seber (CJS) model (Cormack 1964, Jolly 1965, Seber 1965) were fit to detection data of Cultus Lake sockeye smolts to estimate survival probabilities (ϕ) in each segment of the migration and detection probabilities (p) at each station encountered. The final segment ϕ leading to Queen Charlotte Strait (QCS) or Strait of Juan de Fuca (JDF) lines is confounded with p at the final station (QCS/JDF). Since the receiver lines were deployed similarly in these areas, we estimated an overall p for the Northern Strait of Georgia (NSOG) line ($\hat{p}_{\text{NSOG}}$, 90.4% for V9 tags in 2007) and assumed this value for the QCS/JDF lines, correcting for slight differences in line geometry ($\hat{p}_{\text{QCS}}$, 92.4%; $\hat{p}_{\text{JDF}}$, 91.8%). The estimate of $\hat{p}_{\text{NSOG}}$ came from a regression model incorporating POST tags crossing the NSOG station in years 2004 to 2007 and allowing year-specific and tag type-specific variation in $\hat{p}$ (details in Melnychuk 2009b, and Welch et al. 2011). After assuming fixed values for the final stage p, we used the 7-digit detection histories (i.e. strings of ‘1’s and ‘0’s representing detection or not of individual fish at each of the 6 stations, all following a ‘1’ for release) for Cultus Lake sockeye in a CJS model implemented with Program MARK (White & Burnham 1999) through the R package RMark (Laake & Rexstad 2009).

Variants of the Burnham joint live-recaptures and dead-recoveries model (Burnham 1993) were fit to detection data of Tenderfoot Creek coho smolts. In addition to survival probabilities (S) in each segment of the migration and p at each detection station, the model involves parameters representing detection efficiency (r) of motionless tags on the seabed of Howe Sound and ‘fidelity’ parameters (F) allowing for migration among mutually exclusive sampling areas (not relevant in this spatial case). The resulting detection history of each fish was comprised of 24 digits, with a ‘1’ for release, 11 representing detection or not at stationary lines, and 12 representing tag recovery periods (i.e. locating tags in fish that died) after release or stationary lines. All F parameters were fixed at 1, and all r values other than those representing the 3 Howe Sound segments (river mouth to HS_{inner}, HS_{inner} to HS_{outer}, and after HS_{outer}) were fixed at 0. Fixing a value of p for the final (aggregated) station was not necessary for the coho data because inferences were limited to Howe Sound. The product of segment-specific survival estimates, either $\hat{\phi}$ or $\hat{S}$, represents the cumulative survivorship decline along migration routes. Uncertainties in these products were calculated using the Delta Method.

We used goodness-of-fit diagnostics in Program RELEASE (Burnham et al. 1987) and Program MARK (White & Burnham 1999) to assess the fit of a reasonably general mark-recapture model to detection data. The model for Cultus Lake sockeye involved full independence among unique combinations of migration segments (Seg) or stations, releases (Rel) and UVB treatments (Treat) in terms of ϕ and p, i.e. [ϕ(Seg×Rel×Treat), p(Station×Rel×Treat)]. The model for Tenderfoot coho involved full independence among combinations of segments, UVB treatments and exposure duration

(Dur), common p at each station among these groups, and common r among groups in each Howe Sound segment, i.e. [S(Seg×Treat×Dur), p(Station), $r(\text{Seg}_{\text{HS}})$, F(=1)]. For both datasets, the goodness-of-fit of the model to detection data was adequate (based on 1000 Monte Carlo parametric bootstrap simulations; p = 0.207 for the Cultus Lake sockeye dataset and p = 0.065 for the Tenderfoot coho dataset). This was confirmed for the Cultus Lake CJS model through a Program RELEASE overall χ^2 goodness-of-fit test ($\chi^2 = 39.4$, df = 37, p = 0.36). An overdispersion parameter, c (Burnham et al. 1987), was estimated using the deviance bootstrap simulation method in Program MARK. The estimated values were $\hat{c} = 1.074$ for Cultus Lake sockeye data and $\hat{c} = 1.132$ for Tenderfoot coho data. Values of $\hat{c}$ were used to adjust Akaike's Information Criterion (AIC) scores for comparing candidate models (Lebreton et al. 1992), and also for expanding confidence limits around parameter estimates (Burnham et al. 1987).

Candidate models were compared using QAICc (Akaike's Information Criterion, adjusted for overdispersion and corrected for small sample size; Burnham & Anderson 2002) on the basis of their goodness-of-fit to the data (i.e. log-likelihood values) and the number of parameters required to achieve that fit. In a set of models specified *a priori*, models with lower QAICc scores are favoured in this balance (i.e. are more parsimonious). Rules of thumb suggest that models with QAICc within 0 to 2 of the lowest value in the model set are similarly well supported, those with QAICc within 2 to 6 have sufficient support from the data to potentially be the best model within the set, while models with QAICc > 10 are not well supported compared to others (Burnham & Anderson 2002, Richards 2008). Akaike weights were also calculated, which provide the probability that a given model is the best within the model set. For both datasets, sub-models for p ([p]) were compared while assuming a general sub-model for survival ([ϕ]), and the best [p] was then held common across models for comparing [ϕ].

Cultus Lake sockeye models

In the Fraser River, water level (or discharge) has a strong influence on p at river stations (Melnychuk 2009a). Higher river levels and faster flows, typically later in the migration season, generally result in decreased p due to greater background noise or smolts spending less time within the detection range of a given receiver as they travel downstream. Since the 2 Cultus Lake sockeye groups were released nearly 3 wk apart, separate $\hat{p}$ for the 2 release periods were allowed in most candidate models for p. Some models assumed an additive effect of release that was consistent across all stations, while others assumed separate p for the 2 releases at each station (i.e. a Station:Release interaction). In one highly constrained model, p was modelled as common among the 2 releases at each station. Finally, to allow for the possibility that p could differ among UVB treatment groups (due to behavioural effects on swimming speeds or depths travelled), some [p] allowed for either an additive effect of UVB treatment consistent across all stations, or else a fully independent effect of UVB treatment at each station. In total, 6 [p] were considered while holding common across models a general [ϕ], [ϕ(Seg×Rel×Treat)]:

1. p(Station×Rel×Treat)	Fully independent $\hat{p}$ among release periods and UVB treatments at each station
2. p(Station×Rel)	Independent $\hat{p}$ among release periods at each station
3. p(Station×Rel+Treat)	Independent $\hat{p}$ among release periods at each station, with an additive effect of UVB treatment across all stations
4. p(Station+Rel)	Additive effect of release period on p across all stations
5. p(Station+Rel+Treat)	Additive effects of release and treatment on p across all stations
6. p(Station)	Fully pooled $\hat{p}$ across releases and UVB treatments at each station

The [p] with the lowest QAICc score was held common across models for comparing [ϕ].

