A pragmatic approach for managing Fraser River Eulachon (*Thaleichthys pacificus*) fisheries: rapid prototyping operating model development and management procedure evaluation

To: Someone1, Someone2

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Abstract

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STRATEGY | ASSESSMENT | TRAINING

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1 BACKGROUND

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1.1 Subsection

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2 CONSERVATION OBJECTIVES

The primary management objective for BC Eulachon aims to promote stock rebuilding to a level consistent with a COSEWIC categorization of 'special concern' (Schweigert et al. 2012; DFO 2023). This objective is interpreted as achieving positive growth in Eulachon spawning biomass in the short-term, and achieving historical levels of biomass over the long-term.

Formal conservation objectives for FR Eulachon that are consistent with the SFF and FSP policies (DFO 2009, 2022) have not been defined, but at a minimum they require a choice of i) a limit reference point, ii) the removal reference (RR) rate (i.e., the maximum acceptable harvest rate), with desired probabilities for biomass being above the LRP and harvest rates below the RR over a specific timeframe.

3 OPERATING MODEL

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3.1 Subsection

3.1.1 Smaller subsection

Reference tables like this: Model notation is given in Table 1 and population dynamics and statistical model equations in Tables 2 and 3, respectively.
Reference figures like this: Figure 1 and Figure 2.

4 MANAGEMENT PROCEDURE EVALUATION

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5 DISCUSSION

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REFERENCES

DFO. 2009. "A Fishery Decision-Making Framework Incorporating the Precautionary Approach." www.dfo-mpo.gc.ca/reports-rapports/regs/sff-cpd/precaution-eng.htm.

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Schweigert, Jake, Chris Wood, Doug Hay, Murdoch McAllister, Jennifer Boldt, Bruce McCarter, Thomas W Therriault, and Heather Brekke. 2012. "Recovery Potential Assessment of Eulachon (*Thaleichthys Pacificus*) in Canada." *DFO Can Sci Advis Secr Res Doc* 98.

6 TABLES

Table 1: Notation used in the specification of the SISCAL-EUL stock assessment model, along with a description of each variable, and possible fixed values.

Symbol	Value	Description
T	53	Total number of time steps 1965 - 2021
A	35	Plus group age-class
L	32	Number of length bins (4cm width)
t	$1, 2, \dots, T$	Time step
a	$1, 2, \dots, A$	Age-class index
l	$2, 6, \dots, 112$	Length-bin mid-points ($L = 32$ total length bins)
g	$1, ..., 9$	Gear index as described in Table XX ($g = 9$ only used in projections)
x	$1, 2$	Sex index for males ($x = 1$) and females ($x = 2$)
B_0		Unfished female spawning stock biomass
h		Ricker stock-recruitment steepness
R_0		Unfished equilibrium age-1 recruitment
$S_{a,x}$		Unfished equilibrium survivorship-at-age and sex
ϕ_0		Unfished equilibrium spawning biomass per recruit
β_1, β_2	$28.82, 10.55$	Beta prior parameters for steepness
ω_t		Annual recruitment processs error log-deviations
σ_R	1	Standard error of ω_t recruitment deviations
q_g		Catchability coefficient for RV surveys ($g = 7, 8, 9$)
q_t		Time-varying catchability coefficient for commercial CPUE index
$M_{x,t}$		Time-varying natural mortality rate for males ($x = 1$) and females ($x = 2$)
$M_{0,x}$		Time-averaged natural mortality rate for males ($x = 1$) and females ($x = 2$)
μ_M	0.14	Natural mortality prior mean for males and females
σ_M	0.05	Natural mortality prior standard deviation for males and females
$\epsilon_{M,t}$		Time-varying natural mortality random walk log-deviations
$L_{\infty,x}$	$68, 72$	Asymptotic length (cm) for males ($x = 1$) and females ($x = 2$)
$\sigma_{L,x}$	$0.08, 0.11$	CV in length-at-age distribution
K_x	$0.10, 0.068$	von Bertalanffy growth constant for males and females
$L_{1,x}$	$16.26, 16.53$	Length-at-age 1 (same for males and females)
c_1, c_2	$3.86e-6, 3.22$	Allometric length-weight transformation coefficients
l_{50}, l_{95}	$67, 78$	Length-at-50% and -95% maturity
$L_{a,x}$		Mean length-at-age (cm) for males and females
$w_{a,x}$		Mean weight-at-age (cm) for males and females
m_l		Proportion females mature-at-length

