Trend analysis for USFWS species status assessment for bull trout (*Salvelinus confluentus*)

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Background

Bull trout (*Salvelinus confluentus*) in the western U.S. were listed as threatened under the U.S. Endangered Species Act in 1998. The purpose of this analysis is to estimate trends in the abundance (counts) of bull trout within predefined core areas spread across Oregon, Washington, Idaho, and Montana, as part of the current Species Status Assessment (SSA).

Data

I provided a MS Excel template for the desired data in a "tidy" format, which consisted of the following 8 fields (columns):

- `dataset` (i.e., integer value for unique ID)
- `recovery unit` (e.g., Mid Columbia)
- `core area` (e.g., South Fork Clearwater)
- `popn/stream` (e.g., Crooked River)
- `metric` (e.g., abundance)
- `method` (e.g., redd survey)
- `year`
- `value` (i.e., counts)

The data coordinators also provided me with some metadata indicating which of the data specific to a location were generally for adults versus juveniles. Data files were subsequently provided to me by data coordinators from each of the four states:

- Oregon: Stephanie Gunckel (ODFW)
- Washington: Marie Winkowski (WDFW)
- Idaho: Brett Bowersox (IDFG)
- Montana: Dan Brewer (USFWS)

The data from Montana came via biologists with the USGS (Clint Muhlfeld, Tim Cline), and did not conform to the template file I had provided. Thus, those data were subjected to additional cleaning prior to their inclusion with the data from other states (see below).

Prior to analysis, all of the count data were log-transformed and standardized to a mean of zero and variance of one, which aided in model fitting and, in particular, the estimation of the process and observation (sampling) variances.

Modeling framework

Population model

I fit discrete-time versions of exponential models for population growth (decline), such that the abundance of bull trout (N) is a function of the initial population size N_0, time (t), the population growth rate (u), and a time-dependent stochastic effect of the environment (w). Specifically, in continuous time the model is

$$N(t) = N_0 \exp(u) \exp(wt). \tag{1}$$

In discrete time, with a time step of 1 unit (e.g., a year), the model becomes

$$N_t = N_{t-1} \exp(u + w_t). \tag{2}$$

If we take the logarithm of both sides and define $x_t = \log(N_t)$, we have

$$x_t = x_{t-1} + u + w_t. \tag{3}$$

Further defining $w_t \sim \mathrm{N}(0, q)$ leads us to a so-called "biased random walk" model, where u is the tendency for the population to increase or decrease each time step (i.e., the bias), and w_t is some unknown stochastic aspect of the environment that partially drives population dynamics.

Observation model

The data available to us rarely come from complete censuses, and instead are typically derived from partial counts. Furthermore, mistakes may occur when counting individuals or redds. Thus, we should account for these possible sampling or observation errors with a so-called "data model."

In this case, we assume that the data in hand are a somewhat distorted view of the "true state of nature," such that the logarithm of the observed count at time t (y_t) equals that of the true count plus or minus some error. Specifically, we can write this as

$$y_t = x_t + a + v_t \tag{4}$$

where a is an offset to account for partial sampling, and $v_t \sim \mathrm{N}(0, r)$.

State-space model

We can combine equations (3) and (4), along with a definition for the initial state (x_0), into a so-called "state-space model," where

$$\begin{aligned} y_t &= x_t + a + v_t \\ x_t &= x_{t-1} + u + w_t \\ x_0 &\sim \mathrm{N}(\mu, \sigma) \end{aligned} \tag{5}$$

Multiple populations

Here we want to estimate the annual change in population size for each of the many different core areas across the four states. Furthermore, some core areas comprise several different populations/locations, so we need to frame our state-space model in a multivariate context.

Observation model

If we have n different populations within a core area, then our observation model becomes

$$y_{i,t} = x_{i,t} + a_i + v_{i,t} \tag{6}$$

where $y_{i,t}$ is the log-count for population i and year t, a_i is an offset to account for partial sampling in population i, and $v_{i,t} \sim \mathrm{N}(0, r_i)$[1]. We can combine each of the population specific observation models into a matrix form, such that

$$\begin{aligned} y_{1,t} &= x_{1,t} + a_1 + v_{1,t} \\ y_{2,t} &= x_{2,t} + a_2 + v_{2,t} \\ &\vdots \\ y_{n,t} &= x_{n,t} + a_3 + v_{n,t} \end{aligned} \tag{7}$$

becomes

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix}_t = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}_t + \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{bmatrix} + \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \end{bmatrix}_t, \tag{8}$$

[1] Here the variance of the observation errors is assumed to be population specific, but it might be reasonable to assume that each survey/census type might have the same variance, such that $v_{i,t} \sim \mathrm{N}(0, r)$.

or more compactly in matrix notation as

$$\mathbf{y}_t = \mathbf{x}_t + \mathbf{a} + \mathbf{v}_t. \tag{9}$$

where $\mathbf{y}_t$, $\mathbf{x}_t$, $\mathbf{a}$, $\mathbf{v}_t$ are all $n \times 1$ vectors, and $\mathbf{w}_t \sim \text{MVN}(\mathbf{0}, \mathbf{Q})$.

Population model

Just as we did for the observation model, we can write the models for population dynamics as

$$x_{j,t} = x_{j,t-1} + u_j + w_{j,t} \tag{10}$$

where u_i is the bias, which is unique to each population[2], and $w_{j,t} \sim \text{N}(0, q)\}$.

We can again express all of the population models in matrix form, such that

$$\begin{aligned} x_{1,t} &= x_{1,t-1} + u_1 + w_{1,t} \\ x_{2,t} &= x_{2,t-1} + u_2 + w_{2,t} \\ &\vdots \\ x_{n,t} &= x_{n,t-1} + u_3 + w_{n,t} \end{aligned} \tag{11}$$

becomes

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}_t = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}_t + \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_n \end{bmatrix} + \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix}_t, \tag{12}$$

or more compactly in matrix notation as

$$\mathbf{x}_t = \mathbf{x}_{t-1} + \mathbf{u} + \mathbf{w}_t \tag{13}$$

where $\mathbf{x}_t$, $\mathbf{x}_{t-1}$, $\mathbf{u}$, $\mathbf{w}_t$ are all $n \times 1$ vectors, and $\mathbf{w}_t \sim \text{MVN}(\mathbf{0}, \mathbf{Q})$.

[2]It might be reasonable to assume that some/all of the populations have the same bias, given their membership within a core area.

State-space forms

At this point, however, we are assuming that the monitoring data for each population is telling us something about only the specific population itself, rather than contributing information to the population trend at the larger scale of their core area, which is the really the scale of interest here. Thus, we need to modify our equations to accommodate this hierarchical framework.

For example, assume that we have $p = 2$ core areas (call them A and B), each with data from 2 representative populations. In this case, $n = 4$, but the number of states (i.e., the number of rows in $\mathbf{x}_t$) is 2, so we need a way to "map" each of the observed time series onto its respective core area. We begin by writing out the equations for the observations in long matrix form akin to equation (8), such that

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix}_t = \begin{bmatrix} x_A \\ x_A \\ x_B \\ x_B \end{bmatrix}_t + \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix} + \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{bmatrix}_t, \tag{14}$$

Because both x_A and x_B appear twice in equation (14), we can use a 4×2 matrix of 1's and 0's as our map. Specifically, we have

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix}_t = \begin{bmatrix} 1 & 0 \\ 1 & 0 \\ 0 & 1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_A \\ x_B \end{bmatrix}_t + \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix} + \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{bmatrix}_t, \tag{15}$$

We can write equation (15) more compactly in matrix notation as

$$\mathbf{y}_t = \mathbf{Z}\mathbf{x}_t + \mathbf{a} + \mathbf{v}_t. \tag{16}$$

where $\mathbf{y}_t$, $\mathbf{a}$, and $\mathbf{v}_t$ are all $n \times 1$ vectors, $\mathbf{Z}$ is an $n \times k$ matrix, and $\mathbf{x}_t$ is a $k \times 1$ vector.

The equation for the population dynamics in each of the 2 core areas then becomes

$$\begin{bmatrix} x_A \\ x_B \end{bmatrix}_t = \begin{bmatrix} x_A \\ x_B \end{bmatrix}_{t-1} + \begin{bmatrix} u_A \\ u_B \end{bmatrix} + \begin{bmatrix} w_A \\ w_B \end{bmatrix}_t, \tag{17}$$

which can be written more compactly in matrix notation as

$$\mathbf{x}_t = \mathbf{x}_{t-1} + \mathbf{u} + \mathbf{w}_t, \tag{18}$$

and combined with equation (16) to form the full multivariate state-space model

$$\begin{aligned} \mathbf{y}_t &= \mathbf{Z}\mathbf{x}_t + \mathbf{a} + \mathbf{v}_t \\ \mathbf{x}_t &= \mathbf{x}_{t-1} + \mathbf{u} + \mathbf{w}_t. \end{aligned} \tag{19}$$

Thus, by simply altering the dimensions of $\mathbf{Z}$, and the locations of 1's and 0's within it, we can evaluate any number of different hypotheses about how the population dynamics are structured spatially. For example, if we set $\mathbf{Z}$ equal to an $n \times n$ identity matrix, where

$$\mathbf{Z} = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix}, \tag{20}$$

then each of the time series of data is assumed to represent a unique state of nature. If, on the other hand, we set $\mathbf{Z}$ equal to an $n \times 1$ column vector of 1's, such that

$$\mathbf{Z} = \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix}, \tag{21}$$

then each of the time series of data is assumed to represent a sample from a single state of nature.

Variance specification

The multivariate state-space model allows us to be quite specific about how the observation errors ($\mathbf{v}_t$) and process errors ($\mathbf{w}_t$) are related to one another, if at all. In the most simple case, the errors could be independent and identically distributed (IID), such that (for the observation variance)

$$\mathbf{R} = \begin{bmatrix} r & 0 & \cdots & 0 \\ 0 & r & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & r \end{bmatrix}. \tag{22}$$

Alternatively, the errors might be independent, but not identically distributed

$$\mathbf{R} = \begin{bmatrix} r_1 & 0 & \cdots & 0 \\ 0 & r_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & r_n \end{bmatrix}, \tag{23}$$

or identically distributed, but not independent

$$\mathbf{R} = \begin{bmatrix} r & c & \cdots & c \\ c & r & \cdots & c \\ \vdots & \vdots & \ddots & \vdots \\ c & c & \cdots & r \end{bmatrix}. \tag{24}$$

Model fitting

The adult data come from 244 populations within 62 core area spread across the 6 recovery domains. Thus, $\mathbf{y}_t$ is a 244×1 vector of transformed observed counts in year t, and $\mathbf{x}_t$ is a 62×1 vector of underlying states in year t. The matrix $\mathbf{Z}$ is a 244×62 matrix of 1's and 0's that maps each of the respective observations onto their respective states.

The juvenile data are much more restricted, coming from 31 populations within 15 core area spread across the 6 recovery domains. Thus, $\mathbf{y}_t$ is a 31×1 vector of transformed observed counts in year t, and $\mathbf{x}_t$ is a 15×1 vector of underlying states in year t. The matrix $\mathbf{Z}$ is a 31×15 matrix of 1's and 0's that maps each of the respective observations onto their respective states.

All trends were estimated for the period covering 2008-2020 to reflect the most recent data.

Because the source of the data varies by location, I estimated different variance terms for each of the methods (e.g., screw trap, snorkel survey, weir). Specifically, the covariance matrix is given by

$$\mathbf{R} = \begin{bmatrix} r_i & 0 & \cdots & 0 \\ 0 & r_i & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & r_i \end{bmatrix}. \tag{25}$$

where i indicates the source of the data.

In this particular case, the data were standardized prior to model fitting, so I assumed that the process errors ($w_{j,t}$) were independent and identically distributed, such that

$$\mathbf{Q} = \begin{bmatrix} q & 0 & \cdots & 0 \\ 0 & q & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & q \end{bmatrix}. \tag{26}$$

All models were fit using the `{MARSS}` package (Holmes *et al.* 2012; 2021b, a) for the **R** computing software (R Core Team 2020). I estimated 90% confidence intervals (CI's) around each of the estimated bias terms (u_j) using the `MARSSparamCIs()` function based upon an asymptotic variance assumption. All of the data and code necessary to reproduce the results of the analysis can be found online at https://github.com/mdscheuerell/bulltrout.

Results

Adult abundance

Estimated trends in adult abundance were rather mixed (Tables 1-4), such that 37 out of 62 core areas showed decreasing trends, but only 3 of trends had 90% CI's that did not overlap 0. The remaining 25 core areas had decreasing trends, but only 5 of them had 90% CI's that did not overlap 0. Fitted trend lines and their associated CI's are provided in Appendix A.

Juvenile abundance

Estimated trends in juvenile abundance were also rather mixed (Table 5), such that 37 out of 62 core areas showed decreasing trends, but only 3 of trends had 90% CI's that did not overlap 0. The remaining 25 core areas had decreasing trends, but only 5 of them had 90% CI's that did not overlap 0. Fitted trend lines and their associated CI's are provided in Appendix B.

References

Holmes EE, Scheuerell MD, and Ward EJ. 2021a. Analysis of multivariate time-series using the MARSS package. Version 3.11.4.

Holmes EE, Ward EJ, Scheuerell MD, and Wills K. 2021b. MARSS: Multivariate autoregressive state-space modeling.

Holmes EE, Ward EJ, and Wills K. 2012. MARSS: Multivariate autoregressive state-space models for analyzing time-series data. *The R Journal* **4**: 30.