Candidate models for ϕ involved possible effects of UVB treatment, release period, and body size. Some [ϕ] incorporated treatment or release period as additive effects on ϕ, whereas one model assumed separate ϕ for each combination of these factors in each migration segment. In 2 models, the potential effect of UVB treatment was assumed to occur only after ocean entry, in the case that survival consequences of UVB exposure were related to saltwater tolerance. Two models incorporated body size as an additive covariate. In total, 10 [ϕ] were compared on the basis of QAICc scores, while holding common across models the best [p] from the previous step, [p(Station×Rel)]:

1. ϕ(Seg)	Fully-pooled $\hat{\phi}$ among treatments and releases in each segment
2. ϕ(Seg+FL)	Fully-pooled ϕ among UVB treatments and releases in each segment, with fork length as an additive individual covariate
3. ϕ(Seg+Rel)	$\hat{\phi}$ pooled among UVB treatments; additive effect of release period
4. ϕ(Seg+Treat)	$\hat{\phi}$ pooled among release periods; additive effect of UVB treatment
5. ϕ(Seg+Treat$_{\text{ocean}}$)	$\hat{\phi}$ pooled among release periods; additive effect of UVB treatment in ocean segments only (pooled in freshwater segments)
6. ϕ(Seg+Rel+Treat)	Additive effects of both release period and UVB treatment
7. ϕ(Seg+Rel+Treat$_{\text{ocean}}$)	Additive effect of release period, and additive effect of UVB treatment in ocean segments only (pooled in freshwater segments)
8. ϕ(Seg+Rel×Treat)	Additive effects and interaction between release period and UVB treatment on ϕ
9. ϕ(Seg+Rel×Treat+FL)	Additive effects and interaction between release period and UVB treatment on ϕ; fork length as an additive individual covariate
10. ϕ(Seg×Rel×Treat)	Fully independent $\hat{\phi}$ among releases and treatments in each segment

After comparing the above [ϕ], we suspected that the best model in terms of QAICc scores may have over-fit the data (i.e. chased patterns specific to the dataset; which sometimes results in poor predictability of future datasets). This was the general model; the other 9 models were much more constrained. It was not necessarily true that detection data supported independent effects of both release period and UVB treatment in each segment, since none of the above models considered only one of these factors interacting with segment. We conducted a further, post-hoc comparison of [ϕ] to gauge whether reductions from the general model would result in more parsimonious [ϕ]. Since models in this post-hoc comparison were not a part of the initial model set prior to analyses, we note that the results from this further comparison should be treated as preliminary (Anderson et al. 2001, Burnham & Anderson 2002). Four additional [ϕ] were compared, again holding [p(Station×Rel)] common across models:

1. ϕ(Seg×Rel×Treat)	Fully independent $\hat{\phi}$ among releases and treatments in each segment
2. ϕ(Seg×Rel)	Fully independent $\hat{\phi}$ among release periods in each segment
3. ϕ(Seg×Rel+Treat)	Fully independent $\hat{\phi}$ among release periods in each segment, with an additive effect of UVB treatment
4. ϕ(Seg×Treat)	Fully independent $\hat{\phi}$ among UVB treatments in each segment
5. ϕ(Seg×Treat+Rel)	Fully independent $\hat{\phi}$ among UVB treatments in each segment, with an additive effect of release period

Tenderfoot Creek coho models

Coho smolts from all 4 treatment groups were released together. Although neither effects of UVB treatment nor exposure duration on p were expected, this possibility was still allowed for in some candidate models, with UVB treatment and/or exposure duration as additive effects on p across stations. One model assumed fully-independent effects of treatment and exposure duration on p at each station. In total, the following 5 [p] were considered while assuming a general [S], a segment-independent but group-pooled sub-model for mobile detection efficiency in Howe Sound segments, and fidelity parameters fixed to 1, [S(Seg×Treat×Dur),r(Seg$_{\text{HS}}$),F(=1)]:

1. p(Station×Treat×Dur)	Fully independent $\hat{p}$ among UVB treatments and exposure durations in each segment
2. p(Station+Treat)	Additive effect of UVB treatment on p across all stations
3. p(Station+Dur)	Additive effect of exposure duration on p across all stations
4. p(Station+Treat+Dur)	Additive effects of treatment and duration on p across all stations
5. p(Station)	Fully pooled $\hat{p}$ among treatments and durations in each segment

The [p] with the lowest QAICC score was carried forward to the comparison of [ϕ].[1]

In terms of survival (S), instead of different release periods, UVB treatments were crossed with different exposure durations. Otherwise, the same 10 [S] for Tenderfoot coho were considered as the [ϕ] for Cultus Lake sockeye, while holding the other sub-models in common, [p(Station+Treat+Dur), $r(\text{Seg}_{\text{HS}})$, $F(=1)$]:

1. S(Seg)	Fully pooled $\hat{S}$ among treatments and durations in each segment
2. S(Seg+FL)	Fully pooled $\hat{S}$ among UVB treatments and exposure durations in each segment, with fork length as an additive individual covariate
3. S(Seg+Dur)	$\hat{S}$ pooled among UVB treatments; additive effect of duration
4. S(Seg+Treat)	$\hat{S}$ pooled among durations; additive effect of UVB treatment
5. S(Seg+Treat$_{\text{ocean}}$)	$\hat{S}$ pooled among durations; additive effect of UVB treatment in ocean segments only (pooled in freshwater segments)
6. S(Seg+Dur+Treat)	Additive effects of both exposure duration and UVB treatment
7. S(Seg+Dur+Treat$_{\text{ocean}}$)	Additive effect of exposure duration, and additive effect of UVB treatment in ocean segments only (pooled in freshwater segments)
8. S(Seg+Dur×Treat)	Additive effects and interaction between exposure duration and UVB treatment on S
9. S(Seg+Dur×Treat+FL)	Additive effects and interaction between duration and UVB treatment on S; fork length as an additive individual covariate
10. S(Seg×Dur×Treat)	Fully independent $\hat{S}$ among exposure durations and UVB treatments in each segment

To guard against the possibility that detection data were sparse and the best [p] from the previous step, [p(Station+Treat+Dur)], consequently over-fit the data, these 10 candidate models for survival were also compared assuming a more constrained [p], [p(Station)].