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Symbol	Value	Description
m_a		Proportion females mature-at-age
$s_{l,g}$		Mean selectivity-at-length l for gear g
$s_{a,x,g}$		Mean selectivity-at-age a for gear g and sex x
$L^A_{50,g}$		Length-at-50% selectivity for ascending limb
$L^A_{95,g}$		Length-at-95% selectivity for ascending limb
$L^D_{50,g}$		Length-at-50% selectivity for descending limb
$L^D_{95,g}$		Length-at-95% selectivity for descending limb
$N_{a,x,t}$		Numbers-at-age a for sex x in year t
B_t		Female spawning biomass in year t
$C_{g,t}$		Observed total catch (biomass units) for gear g in year t
$C_{a,x,g,t}$		Expected catch-at-age (numbers) a and sex x by gear g in year t
$C'_{a,x,g,t}$		Expected catch-at-age (biomass units) a and sex x by gear g in year t
B^{exp}_t		Allocation weighted average exploitable biomass in year t
$U_{g,t}$		Exploitation rate by gear g in year t
U_t		Total exploitation rate in year t
$I_{g,t}$		Observed biomass/abundance index for gear $g \in \{7,8\}$ in year t
$\hat{I}_{g,t}$		Expected biomass/abundance index for gear $g \in \{7,8\}$ in year t
τ_g		Standard deviation of biomass index observation log-residuals
$u_{l,x,g,t}$		Observed length composition data for sex x in gear g at time t
$\hat{u}_{l,x,g,t}$		Expected length composition data for sex x in gear g at time t
$\hat{\tau}^{len}_{x,g}$		Conditional MLE of length composition sampling error, by sex and gear

Table 2: Process and observation model equations for the SISCAL-EUL stock assessment model

No.	Equation
Model Parameters	
(P.1)	$\Theta^{lead} = \left(B_0, \{\omega_t\}_{t\in 1:T}, h, M, \{\epsilon_t\}_{t\in 1:T}, \{L^A_{50,g}, L^A_{95,g}, L^D_{50,g}, L^D_{95,g}\}_{g\in 1:8}\right)$
(P.2)	$\Theta^{cond} = \left(\{\log q_g\}_{g\in\{7,8\}}, \{\tau_g^{len}\}_{g\in 1:8}\right)$
(P.3)	$\Theta^{fixed} = (l_{mat,50}, l_{mat,95}, \sigma_R, \sigma_M)$
(P.4)	$\Theta^{priors} = \left(m_M, s_M, \{m_{L50,A,g}, m_{L95,A,g}, m_{L50,D,g}, m_{L95,D,g}, \sigma_g^{Sel}\}_{g\in 1:8}\right)$
Growth and maturity	
(G.1)	$l_a = L_1 + (L_1 - L_\infty)\cdot e^{-k(a-1)}$
(G.2)	$D(l \mid a) = e^{-(frac(l-l_a)2\cdot\sigma_L\cdot l_a)^2}$
(G.3)	$P(l \mid a) = \dfrac{D(l \mid a)}{\sum_{l'} D(l' \mid a)}$
(G.4)	$w_a = c_1 l_a^{c_2}$
(G.5)	$m_l = \left(1 + e^{-\log 19 \frac{l - l_{mat,50}}{l_{mat,95} - l_{mat,50}}}\right)^{-1}$
(G.6)	$m_a = \sum_l P(l \mid a) m_l$
Selectivity	
(S.1)	$s^X_{l,g} = \left(1 + e^{-\log 19 \frac{l - L^X_{50,g}}{L^X_{95,g} - L^X_{50,g}}}\right)^{-1}$
(S.2)	$s_{l,g} = s^A_{l,g}\cdot s^D_{l,g}$
(S.3)	$s_{a,g} = \sum_l P(l \mid a) s_{l,g}$
Unfished equilibrium states	
(EQ.1)	$S_a = \begin{cases} 0.5 & a = 1, \\ S_{a-1}e^{-M_0} & 1 < a < A \\ S_{a-1}e^{-M_0}/(1 - e^{-M_0}) & a = A. \end{cases}$
(EQ.2)	$\phi = e^{-M_0}\cdot\sum_a S_a\cdot\bar{w}_a\cdot m_a$
(EQ.3)	$R_0 = B_0/\phi$
(EQ.4)	$N_a^{eq} = R_0\cdot S_a$
Fishery removals	
(C.1)	$N_{a,t+\delta_g} = N_{a,t+\delta_{g-1}}\cdot e^{-1\cdot(\delta_g - \delta_{g-1})M}$
(C.2)	$N_{a,g,t} = N_{a,t+\delta_g}\cdot s_{a,g}$
(C.3)	$B_{a,g,t} = N_{a,g,t}\cdot w_a$
(C.4)	$B_{g,t} = \sum_a B_{a,g,t}$
(C.6)	$C'_{a,g,t} = C_{g,t}\cdot\dfrac{B_{a,g,t}}{\sum_{a'} B_{a',g,t}}$
(C.7)	$C_{a,g,t} = C'_{a,g,t}/w_a$