R Core Team. 2020. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing.

Table 1: Estimated trends and uncertainty for adult bull trout in core areas in Montana. The trend column indicates if the estimated trend was significantly positive (+), negative (-), or neutral (0).

Core area	Lower CI	Mean	Upper CI	Trend
CANADA	-0.0803	0.0225	0.1253	0
Big Salmon Lake	-0.2179	-0.0620	0.0939	0
Bitterroot River	-0.1499	-0.0418	0.0663	0
Blackfoot River	-0.1784	-0.0878	0.0028	0
Bowman	-0.0699	0.1135	0.2969	0
Bull Lake	-0.2344	-0.1367	-0.0391	-
Cerulean/Quartz Mid Lakes	-0.0833	0.0341	0.1515	0
Clearwater	-0.1592	-0.0621	0.0349	0
Cyclone Lake	-0.2273	-0.0938	0.0396	0
Flathead Lake	-0.1186	-0.0304	0.0577	0
Harrison Lake	-0.2647	-0.1256	0.0136	0
Holland Lake	-0.0952	0.0190	0.1332	0
Hungry Horse Reservoir	-0.1628	-0.0697	0.0234	0
Kootenai River	-0.1869	-0.0959	-0.0049	-
Lake Koocanusa	-0.2535	-0.1602	-0.0668	-
Lake Pend Oreille	-0.1472	-0.0606	0.0260	0
Lindbergh Lake	-0.1541	-0.0178	0.1184	0
Logging	-0.2563	-0.1352	-0.0140	-
Lower Quartz Lake	-0.1671	-0.0425	0.0820	0
Middle Clark Fork River	-0.1394	-0.0420	0.0554	0
Rock Creek	-0.1617	-0.0714	0.0189	0
Swan Lake	-0.1932	-0.1042	-0.0151	-
Upper Clark Fork River	-0.0579	0.0398	0.1375	0
Upper Stillwater Lake	-0.0704	0.0349	0.1403	0
Upper Whitefish Lake	-0.0654	0.0511	0.1677	0
West Fork Bitterroot River	-0.1455	-0.0314	0.0828	0
Whitefish Lake	-0.0827	0.0337	0.1500	0
St. Mary River	-0.2103	-0.0917	0.0269	0

Table 2: Estimated trends and uncertainty for adult bull trout in core areas in Idaho. The trend column indicates if the estimated trend was significantly positive (+), negative (-), or neutral (0).

Core area	Lower CI	Mean	Upper CI	Trend
Couer d'Alene	-0.2322	-0.1349	-0.0376	-
Kootenai	-0.2552	-0.1366	-0.0180	-
LPO	-0.1563	-0.0668	0.0227	0
Priest Lakes	-0.0669	0.0317	0.1304	0
North Fork Clearwater	-0.2960	-0.1752	-0.0544	-
Lemhi River	-0.1401	-0.0272	0.0857	0
Little-Lower Salmon River	-0.0662	0.0546	0.1755	0
South Fork Salmon River	0.0034	0.1248	0.2462	+
Upper Salmon	-0.1423	-0.0494	0.0435	0

Table 3: Estimated trends and uncertainty for adult bull trout in core areas in Washington. The trend column indicates if the estimated trend was significantly positive (+), negative (-), or neutral (0).

Core area	Lower CI	Mean	Upper CI	Trend
Chester Morse Lake	-0.1959	-0.0876	0.0207	0
Lewis River	-0.0928	0.0096	0.1119	0
Lower Skagit River	-0.2408	-0.1413	-0.0418	-
Puyallup River	-0.0235	0.0663	0.1561	0
Skokomish River	-0.0891	0.0288	0.1467	0
Snohomish and Skykomish Rivers	-0.2554	-0.1391	-0.0227	-
Stillaguamish River	-0.3338	-0.2098	-0.0858	-
Asotin Creek	-0.1744	-0.0577	0.0589	0
Entiat River	-0.0832	0.0261	0.1353	0
Methow River	-0.1478	-0.0302	0.0874	0
Touchet River	-0.0496	0.0555	0.1605	0
Tucannon River	-0.1008	0.0068	0.1144	0
Wenatchee River	-0.1318	-0.0305	0.0707	0
Yakima River	-0.1329	-0.0358	0.0613	0

Table 4: Estimated trends and uncertainty for adult bull trout in core areas in Oregon. The trend column indicates if the estimated trend was significantly positive (+), negative (-), or neutral (0).

Core area	Lower CI	Mean	Upper CI	Trend
Hood River	-0.1631	-0.0395	0.0841	0
Lower Deschutes River	-0.1315	-0.0231	0.0853	0
Odell Lake	-0.2024	-0.0869	0.0285	0
Upper Willamette River	-0.0653	0.0294	0.1241	0
Imnaha River	-0.1952	-0.0906	0.0140	0
Lookingglass/Wenaha	-0.0705	0.0428	0.1561	0
Pine-Indian-Wildhorse Creeks	-0.2619	-0.1318	-0.0018	-
Umatilla River	-0.1542	-0.0399	0.0744	0
Upper Grande Ronde	-0.0119	0.0942	0.2003	0
Walla Walla River	-0.1587	-0.0506	0.0576	0
Wallowa/Minam	-0.0797	0.0288	0.1372	0

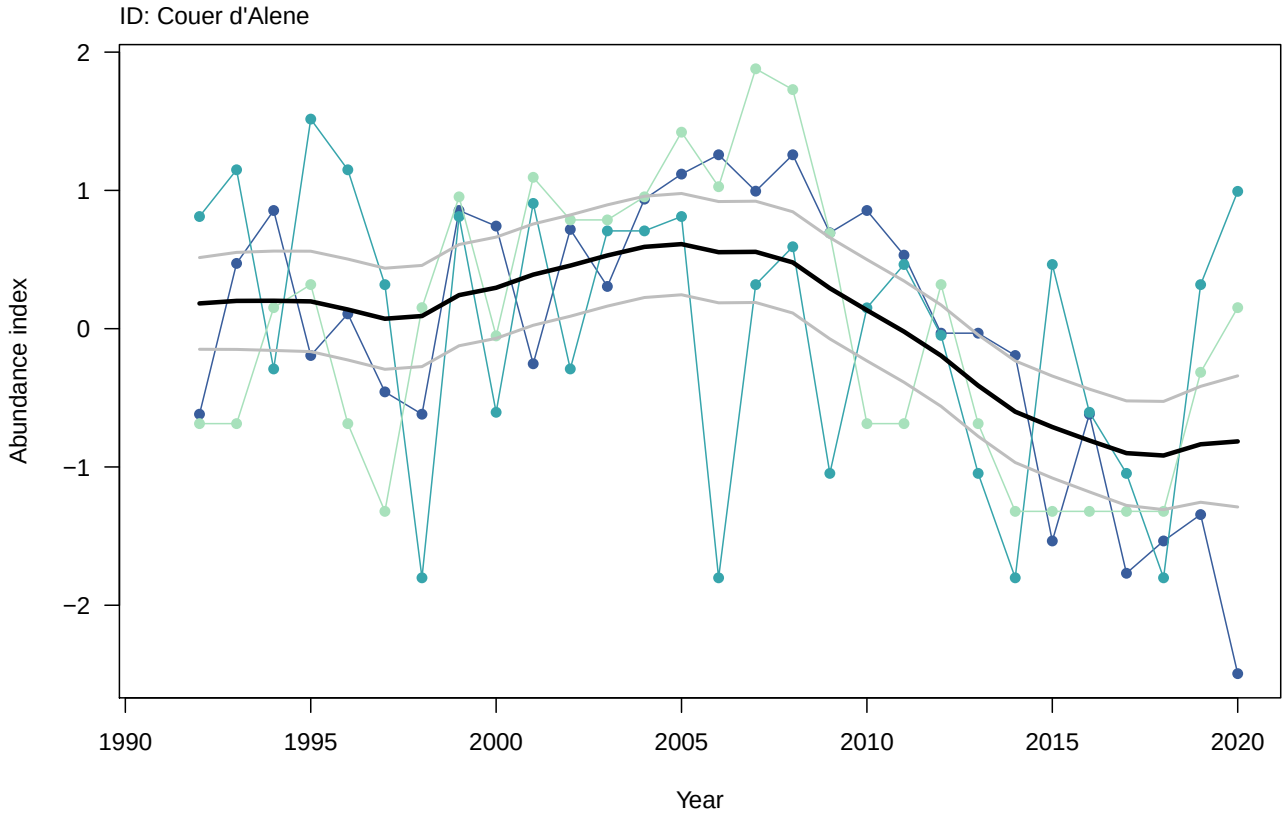
Table 5: Estimated trends and uncertainty for juvenile bull trout in Idaho, Washington, and Oregon. The trend column indicates if the estimated trend was significantly positive (+), negative (-), or neutral (0).

State	Core area	Lower CI	Mean	Upper CI	Trend
ID	Lochsa River	-0.0560	0.0067	0.0695	0
ID	Selway River	-0.1758	-0.0878	0.0001	0
ID	South Fork Clearwater	-0.0265	0.0362	0.0988	0
ID	Lemhi River	-0.0032	0.0526	0.1085	0
ID	Little Lost	-0.0346	0.0836	0.2018	0
ID	Little-Lower Salmon River	-0.1432	-0.0846	-0.0261	-
ID	Mid Salmon - Panther	-0.1400	-0.0499	0.0402	0
ID	Middle Fork Salmon River	-0.0981	-0.0400	0.0180	0
ID	Pahsimeroi	-0.0199	0.0911	0.2020	0
ID	South Fork Salmon River	0.0576	0.1628	0.2680	+
ID	Upper Salmon	0.0468	0.1040	0.1613	+
ID	Weiser River	-0.2138	-0.0841	0.0455	0
OR	Odell Lake	-0.0637	0.0651	0.1939	0
WA	Dungeness	-0.1678	-0.0841	-0.0004	-
WA	Lower Skagit River	-0.1705	-0.1074	-0.0443	-
WA	Asotin Creek	-0.1867	-0.1229	-0.0591	-
WA	Entiat River	-0.3436	-0.2126	-0.0815	-
WA	Tucannon River	-0.1221	-0.0688	-0.0154	-
WA	Wenatchee River	-0.1084	-0.0496	0.0091	0

Appendix A

The following pages contain plots of standardized indices of log-abundance for adults over time by core area (i.e., location indicated on plots by `State: Core area`). Fitted trend lines (black) and associated 90% confidence intervals (gray) are also shown.

163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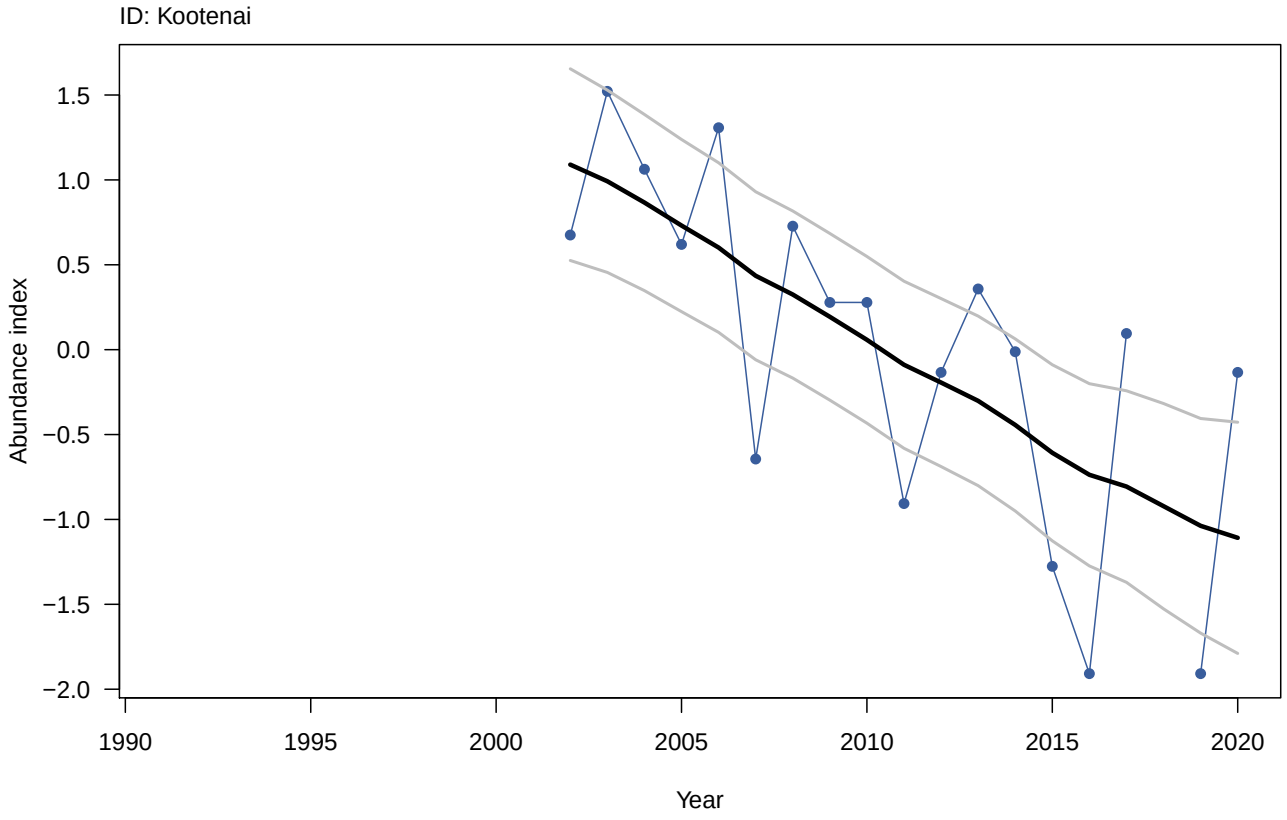
2
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