General migration patterns

Cultus Lake sockeye smolts generally migrated downstream rapidly, reaching the mouth of the Fraser River on average 2.5 to 4.4 d after release. Fish from the second release period took slightly longer to travel through Sweltzer Creek, Vedder River and Sumas River, but after arriving in the Fraser River, travel times in remaining river segments were similar between release periods (Fig. S3a). Smolts continued to migrate rapidly through the Strait of Georgia. There was little difference among UVB treatments in travel speeds for either release period, in either freshwater or ocean segments (Fig. S3a). There were slight differences among release groups in the direction taken after ocean entry: in the first release, fish (24) were only detected at QCS, while in the second release group, 44 fish were detected at QCS and 6 at JDF. There were also slight differences between release groups in the proportion of fish that remained in Cultus Lake: in the first release group, 1 (UVB-shaded) of 119 tagged fish was detected in Cultus Lake on a stationary array operated by Fisheries and Oceans Canada, while in the second group, 12 of 200 tagged fish (8 of which were UVB-shaded) were detected in the lake. This proportion of fish remaining varied significantly by release group (since a $2 \times 2 \times 2$ χ^2 goodness-of-fit test showed no interactions, $\chi^2 = 0.491$, 1 df $p = 0.484$, a Fisher exact test was used with UVB treatments pooled, $p = 0.036$), but not by UVB treatment (Fisher exact test with release groups pooled, $p = 0.167$). It is unclear whether fish that remained in the lake actually residualized or were eaten by predators after release and subsequently detected in the lake. Either possibility leads to reduced 'apparent survival' in mark-recapture model estimates.

---

[1] In a previous assessment of detection probabilities for Tenderfoot coho in 2007, an index of tag strength was measured while activating the 199 V7 tags, prior to implanting tags into smolts (Melnychuk in press). Models incorporating this tag strength index as an individual covariate of p were also considered, but are not listed here as the covariate was only weakly supported

Tagged coho smolts also migrated downstream after release at Tenderfoot Creek Hatchery. On average, smolts took 2.7 to 4.1 d to arrive in the Squamish River estuary (range, 1.4 to 11.1 d). There was little difference among treatment groups in downstream travel time (Fig. S3b). One smolt from the 9 mo UV-exposed group was detected in the Cheakamus River upstream of the confluence with Tenderfoot Creek. It was detected >1000 times between May 12 and May 25 but was not detected at any other station. This smolt could have reverted to parr and remained in freshwater, delayed its migration at least several weeks, or been consumed by a predator and transported upriver past the receiver. Otherwise, coho smolts spent little time in the rivers or estuary. After ocean entry, most smolts continued to migrate rapidly out of Howe Sound. Two smolts (from the 9 mo UVB-shaded group) spent considerable time in Howe Sound, not crossing HS_{outer} until 38 or 72 d after release and contributing to the high variance in average travel time for this group (Fig. S3b). Excluding these 2 fish, average travel time from release to HS_{outer} was 6.5 d, similar to other treatment groups. Of the smolts that were detected at the HS_{outer} line, 78% took the eastern route around Gambier Island (Fig. 4), and this proportion differed little among treatment groups. Only 9 fish were detected at NSOG and 1 at QCS, with all 4 treatment groups represented in these 10 fish.

Survival comparison of UVB-exposed and UVB-shaded groups

There was no observed effect of UVB treatment on survival of either sockeye or coho populations. This is observed by initially fitting general, very flexible models to detection data allowing for the best possible fit (at the potential expense of poor precision and over-fitting to sparse data; Lebreton et al. 1992). These general models for both populations involve survival and detection probabilities that are fully independent for each of the 4 treatment groups in each segment (or station) of the migration, i.e. [ϕ(Seg×Rel×Treat), p(Station×Rel×Treat)] for Cultus Lake sockeye (see Fig. 5a) and [S(Seg×Treat×Dur), p(Station×Treat×Dur), $r(\text{Seg}_{HS})$, $F(=1)$] for Tenderfoot coho (see Fig. 5b). We now turn to comparisons of candidate models to evaluate whether other models provide more parsimonious fits to detection data than the general models.

Cultus Lake sockeye

Detection probabilities of fish at receiver stations varied among release periods (Table S1). The top 3 candidate models all involved an interaction between release group and station, whereas models with only an additive effect of release group across stations or no effect of release group had no support from the data within the model set (i.e. no support in the balance of goodness-of-fit with model complexity). Once release group was accounted for, there was very little support for an additive effect of UVB treatment on p (ΔQAICc was 1.6, but these were nested models with a difference of a single parameter, so there is little support for the larger model; Richards 2008) and no support for an interaction between treatment and station (ΔQAICc = 13.4). The best [p] from this comparison, [p(Station×Rel)], seems reasonable; p at river stations are expected to differ among releases, since during the 3 wk period between releases, the Fraser River flow increased such that background noise was greater and tagged fish were likely within detection range for less time (Melnychuk 2009a). We carry forward this [p] to compare candidate models for ϕ.

In the initial model set considered, the greatest support by far was found in the general [ϕ] (Table S2), with interaction effects of release group and treatment in each segment of the migration on ϕ. All other models involved only additive effects of release, treatment, fork length (FL) or combinations thereof across segments. The AIC preference for the general model could be a result of only one of the interactions with segment being important, not necessarily both release and treatment. After noting this result (Table S2), additional [ϕ] were considered that involved only one of these interactions. Models with an interaction between segment and release had great support relative to models with a treatment interaction instead or the general model with both interactions (Table S3). This appears to be driven by the second release group (both of its UVB treatment groups) having lower survival in the first segment after release but higher survival in the 5th segment after release, from the Fraser River mouth to NSOG (see Fig. 5a). Once the interaction between release and segment was accounted for, there was very little effect of UVB treatment as an additive effect on survival (ΔQAICc = 1.8 with a difference of a single parameter; Table S3).