(C.8) $N_{a,t+\delta_g} = e^{-(\delta_g - \delta_{g-1})\cdot M} \cdot N_{a,t+\delta_{g-1}} - C_{a,g,t}$

(C.9) $U_{g,t} = C_{g,t}/B_t$

Spawning biomass, recruitment, and numbers-at-age

(A.1) $SB_t = \sum_a m_a B_{a,t}$

(A.2) $R_{t+1} = \frac{SB_t}{\phi_0}(5h)^{5/4(1-\frac{SB_t}{R_0\phi_0})} \cdot e^{\sigma_R \omega_{R,t}}$

(A.3) $N_{a,t+1} = \begin{cases} 0.5R_{t+1} & a = 1 \\ e^{-(1-\delta_G)M} \cdot N_{a-1,t+\delta_G} & 2 \leqslant a \leqslant A-1 \\ e^{-(1-\delta_G)M} \cdot (N_{a-1,t+\delta_G} + N_{a,t+\delta_G}) & a = A. \end{cases}$

Table 3: Statistical model prior and likelihood functions for the SISCAL-EUL stock assessment model. The function $\mathbf{1}(X)$ is the indicator function, taking value 1 when X is true, and 0 when X is false.

No.	Equation
Observation models for biomass index and composition data	
(O.1)	$\hat{I}_{g,t} = q_g B_{g,t}$
(O.2)	$\hat{u}_{l,g,t} = \dfrac{\sum_a P(l \mid a) s_{a,g} N_{a,g} e^{-f_g Z_{a,x,t}}}{\sum_{l'} \sum_{a'} P(l \mid a') s_{a',g} N_{a',g} e^{-f_g Z_{a',t}}}$
Biomass index likelihood	
(NLL.1)	$n_g = \sum_{t=1}^{T} \mathbf{1}(I_{g,t} > 0)$
(NLL.2)	$z_{g,t} = \begin{cases} \log \frac{I_{g,t}}{B_{g,t}} & g = 5 \\ \log \frac{I_{g,t}}{q_g B_{g,t}} & g = 1,4 \end{cases}$
(NLL.3)	$\hat{q}_g = \dfrac{1}{n_g} z_{g,t}, \quad g = 4$
(NLL.4)	$\hat{\tau}_g^2 = \begin{cases} \frac{1}{n_g} \sum_t \mathbf{1}(I_{g,t} > 0) \cdot (z_{g,t} - \hat{q}_g)^2 & g = 5 \\ \frac{1}{n_g} \sum_t \mathbf{1}(I_{g,t} > 0) \cdot (z_{g,t})^2 & g = 1,4 \end{cases}$
(NLL.5)	$l_{g,1} = \dfrac{1}{2} \left(n_g \log \hat{\tau}^2 + n_g \right)$
Length composition likelihood	
(LL.1)	$n_{g,t}^{len} = \sum_a \mathbf{1}(u_{l,g,t} > 0)$
(LL.2)	$\eta_{l,g,t} = \log u_{l,g,t} - \log \hat{u}_{l,g,t}$
(LL.3)	$Z_g = \sum_t \sum_a \left(\eta_{l,g,t} - \dfrac{1}{n_{g,t}^{len}} \sum_{l'} \eta_{l',g,t} \right)$
(LL.4)	$\hat{\tau}_{len,g}^2 = \dfrac{1}{\sum_t n_{g,t}^{len}} Z_g$
(LL.5)	$l_{g,2} = \left(\dfrac{1}{2} \sum_t n_{g,t}^{len} \cdot \log \hat{\tau}_{age,g}^2 \right)$
Model priors	
(P.1)	$p_h = -\left[(\beta_1 - 1) \log h + (\beta_2 - 1) \log(1 - h) \right]$
(P.2)	$p_M = \dfrac{M_m - \mu_m}{2\sigma_M^2} + \dfrac{M_f - \mu_f}{2\sigma_M^2}$
(P.3)	$p_s = \sum_g \left(\dfrac{\alpha_g - \mu_{\alpha_g}}{2\sigma_{sel,g}^2} + \dfrac{\beta_g - \mu_{\beta,g}}{2\sigma_{sel,g}^2} \right)$
(P.4)	$p_R = \sum_{t=2}^{T} \omega_t^2$
Objective Function	
(OF.1)	$f = \sum_g \left(w_g^{idx} l_{g,1} + w_g^{len} l_{g,2} \right) + p_h + p_M + p_s + p_R$