164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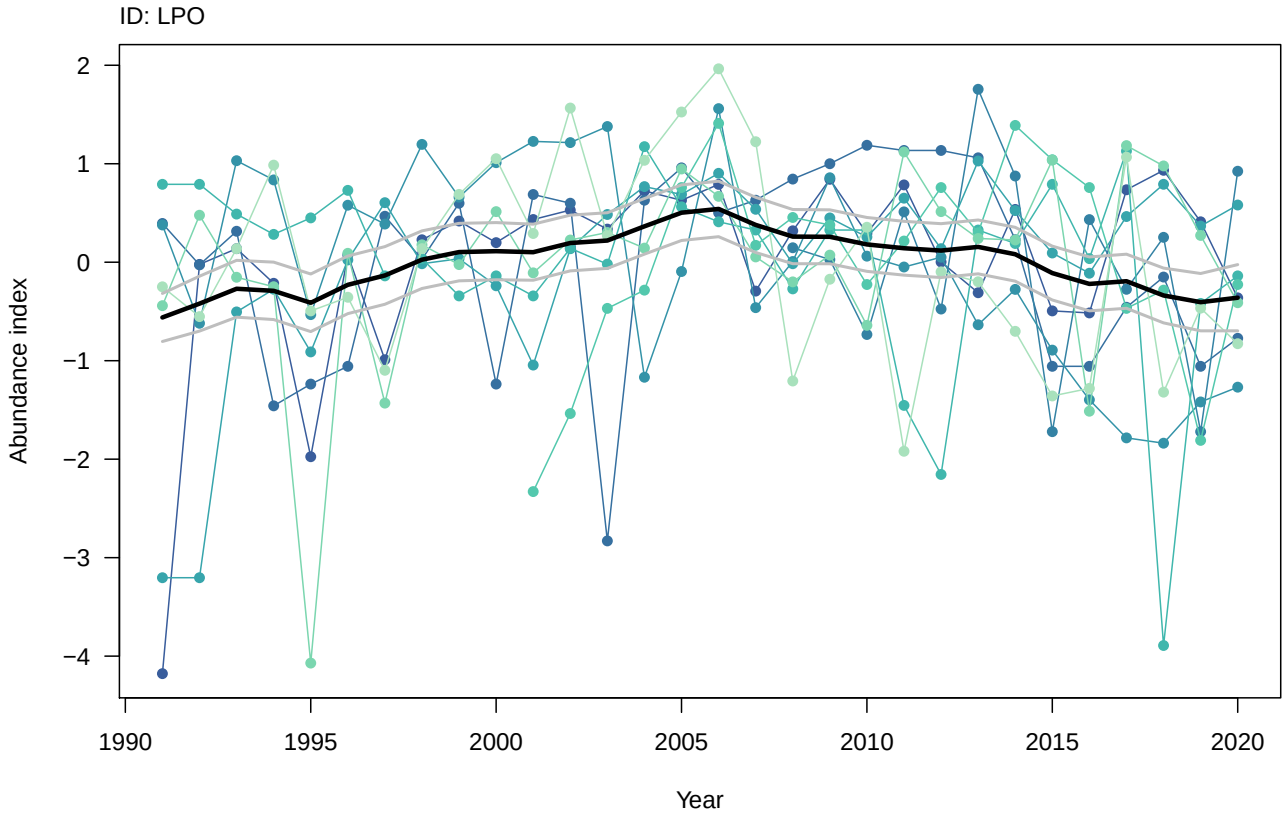
−2.0
1990
1995
2000
2005
2010
2015
2020
Year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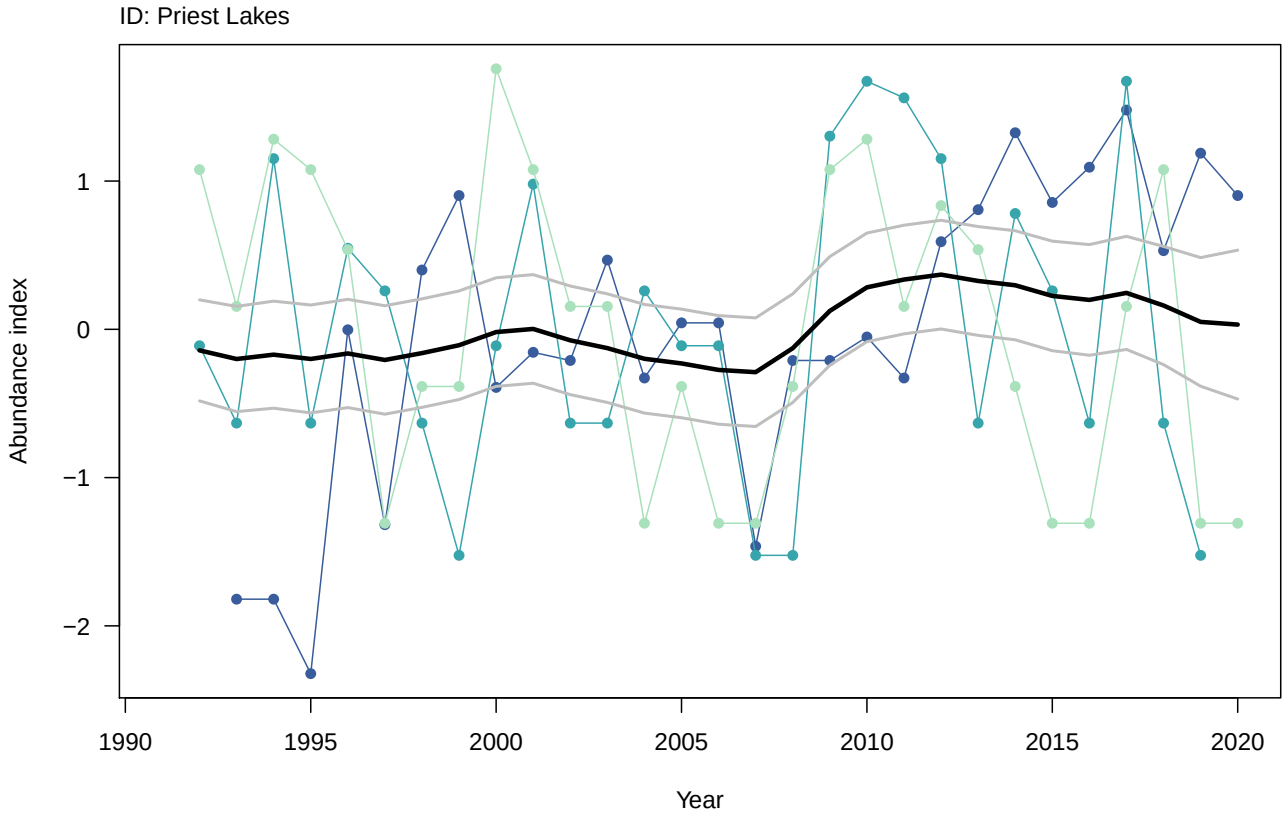
1990
1995
2000
2005
2010
2015
2020
Year

166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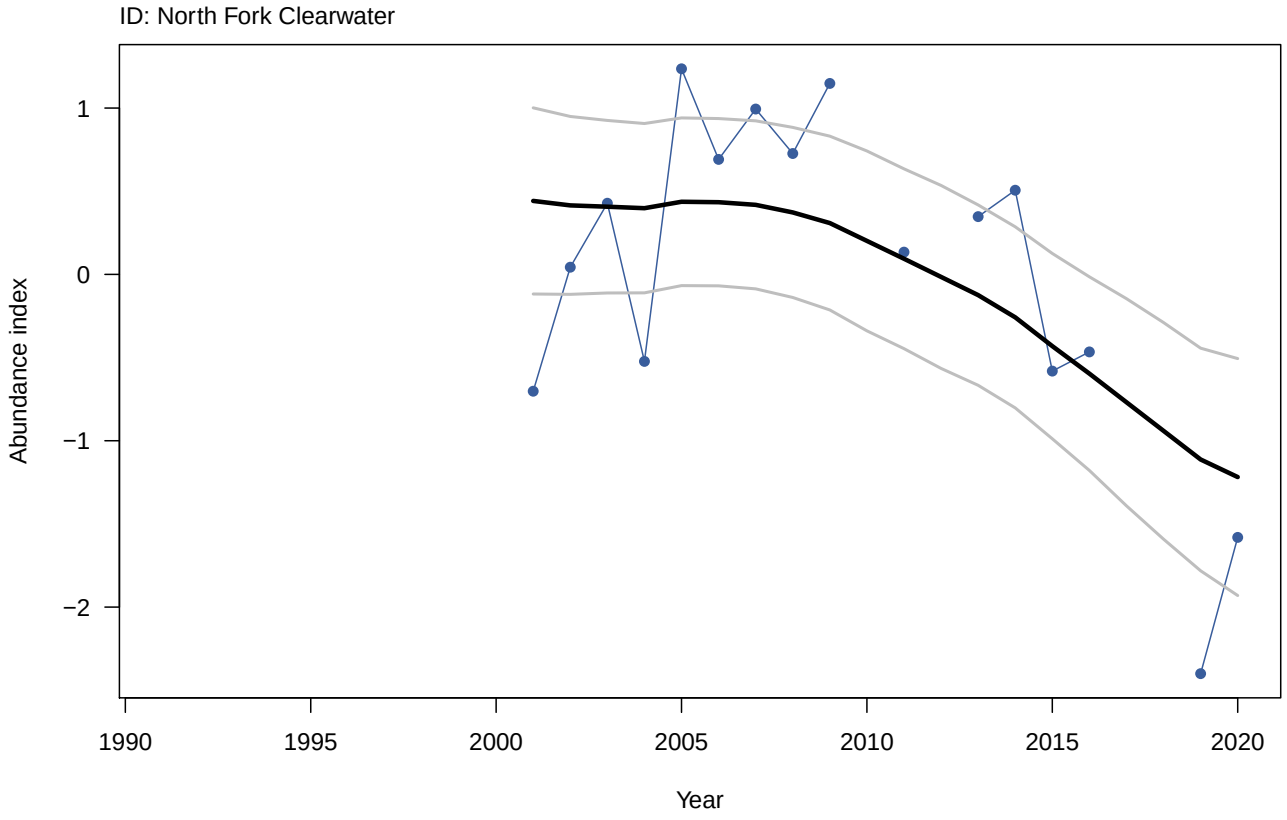
Abundance index
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