Tenderfoot Creek coho

Although all 4 treatment groups were released at the same time (Table 1) and travel speeds were similar among them (Fig. S3), the comparison of [p] showed that UVB treatment and exposure duration both had a slight effect on p (Table S4). The model with additive effects of treatment and duration on p had a lower QAICc score than models involving only one or neither of these factors (Table S4). Of these 2 factors, duration had a slightly stronger effect on p (ΔQAICc = 1.4 compared with 0.4 following single-factor removals; Table S4). The fully independent model with interactions of treatment and duration on p at each station had much less support than the more constrained models. Selection as the best model could reflect behavioural differences among fish in the 9 mo vs. 1 mo exposure durations or UVB treatments. If UVB exposure led to differences in depth or proximity to river banks while migrating, such fine scale habitat selection could have led to differences in p among treatment groups. Alternatively, the observed effect may be spurious, resulting from over-fitting the model to sparse data (i.e. a chance occurrence), where instead a more constrained model, [p(Station)], may actually be more appropriate. We therefore carried forward the best [p], [p(Station+Treat+Dur)], for comparing [S], but in the case that this best [p] over-fit detection data, we also compared the same [S] assuming a more constrained [p], [p(Station)], where fish from all 4 treatment groups shared the same $\hat{p}$ at each station.

When the AIC-best model for *p* is assumed rather than the general [*p*], the lack of survival differences among treatment groups is seen even more clearly (Fig. S4). Similar to Fig. 5b, the general [*S*] is assumed, but [*p*] in Fig. S4 is more parsimonious (Table S4). The best-supported [*S*] was the most constrained, in which *S* were pooled among all 4 treatment groups in each segment of the migration, [*S*(Seg)]. Models with only one extra parameter, an additive effect of either duration, UVB treatment, or fork length, gave very little improvement in goodness-of-fit, so had no support (ΔQAICc = 1.9 to 2.1; Table S5). Models that allowed for a survival difference between UVB treatments only in ocean segments also provided little improvement to the goodness-of-fit. Models with an interaction of treatment and duration on *S*, as well as the general [*S*(Seg×Treat×Dur)], had no support (Table S5).

Similar results for [*S*] comparisons were observed when the [*p*] assumed was the more constrained [*p*(Station)] rather than the AIC-best [*p*(Station+Treat+Dur)]. The ranking of models differed slightly (not shown), but the most constrained sub-model [*S*(Seg)] was still best, and had little improvement in the goodness-of-fit by incorporating one extra parameter as an additive covariate (duration, treatment, or fork length; ΔQAICc = 1.6 to 2.1). The conclusion of no observed effects of duration, treatment, or fork length on *S* thus appears to be robust to choice of models assumed for *p*.

Detection probabilities

Detection probability estimates assuming the most parsimonious model for each dataset are shown in Fig. S5. For Cultus Lake sockeye, the later release period had lower $\hat{p}$ at 3 of 4 stations in the Fraser River under model [ϕ(Seg×Rel), *p*(Station×Rel)] (Fig. S5a). This was especially true for the first station; the large discrepancy between releases at Frs_1 was the dominating factor behind the strong support for a Station**:**Release interaction on *p* (Table S1).

For Tenderfoot coho, there was considerable variation in *p* among stations, with high $\hat{p}$ at receivers in Tenderfoot Creek, the Cheakamus River (Chk_2 and Chk_3), the Squamish River (Sqm_6 and Sqm_7), and the outer Howe Sound line (Fig. S5b). High *p* in the lower Squamish River in particular allowed for precise partitioning between downstream and coastal marine mortality components. Additive treatment group constraints on *p* in the AIC-best [*p*] resulted in consistently higher $\hat{p}$ for UVB-exposed fish than for UVB-shaded fish, and consistently higher $\hat{p}$ for the 1 mo duration group than for the 9 mo duration group. It is unclear whether there is any behavioural basis for this difference, or whether it was simply due to over-fitting of sparse data (recall that all groups were implanted with tags of equal acoustic power and programming, the primary determinants of *p*). The within-station variation among treatment groups was small compared to the among-station variation in $\hat{p}$ (Fig. S5b). Again, these differences in $\hat{p}$ among treatment groups neither mask nor artificially create survivorship effects, since under a model where $\hat{p}$ was instead common across treatment groups, estimated survivorship was also similar among groups.

Models involving an index of tag strength (Melnychuk in press) as an additive individual covariate for *p* of Tenderfoot coho were weakly supported (ΔQAICc = 1.3 based on comparison with the best [*p*], and ΔQAICc = 2.1 based on comparison with the more constrained [*p*(Station)], in both cases with a difference of only one parameter; not shown in Table S4). For both populations, $\hat{p}$ and the precision of $\hat{p}$ seem to be high enough overall that inferences of survival should be reasonable in terms of bias and precision, respectively.

LITERATURE CITED

Anderson DR, Link WA, Johnson DH, Burnham KP (2001) Suggestions for presenting the results of data analyses. J Wildl Manage 65:373–378

Burnham KP (1993) A theory for combined analysis of ring recovery and recapture data. In: Lebreton J-D, North PM (eds) Marked individuals in the study of bird population. Birkhäuser, Basel, p 199–213

Burnham KP, Anderson DR (2002) Model selection and multi-model inference: A practical information-theoretic approach, Springer, New York, NY

Burnham KP, Anderson DR, White GC, Brownie C, Pollock KH (1987) Design and analysis methods for fish survival experiments based on release-recapture. American Fisheries Society (ASF) Monograph no. 5, Bethesda, MD

Cormack RM (1964) Estimates of survival from the sighting of marked animals. Biometrika 51:429–438

Jolly GM (1965) Explicit estimates from capture-recapture data with both death and immigration-stochastic model. Biometrika 52:225–247