7 FIGURES

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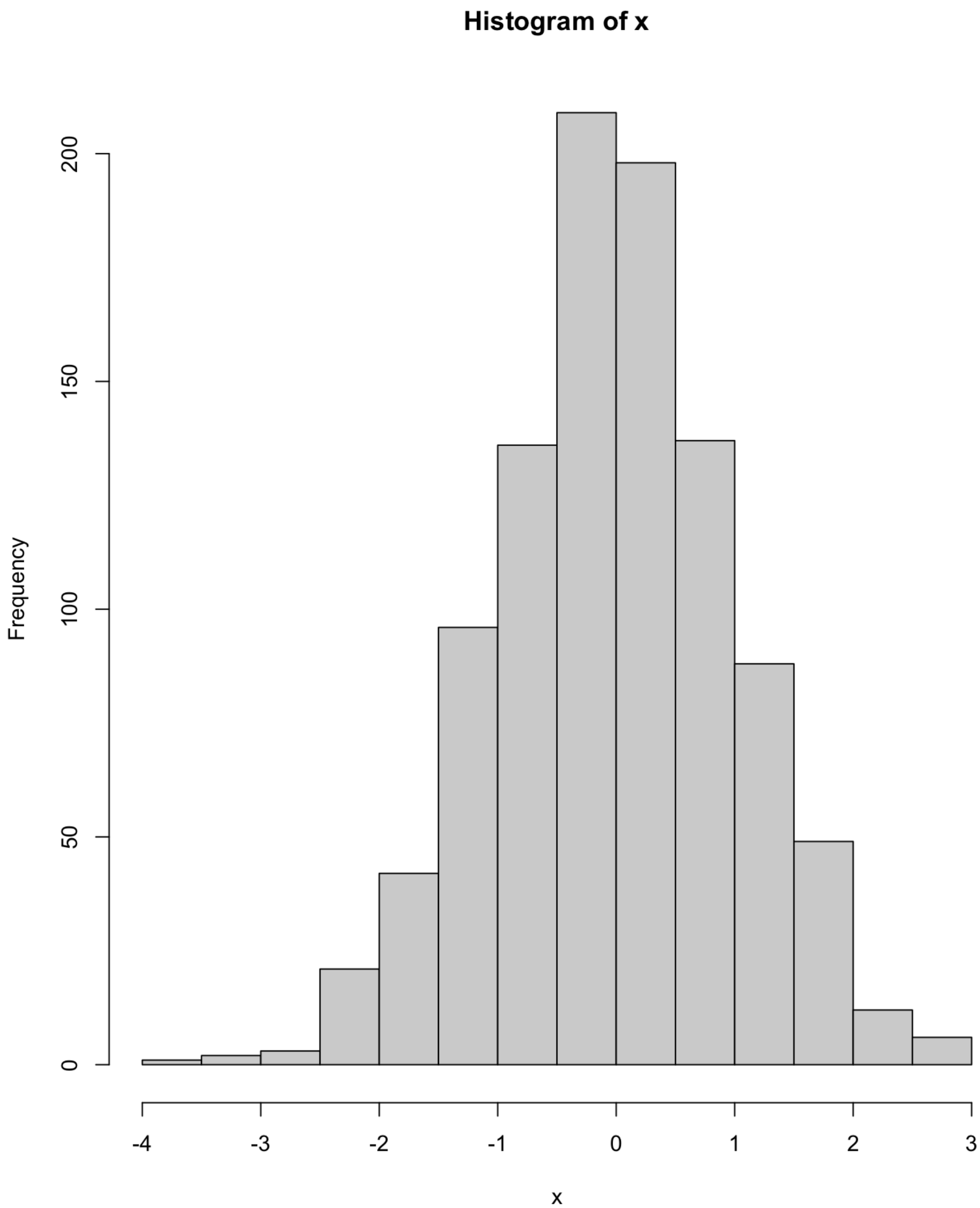