167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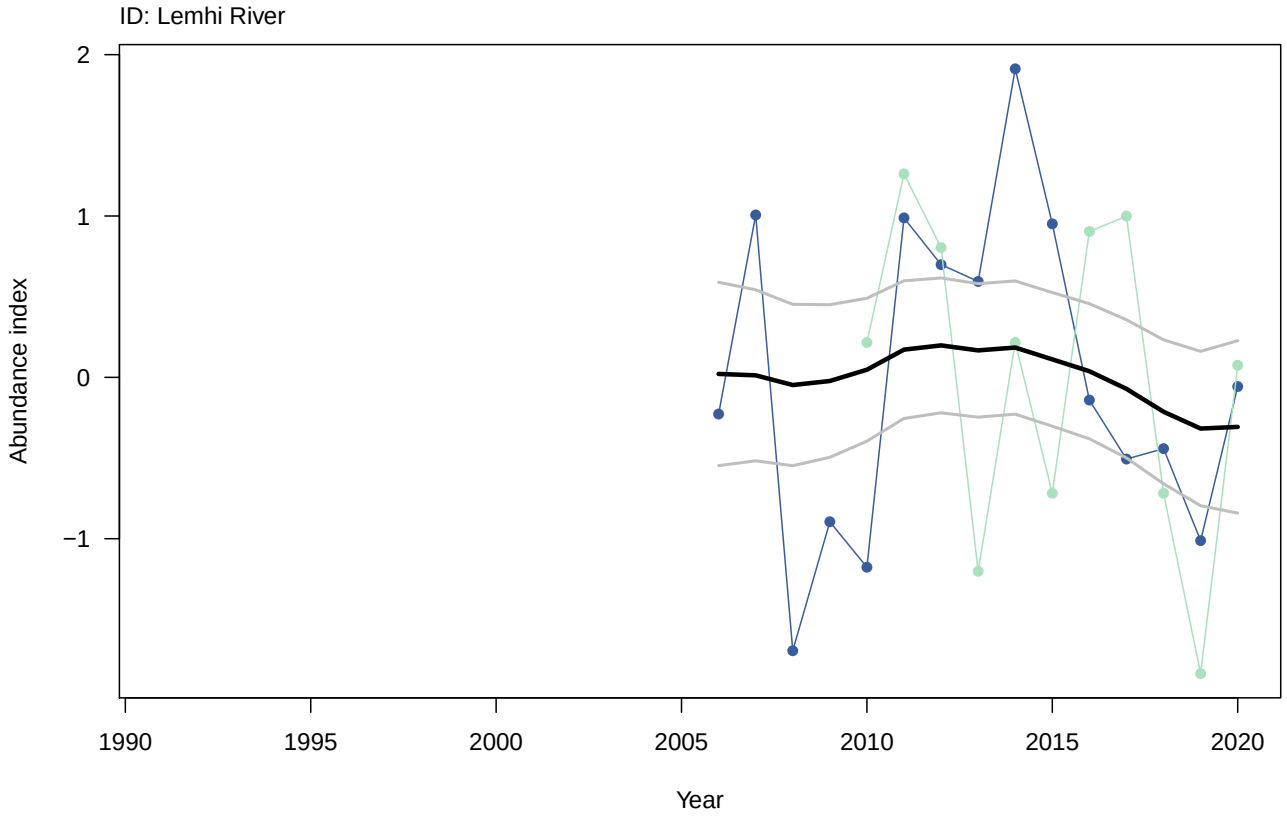
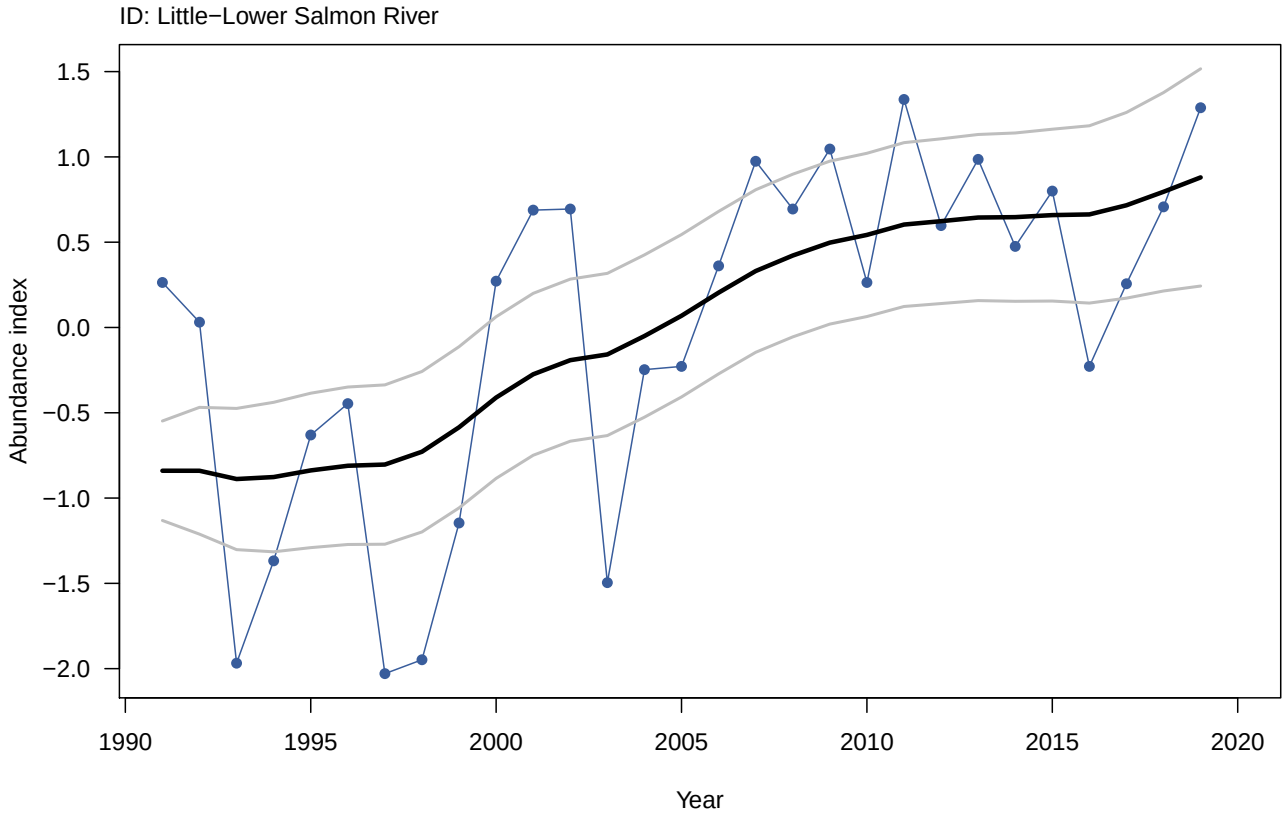
Abundance index
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

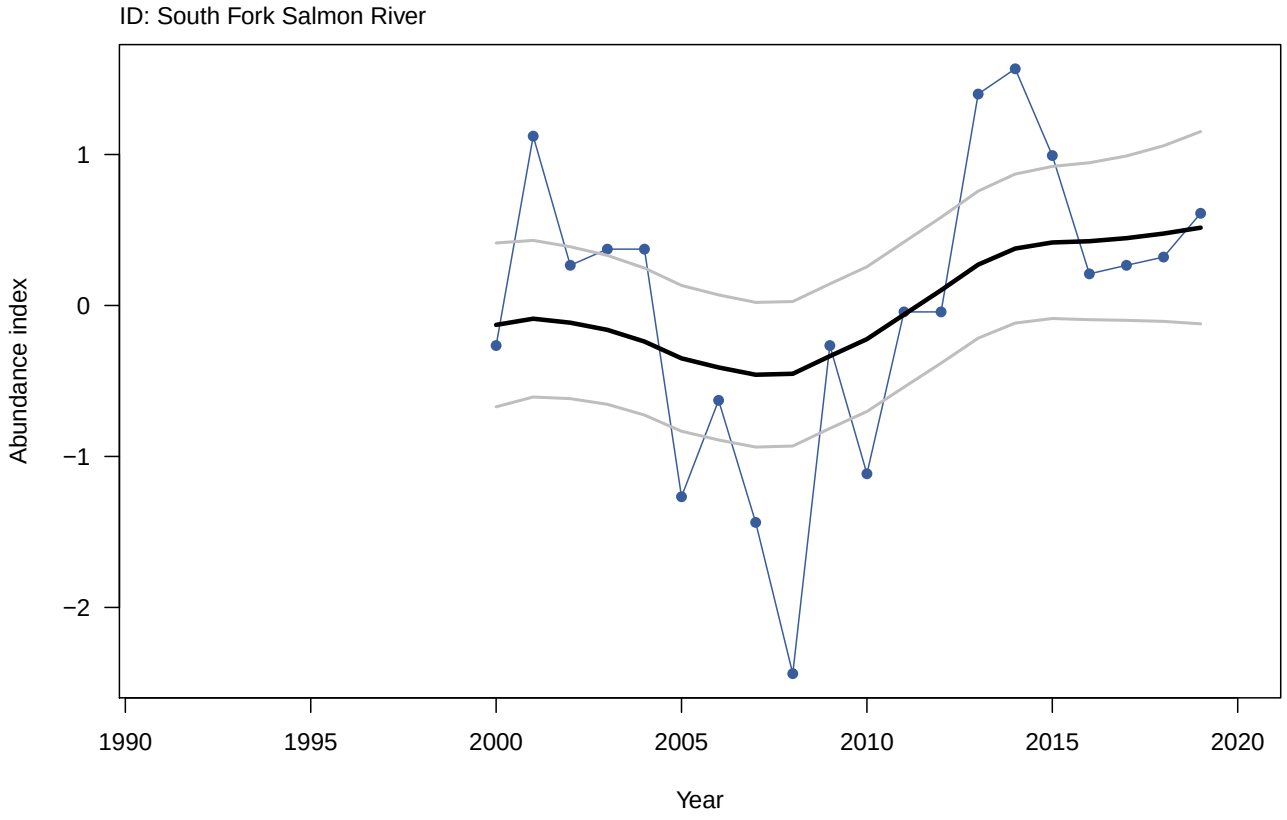
168


ID: Lemhi River
Abundance index
2
1
0
−1
1990
1995
2000
2005
2010
2015
2020
Year

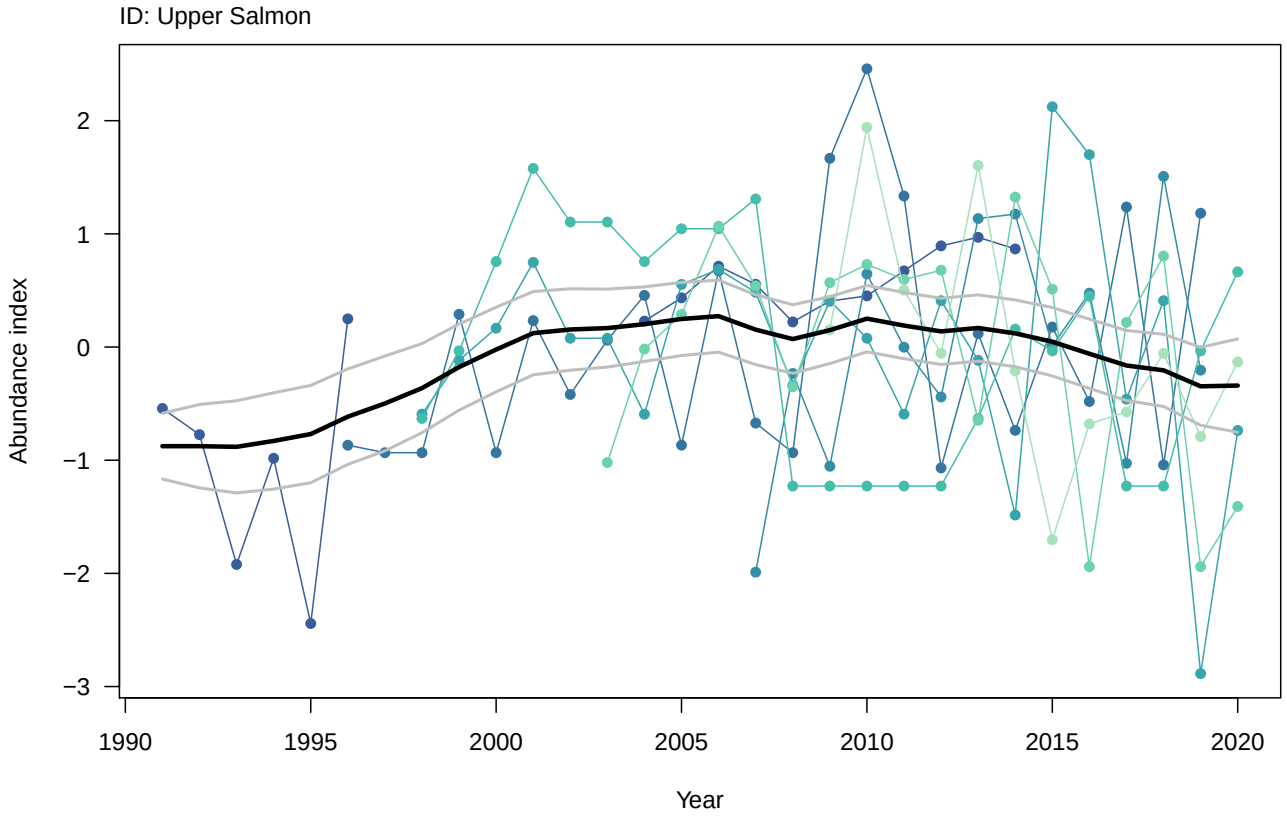
169


ID: Little−Lower Salmon River
Abundance index
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
1990
1995
2000
2005
2010
2015
2020
Year

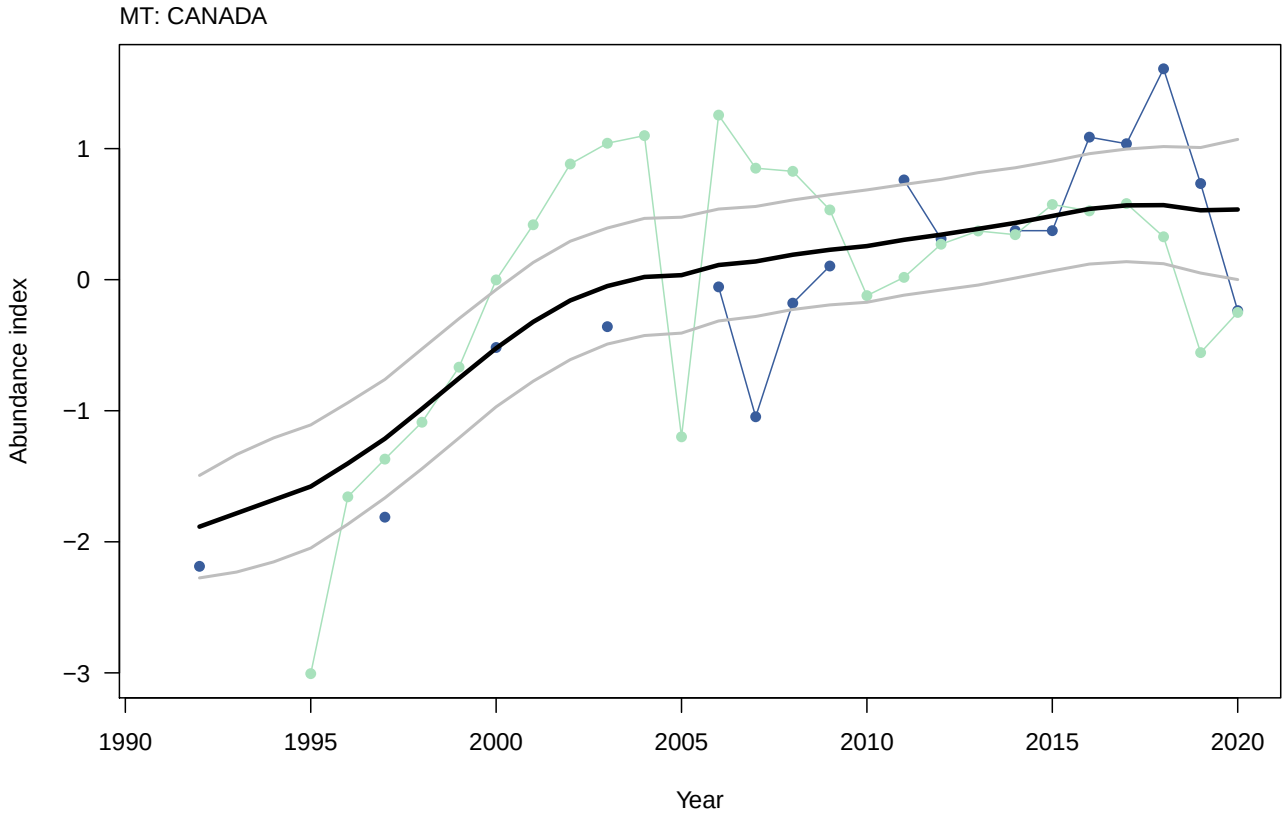
170


ID: South Fork Salmon River
Abundance index
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