Laake J, Rexstad E (2009) RMark - an alternative approach to building linear models in MARK (Appendix C). In: Cooch E, White G (eds) Program MARK: A gentle introduction. 7th edn [Online], p C1-C109

Lebreton JD, Burnham KP, Clobert J, Anderson DR (1992) Modeling survival and testing biological hypotheses using marked animals: A unified approach with case studies. Ecol Monogr 62:67–118

Melnychuk MC (2009a) Estimation of survival and detection probabilities for multiple tagged salmon stocks with nested migration routes, using a large-scale telemetry array. Mar Freshw Res 60:1231–1243

Melnychuk MC (2009b) Mortality of migrating Pacific salmon smolts in southern British Columbia, Canada. PhD Thesis, University of British Columbia, Vancouver

Melnychuk MC (in press) Effects of acoustic tag strength variation on detection probabilities of migrating fish: Recommended measurements prior to tagging. American Fisheries Society Symposium, Advances in Fish Tagging and Marking Technology, Auckland

Richards SA (2008) Dealing with overdispersed count data in applied ecology. J Appl Ecol 45:218–227

Seber GAF (1965) A note on the multiple recapture census. Biometrika 52:249–259

Welch DW, Melnychuk MC, Payne J, Rechisky EL and others (2011) In situ measurement of coastal ocean movements and survival of juvenile Pacific salmon. Proc Natl Acad Sci USA 108:8708–8713

White GC, Burnham KP (1999) Program MARK: Survival estimation from populations of marked animals. Bird Study 46(Suppl.):S120–S139

Table S1. Model selection results for detection probability (*p*) sub-models for Cultus Lake sockeye experiment. Quantities shown are number of parameters (*k*), log-likelihoods, and QAICc values (adjusted for small sample sizes and extra-binomial variation with $\hat{c}$ = 1.074). The final station *p* is fixed for all treatment groups and models at the 2007-specific prediction (0.923) for V9 tags. Rel = release period; Treat = UVB treatment. [a]Sub-models for *p* are compared while the CJS [ϕ] with separate combinations of release and treatment in each segment is common across models, [ϕ(Seg×Rel×Treat)]

Sub-model[a]	*k*	–2ln(*L*)	QAICc	ΔQAICc	Akaike weight
p(Station×Rel)	34	1875.4	1817.0	0.0	0.69
p(Station×Rel+Treat)	35	1874.8	1818.5	1.6	0.31
p(Station×Rel×Treat)	44	1866.3	1830.4	13.4	0.00
p(Station+Rel)	30	1960.8	1887.8	70.9	0.00
p(Station+Rel+Treat)	31	1960.0	1889.3	72.3	0.00
p(Station)	29	2003.3	1925.3	108.3	0.00

Table S2. Model selection results for survival (ϕ) sub-models for Cultus Lake sockeye experiment. See Table S1 legend; Seg = segment; $\mathrm{Treat}_{\mathrm{ocean}}$ = UVB treatment effect only in ocean segments; FL = fork length. [a]Sub-models for ϕ are compared while [*p*] is common across models, [*p*(Station×Rel)]

Sub-model[a]	*k*	–2ln(*L*)	QAICc	ΔQAICc	Akaike weight
ϕ(Seg×Rel×Treat)	34	1875.4	1817.0	0.0	1.00
ϕ(Seg)	16	1940.8	1839.7	22.7	0.00
ϕ(Seg+Treat)	17	1940.4	1841.4	24.5	0.00
ϕ(Seg+FL)	17	1940.5	1841.5	24.5	0.00
ϕ(Seg+Rel)	17	1940.6	1841.6	24.7	0.00
ϕ(Seg+Rel+Treat)	18	1940.3	1843.4	26.4	0.00
ϕ(Seg+$\mathrm{Treat}_{\mathrm{ocean}}$)	18	1940.7	1843.7	26.8	0.00
ϕ(Seg+Rel×Treat)	19	1940.3	1845.5	28.5	0.00
ϕ(Seg+Rel+$\mathrm{Treat}_{\mathrm{ocean}}$)	19	1940.5	1845.7	28.8	0.00
ϕ(Seg+Rel×Treat+FL)	20	1940.1	1847.4	30.4	0.00

Table S3. Post-hoc model selection results for survival (ϕ) sub-models reduced from the general model, for Cultus Lake sockeye experiment. This analysis was not based on candidate models established before data analyses began, but was conducted after the initial model comparison for [ϕ]. See Table S1 legend. [a]Sub-models for ϕ are compared while [*p*] is common across models, [*p*(Station×Rel)]

Sub-model[a]	*k*	–2ln(*L*)	QAICc	ΔQAICc	Akaike weight
ϕ(Seg×Rel)	22	1879.1	1794.8	0.0	0.71
ϕ(Seg×Rel+Treat)	23	1878.7	1796.6	1.8	0.29
ϕ(Seg×Rel×Treat)	34	1875.4	1817.0	22.1	0.00
ϕ(Seg×Treat)	22	1938.8	1850.4	55.5	0.00
ϕ(Seg×Treat+Rel)	23	1938.7	1852.4	57.6	0.00

Table S4. Model selection results for detection probability (*p*) sub-models for Tenderfoot Creek coho experiment. Quantities shown are number of parameters (*k*), log-likelihoods, and QAIC$_c$ values (adjusted for small sample sizes and extra-binomial variation with $\hat{c} = 1.132$). Treat = UVB treatment; Dur = 9 or 1 mo exposure of treatment. [a]Sub-models for *p* are compared while the Burnham [*S*] with separate combinations of duration and treatment in each segment is common across models, [*S*(Seg×Dur×Treat)]. Other sub-models are also in common: mobile tracking detection efficiency in Howe Sound segments, *r*(Seg$_{HS}$), and fidelity, *F*(Station), which is fixed to 1

Sub-model[a]	*k*	–2ln(*L*)	QAICc	ΔQAICc	Akaike weight
p(Station+Treat+Dur)	65	1672.0	1616.0	0.0	0.40
p(Station+Dur)	64	1675.0	1616.4	0.4	0.33
p(Station+Treat)	64	1676.2	1617.4	1.4	0.19
p(Station)	63	1680.7	1619.2	3.2	0.08
p(Station×Treat×Dur)	96	1641.4	1662.1	46.1	0.00