Figure 1: histogram of 1000 draws from normal distribution

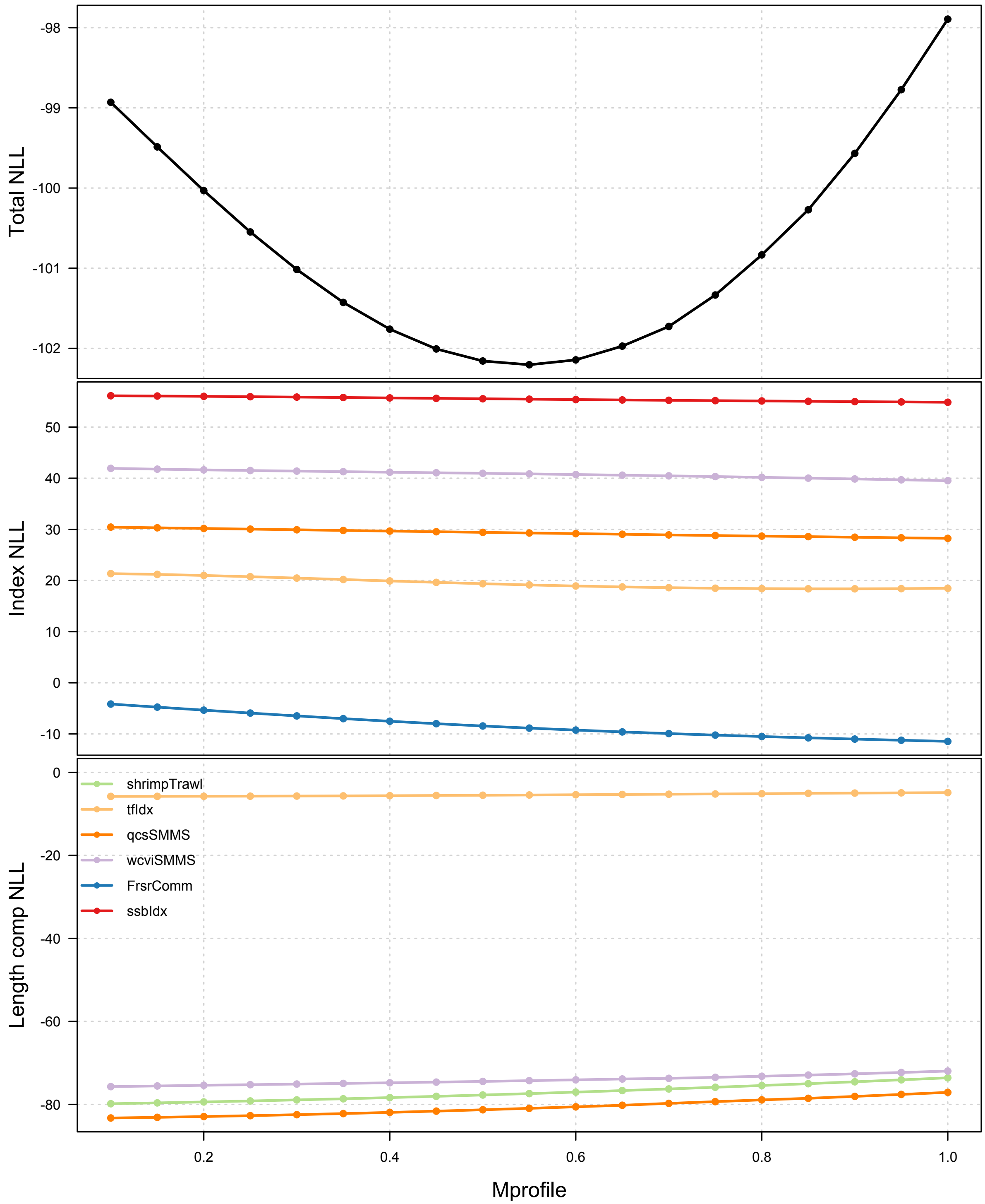

Figure 2: Negative log likelihood (NLL) profile for operating model fits with natural mortaltiy fixed at values ranging from 0.1 to 1.0. The top panel shows the total NLL, while the middle and bottom panels show NLL components for indices and length compositions, respectively.