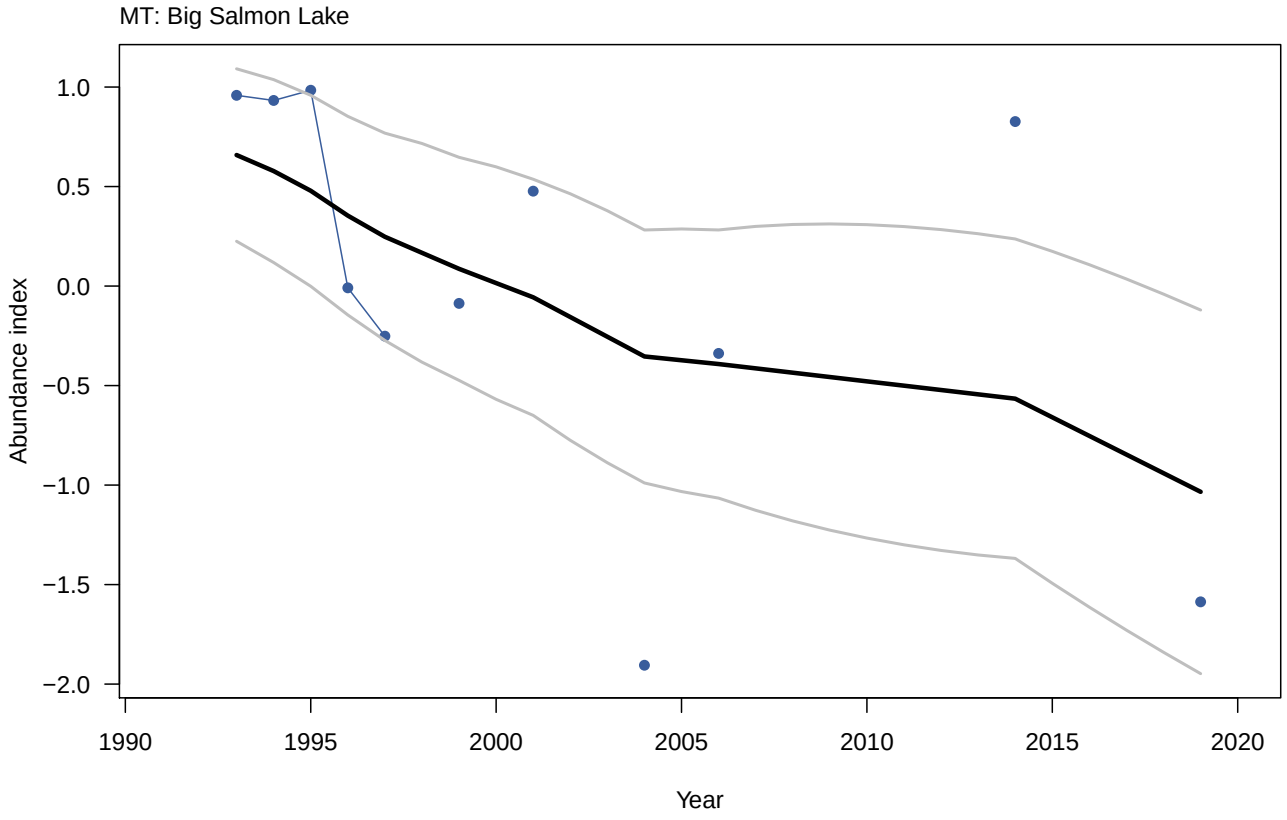
171


ID: Upper Salmon
Abundance index
2
1
0
−1
−2
−3
1990
1995
2000
2005
2010
2015
2020
Year

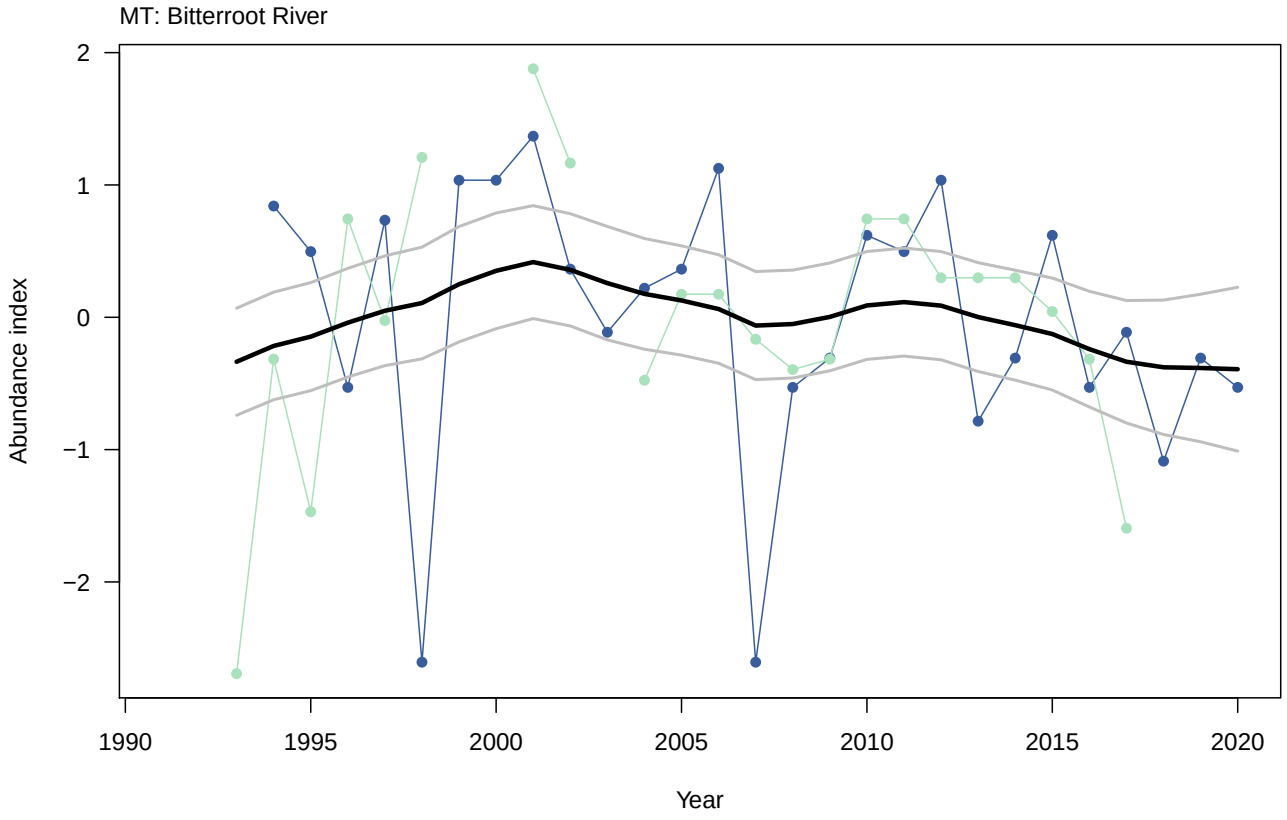
172


MT: CANADA
Abundance index
1
0
−1
−2
−3
1990
1995
2000
2005
2010
2015
2020
Year

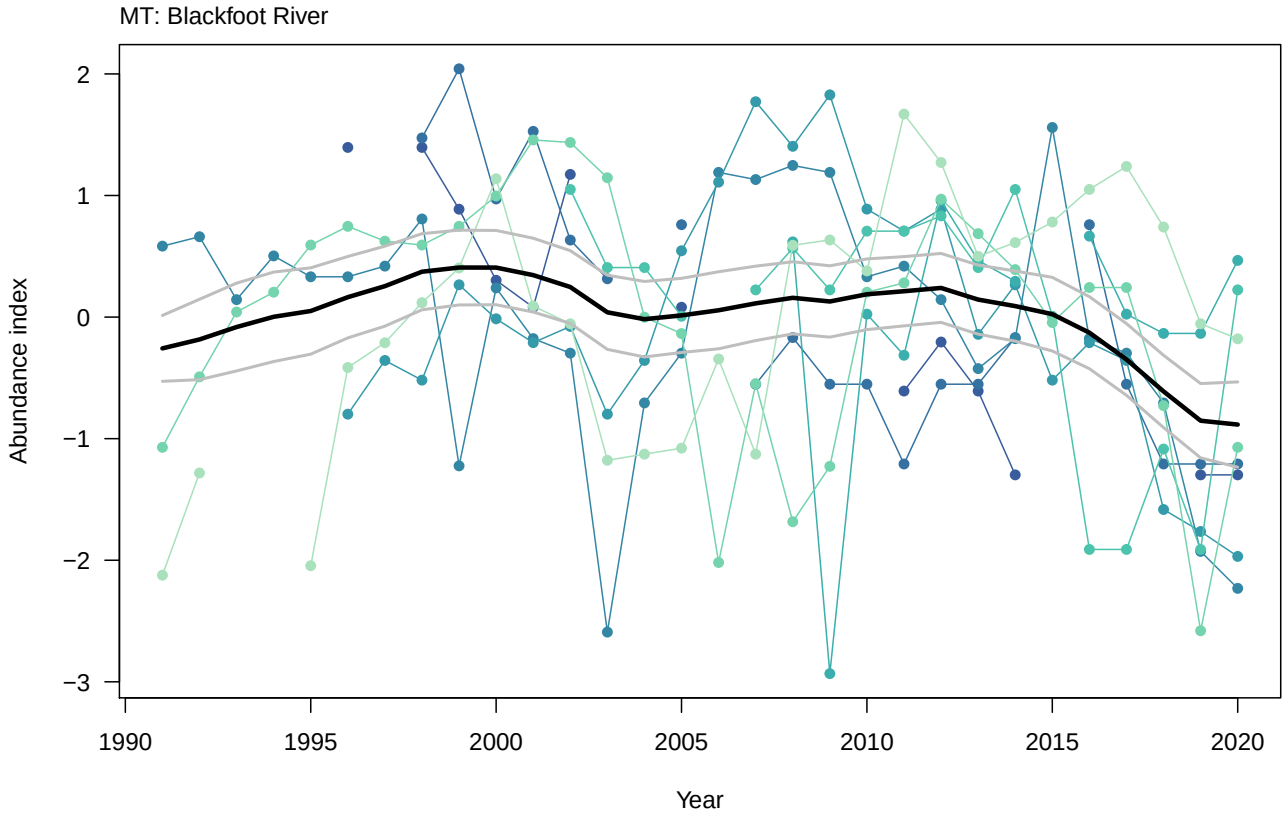
173


MT: Big Salmon Lake
Abundance index
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
1990
1995
2000
2005
2010
2015
2020
Year

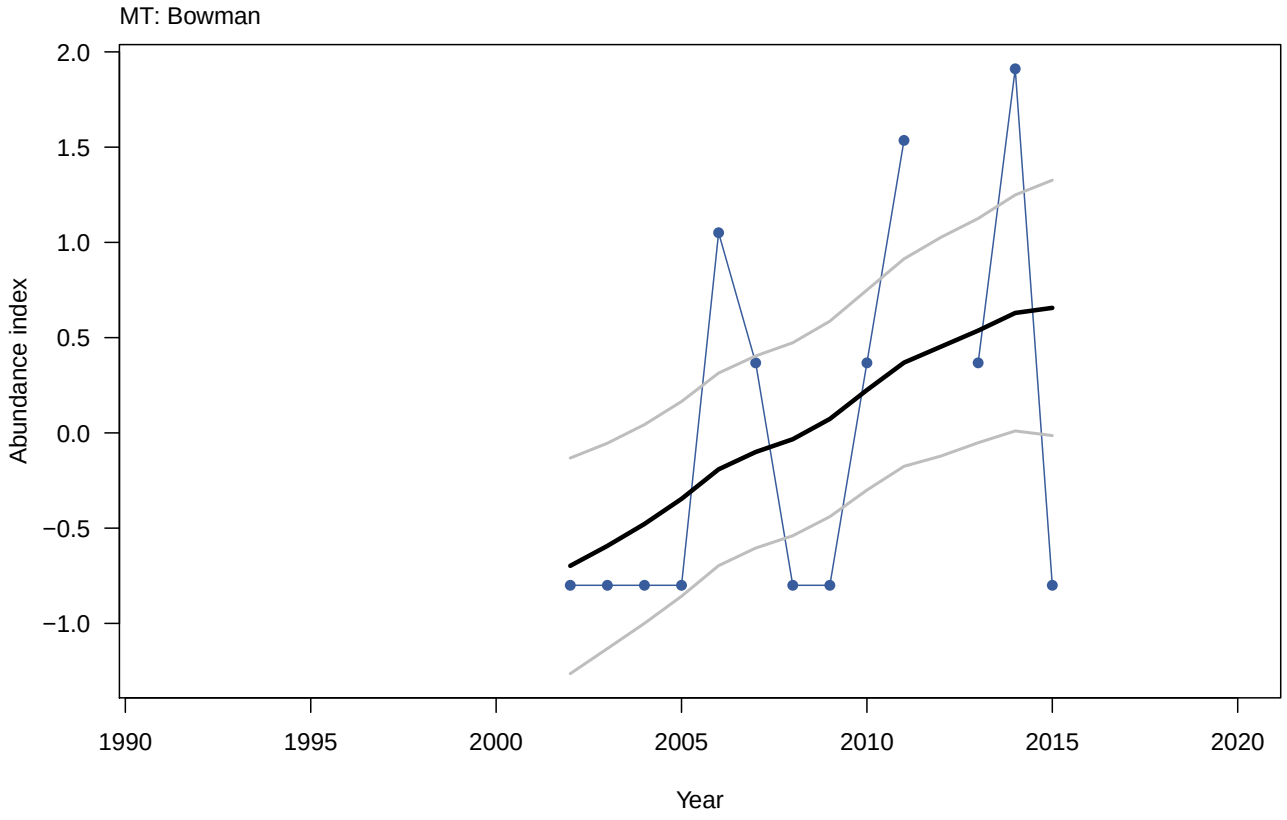
174


MT: Bitterroot River
Abundance index
2
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