Table S5. Model selection results for survival (*S*) sub-models for Tenderfoot Creek coho experiment. See Table S4 legend; Seg = segment; Treat$_{ocean}$ = UVB treatment effect only in ocean segments; FL = fork length. [a]Sub-models for *S* are compared while [*p*] is common across models, [*p*(Station+Treat+Dur)]. Other sub-models are also in common: mobile tracking detection efficiency in Howe Sound segments, *r*(Seg$_{HS}$), and fidelity, *F*(Station), which is fixed to 1

Sub-model[a]	*k*	–2ln(*L*)	QAICc	ΔQAICc	Akaike weight
S(Seg)	29	1690.1	1552.8	0.0	0.37
S(Seg+Dur)	30	1689.9	1554.7	1.9	0.14
S(Seg+Treat)	30	1690.1	1554.9	2.1	0.13
S(Seg+FL)	30	1690.1	1554.9	2.1	0.13
S(Seg+Treat+Dur)	31	1689.9	1556.9	4.1	0.05
S(Seg+Treat$_{ocean}$)	31	1689.9	1556.9	4.1	0.05
S(Seg+Treat$_{ocean}$+Duation)	32	1689.7	1558.8	6.0	0.02
S(Seg+Treat×Dur)	32	1689.9	1559.0	6.2	0.02
S(Seg+Treat×Dur+FL)	33	1689.9	1561.1	8.3	0.01
S(Seg×Treat×Dur)	65	1672.0	1616.0	63.2	0.00

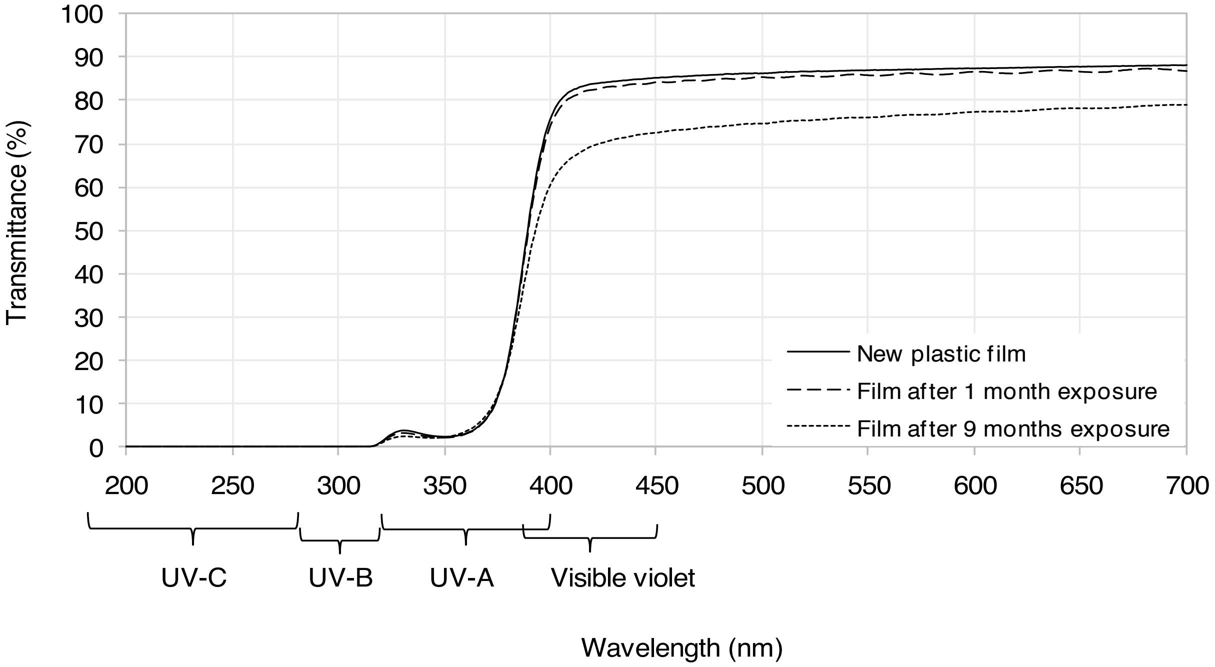

Fig. S1. Percent transmittance of radiation (200 to 700 nm) through the DuPont-Teijin Melinex® 943 plastic film used in the shading experiments. Transmittance spectra are shown for a new film and 2 samples taken directly from hatchery tank shade covers at the end of the experiment, 1 after 1 mo of exposure from April to May 2007 and the other after 9 mo of exposure from July 2006 to May 2007. Scans were conducted with a spectrophotometer blanked against air at 1 nm intervals