Appendix A Cool Appendix

A.1 Subsection

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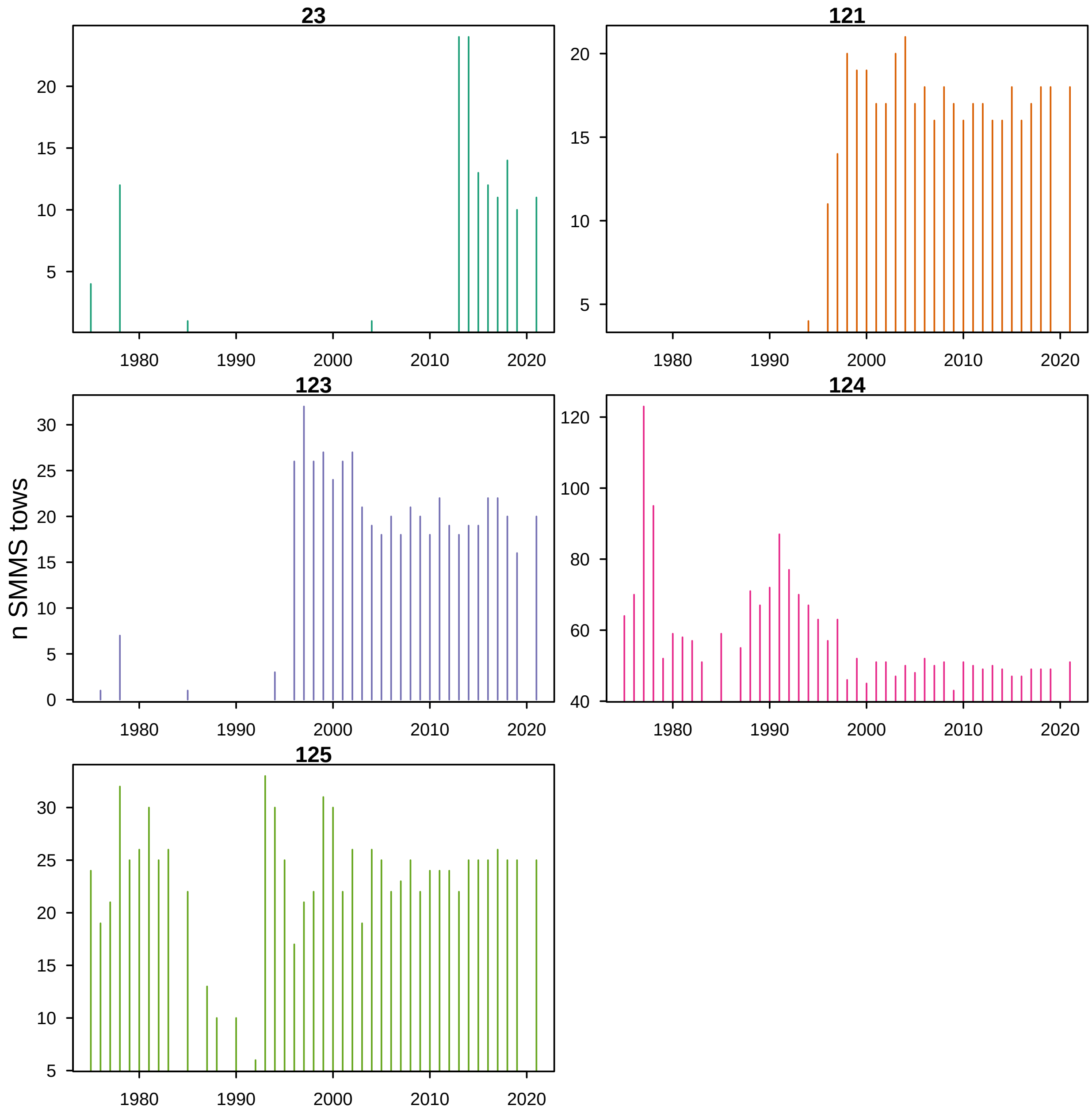