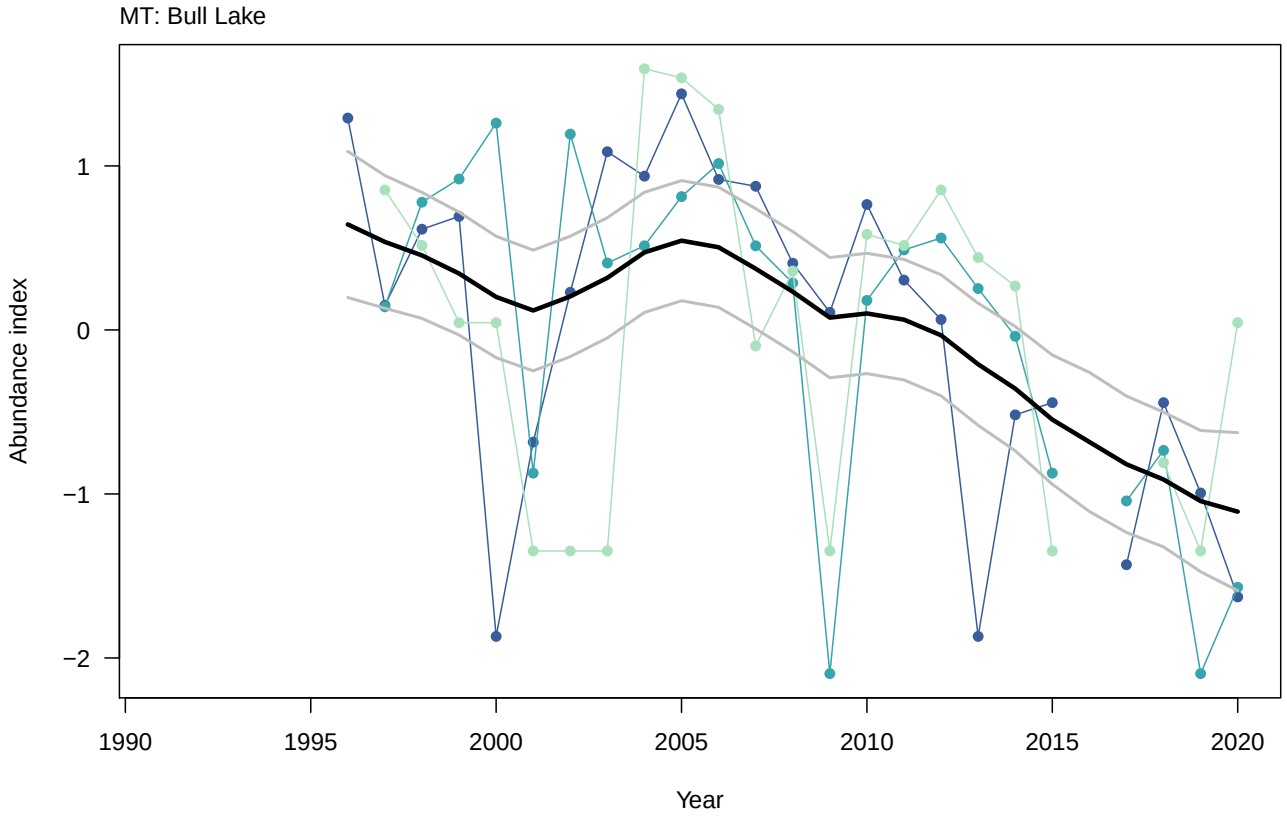
175


MT: Blackfoot River
Abundance index
2
1
0
−1
−2
−3
1990
1995
2000
2005
2010
2015
2020
Year

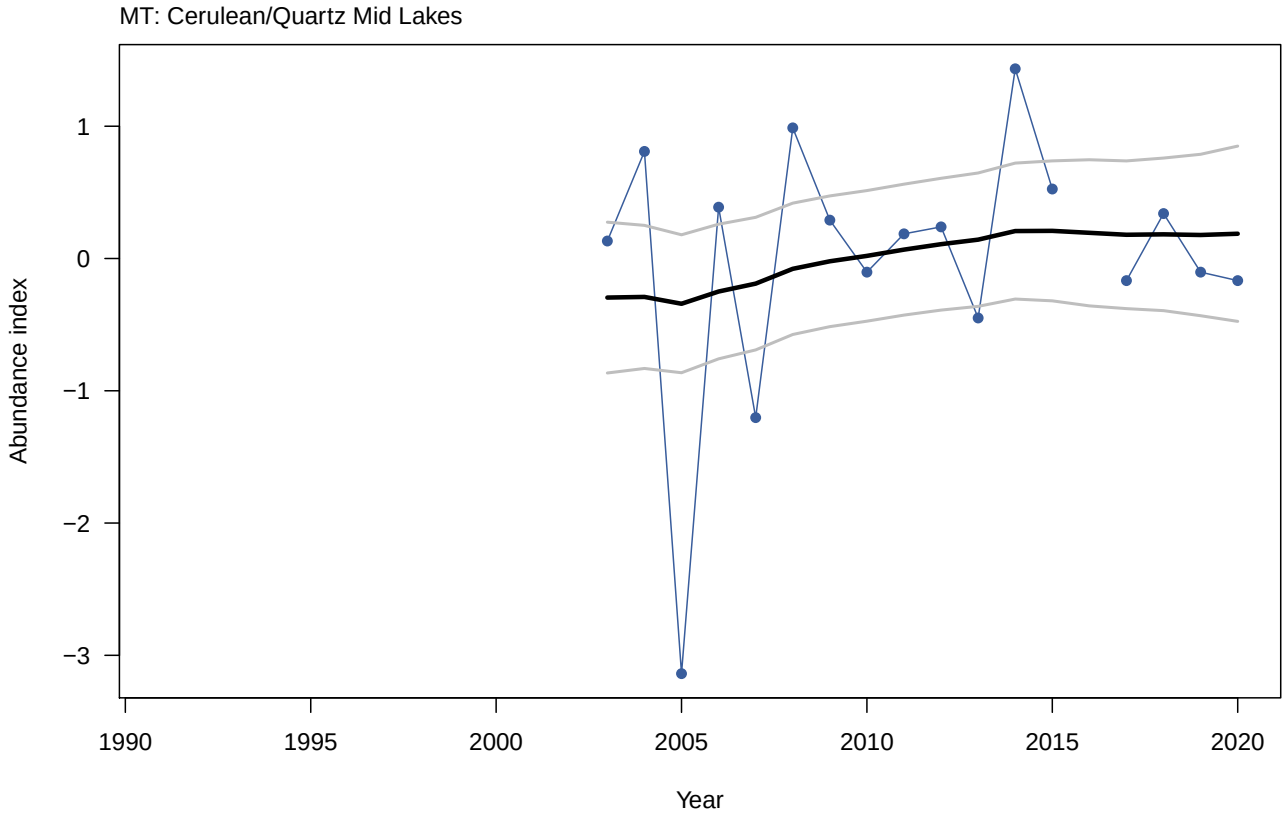
176


MT: Bowman
Abundance index
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
1990
1995
2000
2005
2010
2015
2020
Year

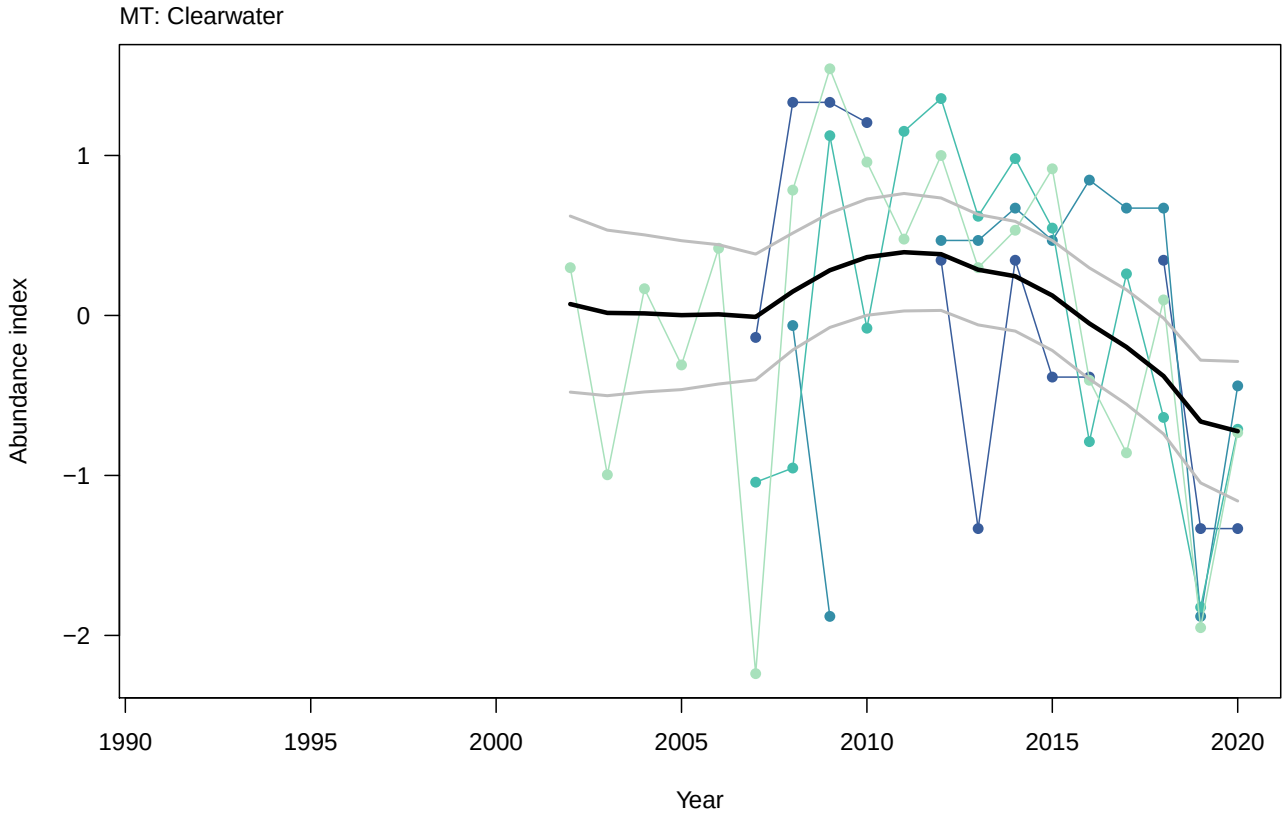
177


MT: Bull Lake
Abundance index
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