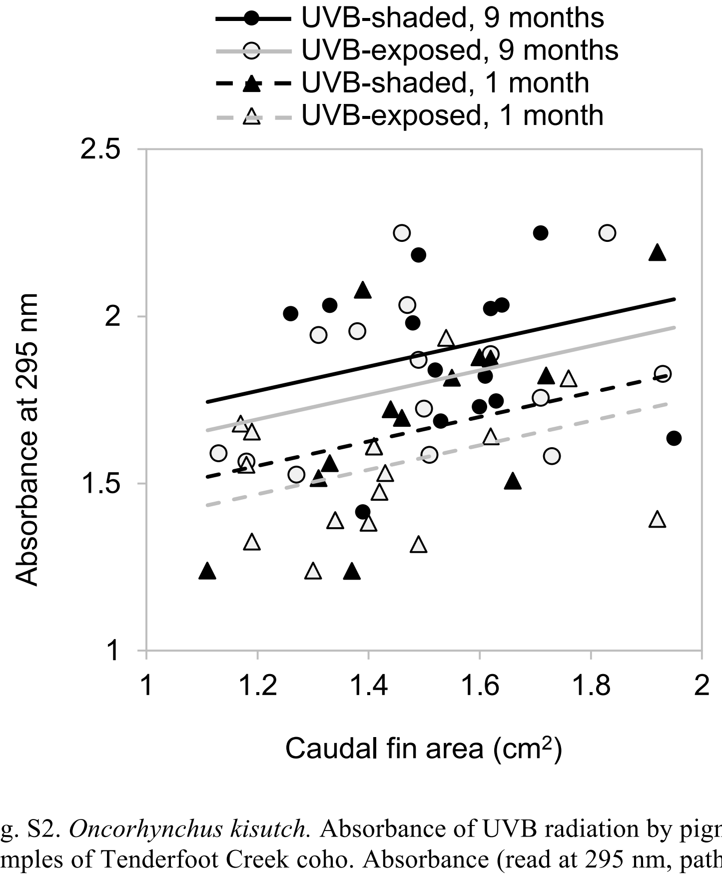

Fig. S2. *Oncorhynchus kisutch.* Absorbance of UVB radiation by pigments in extracts of the epithelial mucus of caudal fin samples of Tenderfoot Creek coho. Absorbance (read at 295 nm, path length 1 cm) provides an index of the concentration of UVB-absorbing pigments in the tissue. Absorbance readings and fitted regression lines are shown for the 4 UVB treatment and exposure duration groups, plotted against fin surface area

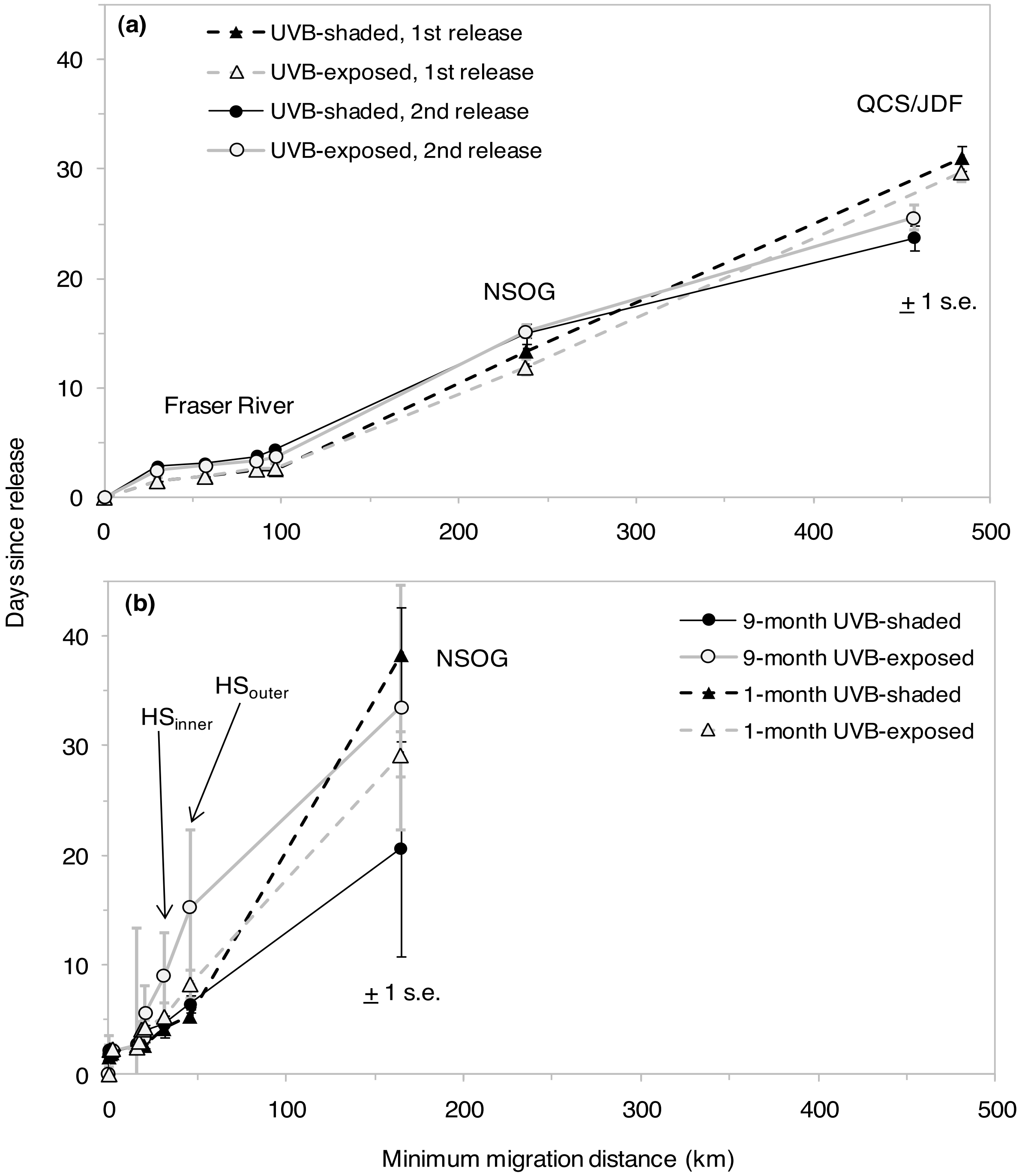

Fig. S3. *Oncorhynchus nerka* and *O. kisutch.* Average travel time past successive detection stations during the smolt migration for (a) Cultus Lake sockeye and (b) Tenderfoot Creek coho. Estimates are separated by treatment groups, and points show cumulative travel time estimates since release plotted against cumulative distance travelled. Error bars show 1 SE