Figure A.1: Number of SMMS tows in WCVI PFMAs from 1975-2021

Table A.1: Iris data

Sepal.Length	Sepal.Width	Petal.Length	Petal.Width	Species
5.1	3.5	1.4	0.2	setosa
4.9	3.0	1.4	0.2	setosa
4.7	3.2	1.3	0.2	setosa
4.6	3.1	1.5	0.2	setosa
5.0	3.6	1.4	0.2	setosa
5.4	3.9	1.7	0.4	setosa

Appendix B Appendix B

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B.1 Subsection

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B.2 Figures

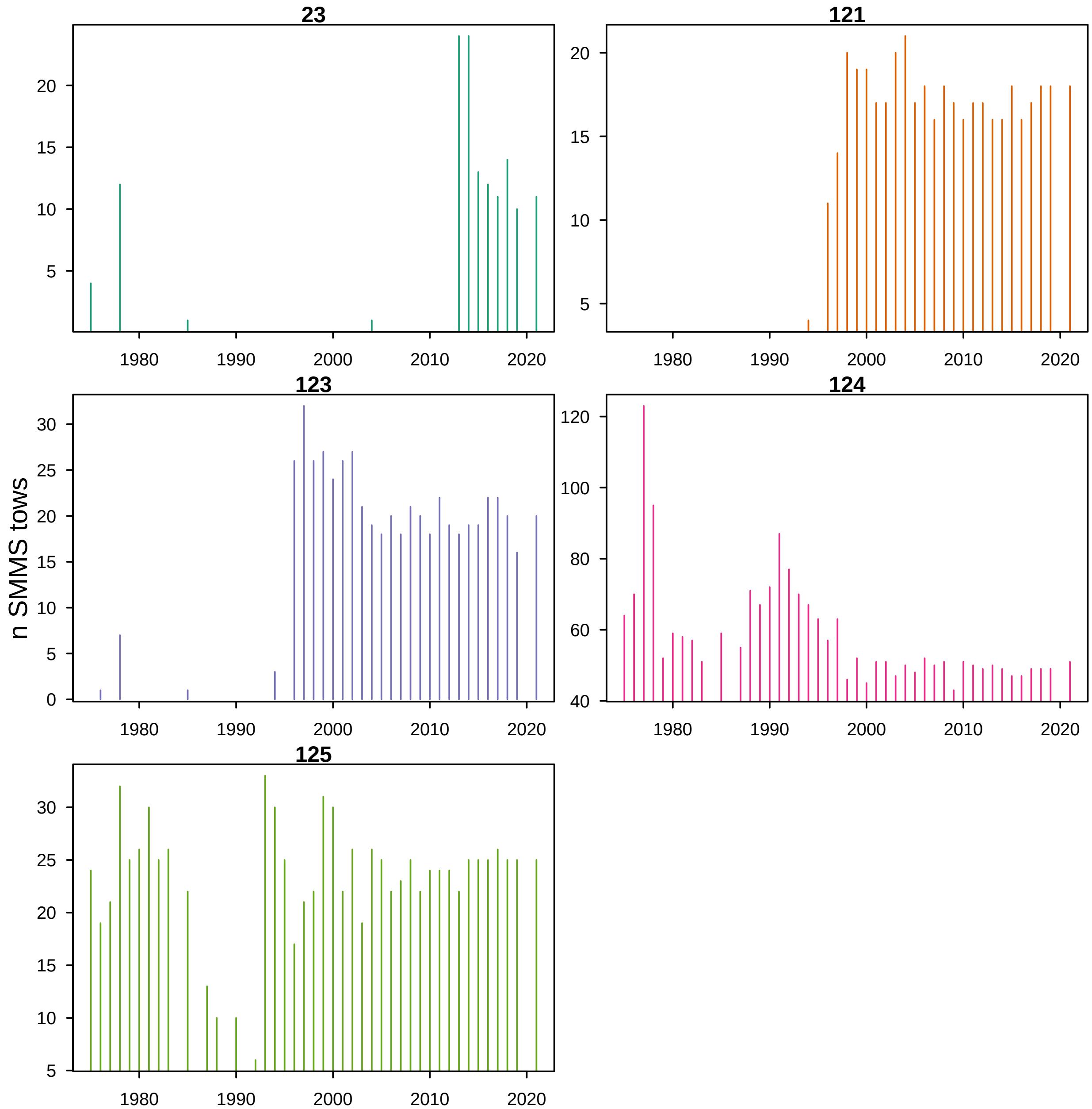

Figure B.1: Number of SMMS tows in WCVI PFMAs from 1975-2021