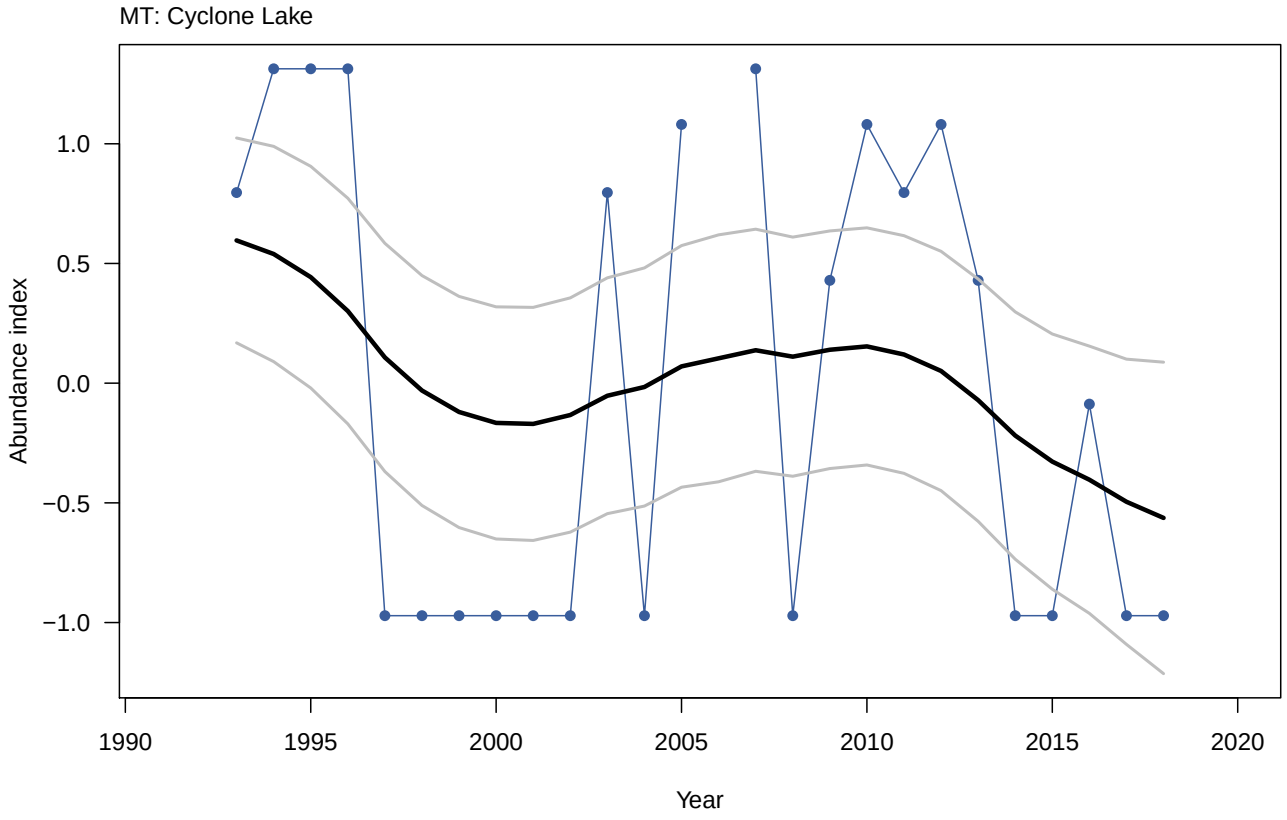
178


MT: Cerulean/Quartz Mid Lakes
Abundance index
1
0
−1
−2
−3
1990
1995
2000
2005
2010
2015
2020
Year

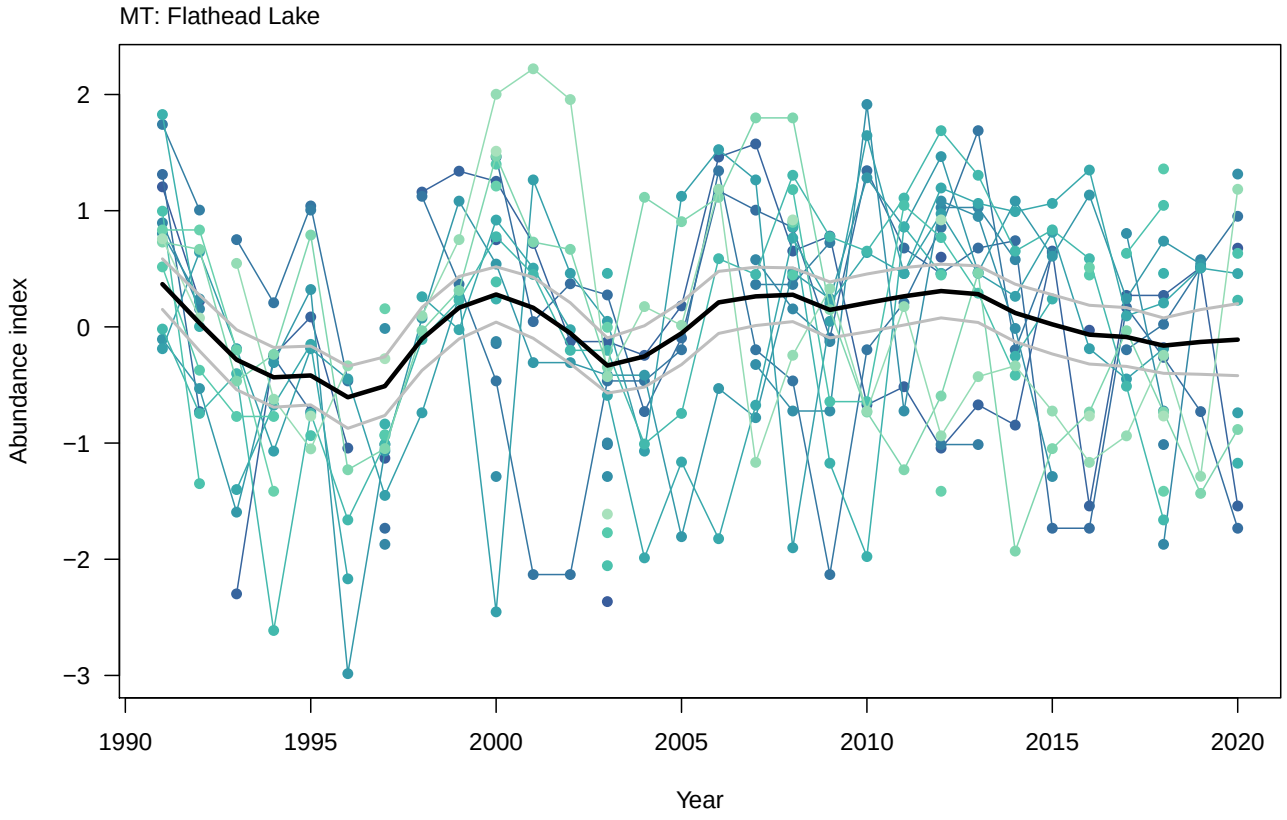
179


MT: Clearwater
Abundance index
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

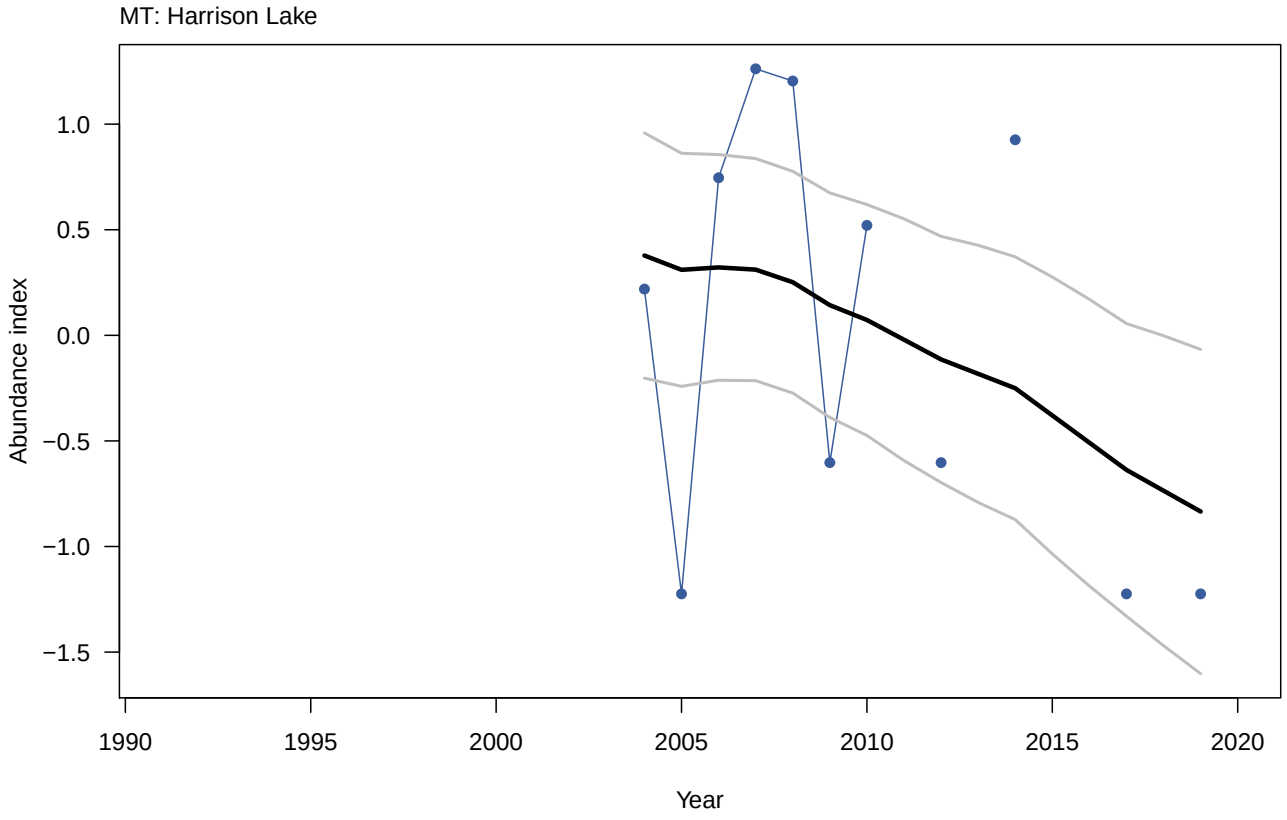
180


MT: Cyclone Lake
Abundance index
1.0
0.5
0.0
−0.5
−1.0
1990
1995
2000
2005
2010
2015
2020
Year

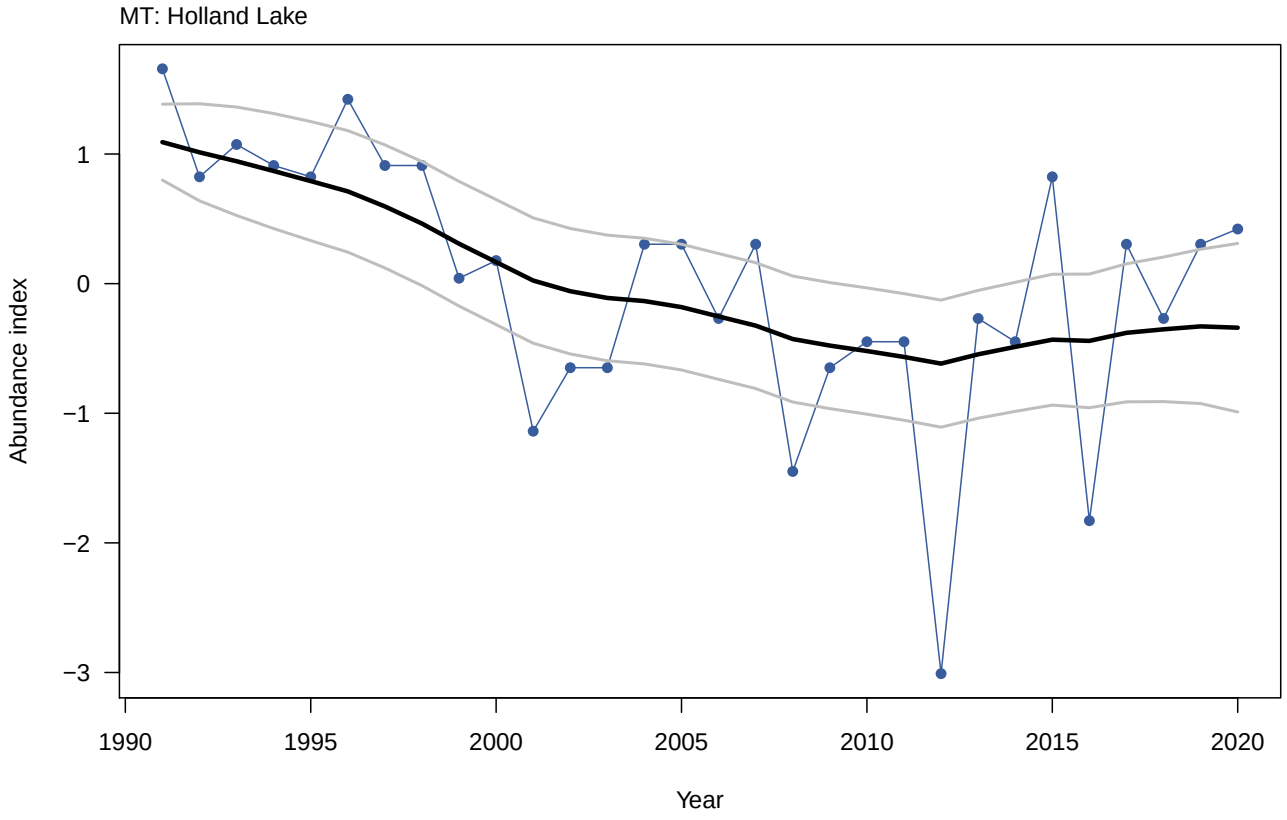
181


MT: Flathead Lake
Abundance index
2
1
0
−1
−2
−3
1990
1995
2000
2005
2010
2015
2020
Year