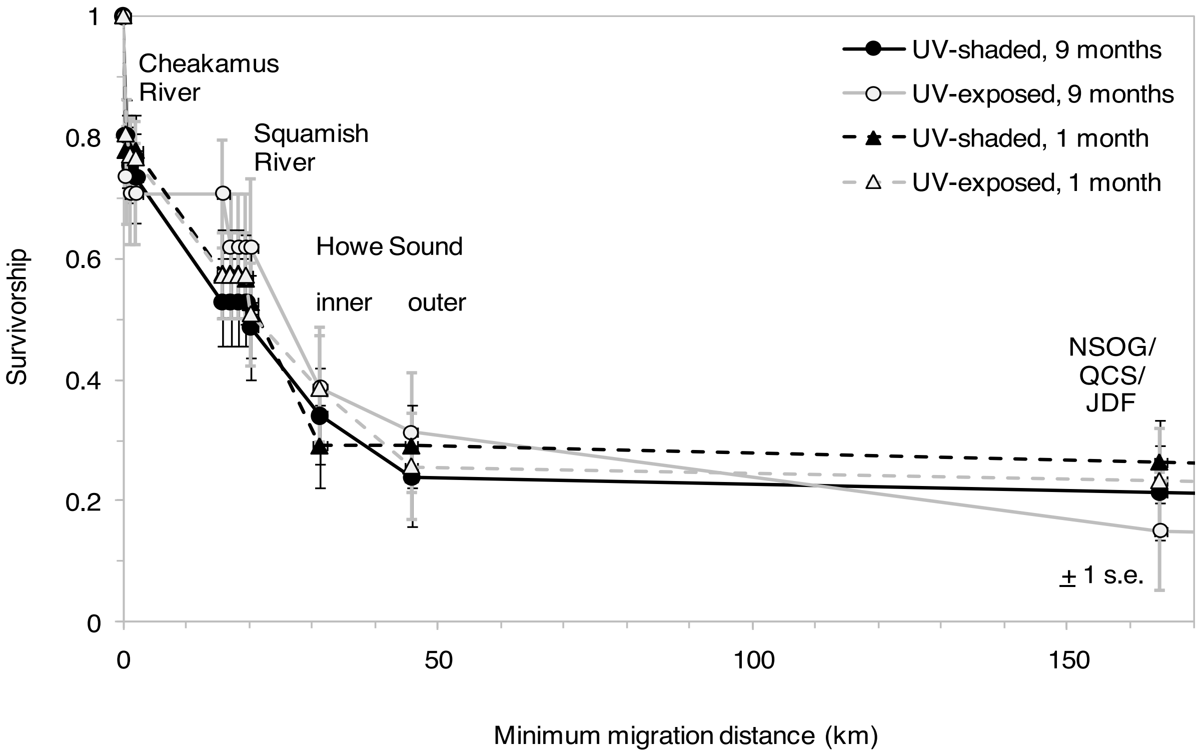

Fig. S4. *Oncorhynchus kisutch.* Survivorship curves for Tenderfoot Creek coho salmon from release to the northern Strait of Georgia line under alternate assumptions of detection probability (p). Survivorship estimates are shown for each treatment group, plotted against the cumulative distance from release to detection station. The Burnham model involves fully independent survival probabilities for each treatment group in each segment, mobile tracking detection efficiencies in each Howe Sound segment that are pooled across treatment groups, and fidelity parameters fixed at 1. Detection probabilities are station-specific but p is constrained with an additive difference among treatment groups which is consistent across stations, i.e. model [S(Seg×Treat×Dur), p(Station+Treat+Dur), $r(\mathrm{Seg}_{HS})$, F(=1)]. Error bars show 1 SE

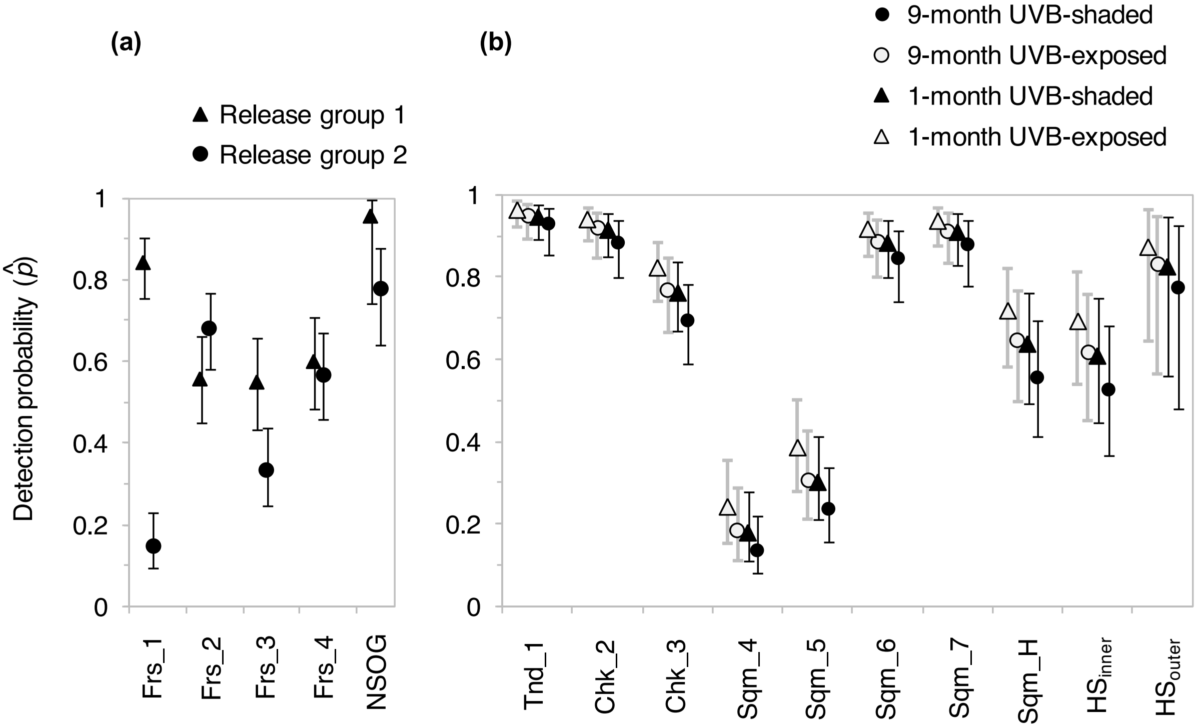

Fig. S5. *Oncorhynchus nerka* and *O. kisutch.* Detection probability estimates at successive receiver stations for (a) Cultus Lake sockeye and (b) Tenderfoot Creek coho in 2007. For sockeye, separate $\hat{p}$ are assumed for the 2 release groups at each station, but UVB treatments within each release group share the same p, i.e. model [ϕ(Seg×Rel), p(Station×Rel)]. For coho, the 4 treatment groups are constrained by additive differences of UVB treatment and exposure duration on p across all stations, i.e. model [S(Seg), p(Station+Treat+Dur), $r(\mathrm{Seg}_{HS})$, F(=1)]. Error bars show 95% confidence limits estimated with profile likelihoods.