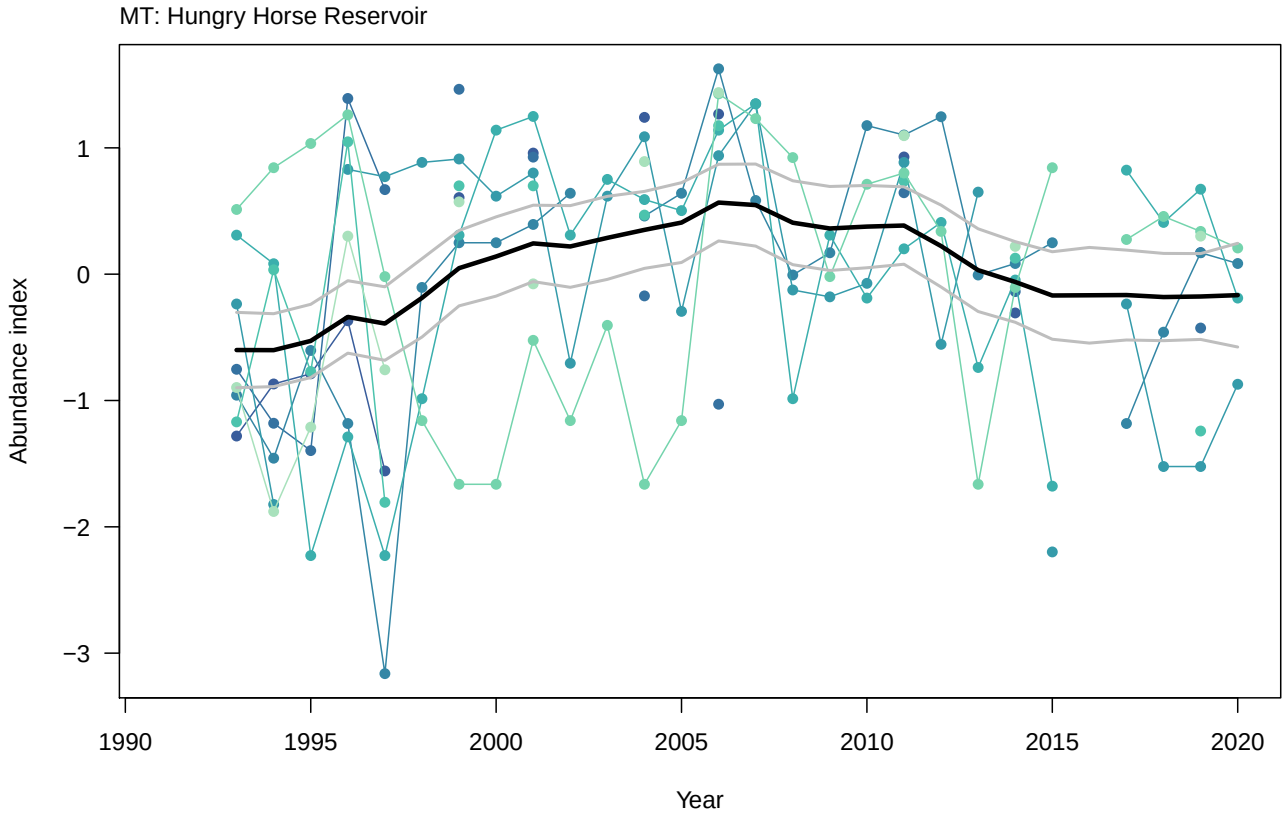
182


MT: Harrison Lake
Abundance index
1.0
0.5
0.0
−0.5
−1.0
−1.5
1990
1995
2000
2005
2010
2015
2020
Year

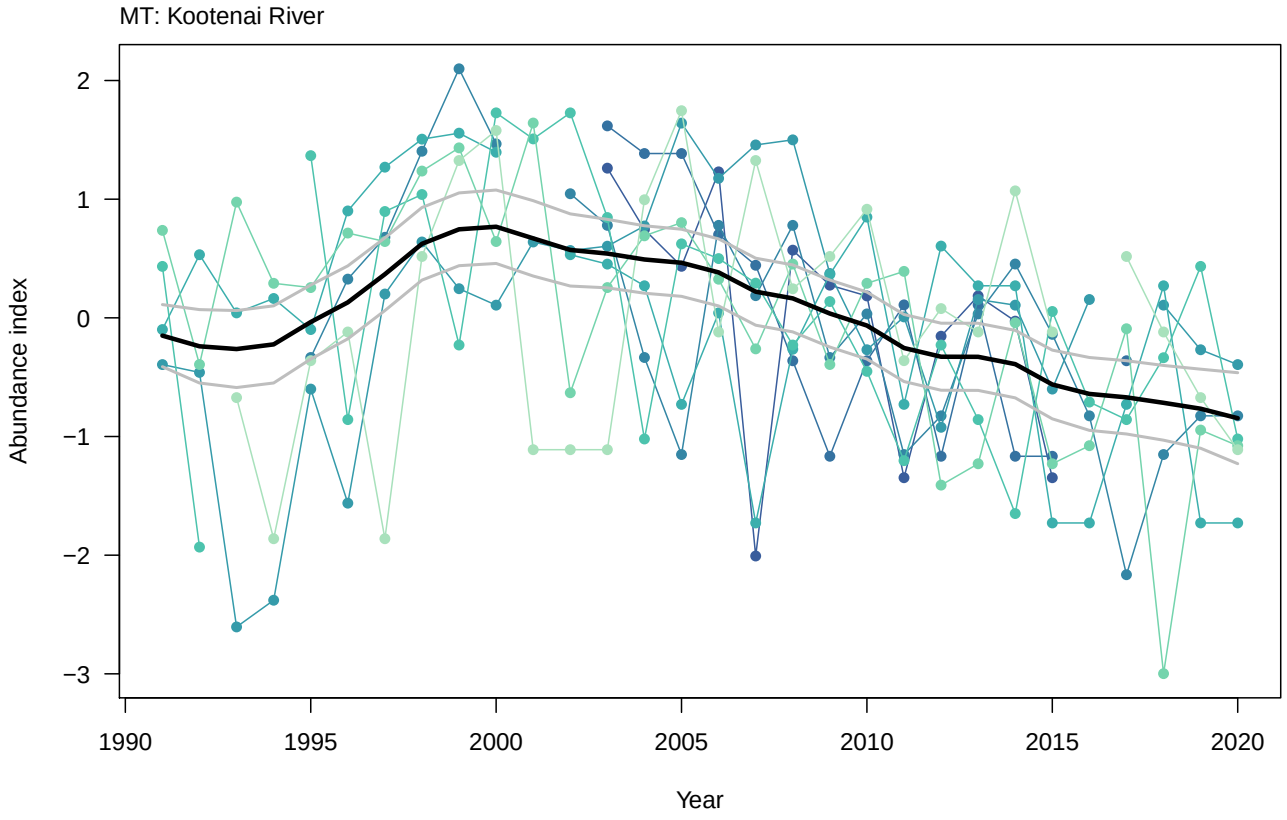
183


MT: Holland Lake
Abundance index
1
0
−1
−2
−3
1990
1995
2000
2005
2010
2015
2020
Year

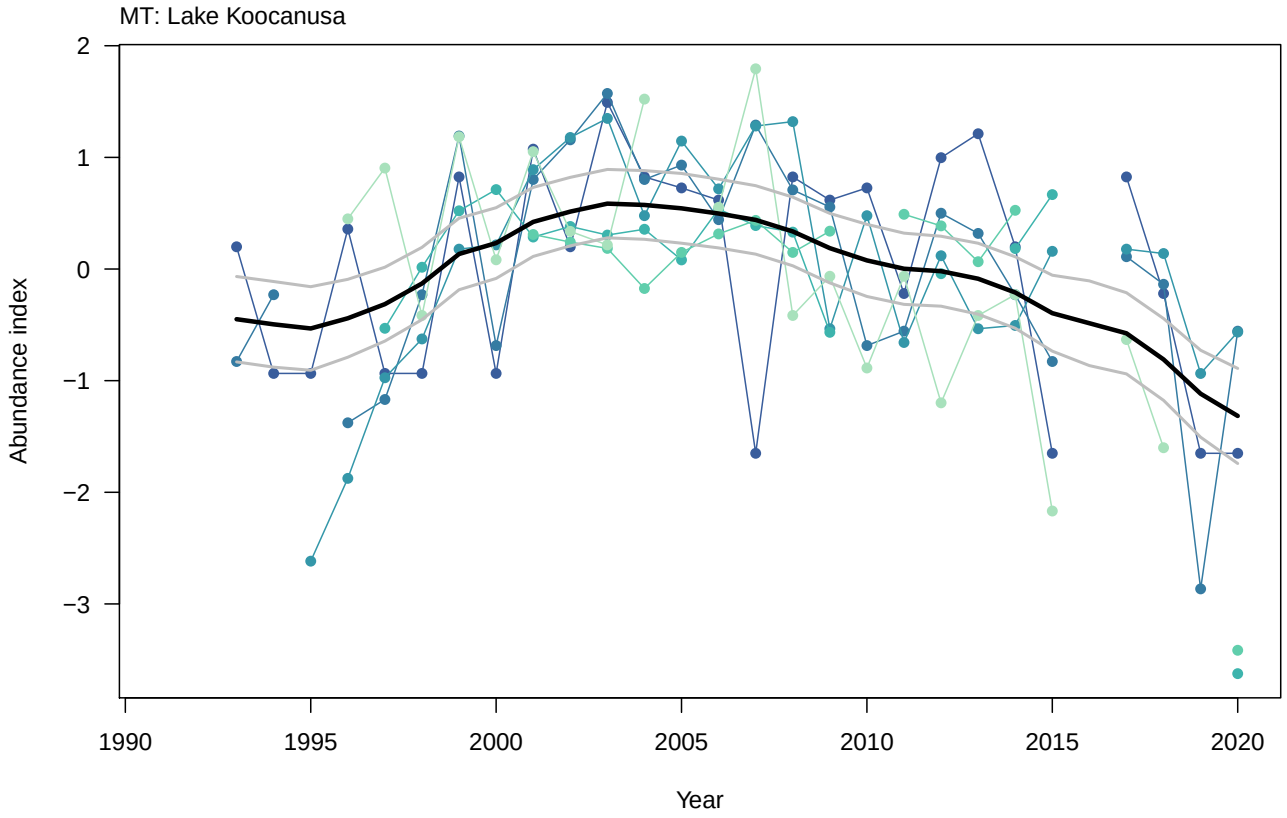
184


MT: Hungry Horse Reservoir
Abundance index
1
0
−1
−2
−3
1990
1995
2000
2005
2010
2015
2020
Year

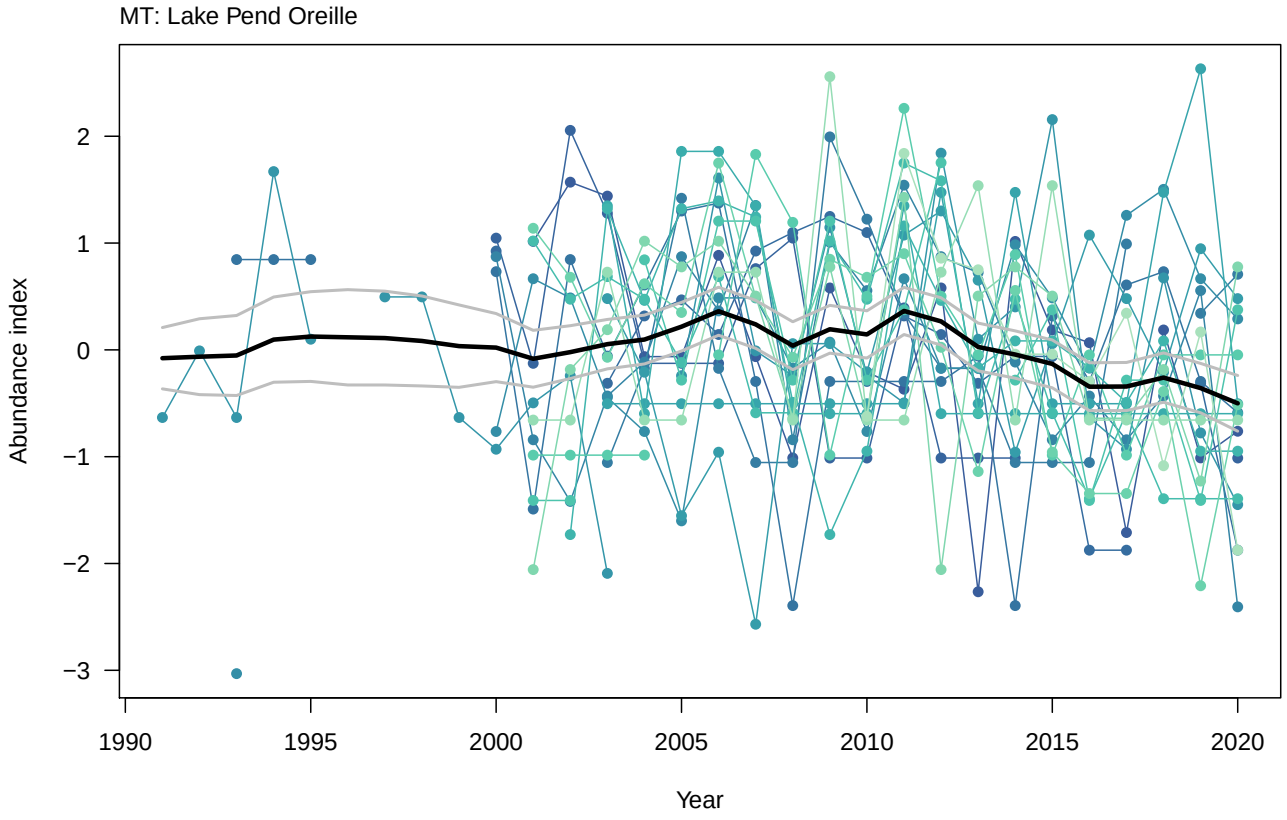
185


MT: Kootenai River
Abundance index
2
1
0
−1
−2
−3
1990
1995
2000
2005
2010
2015
2020
Year

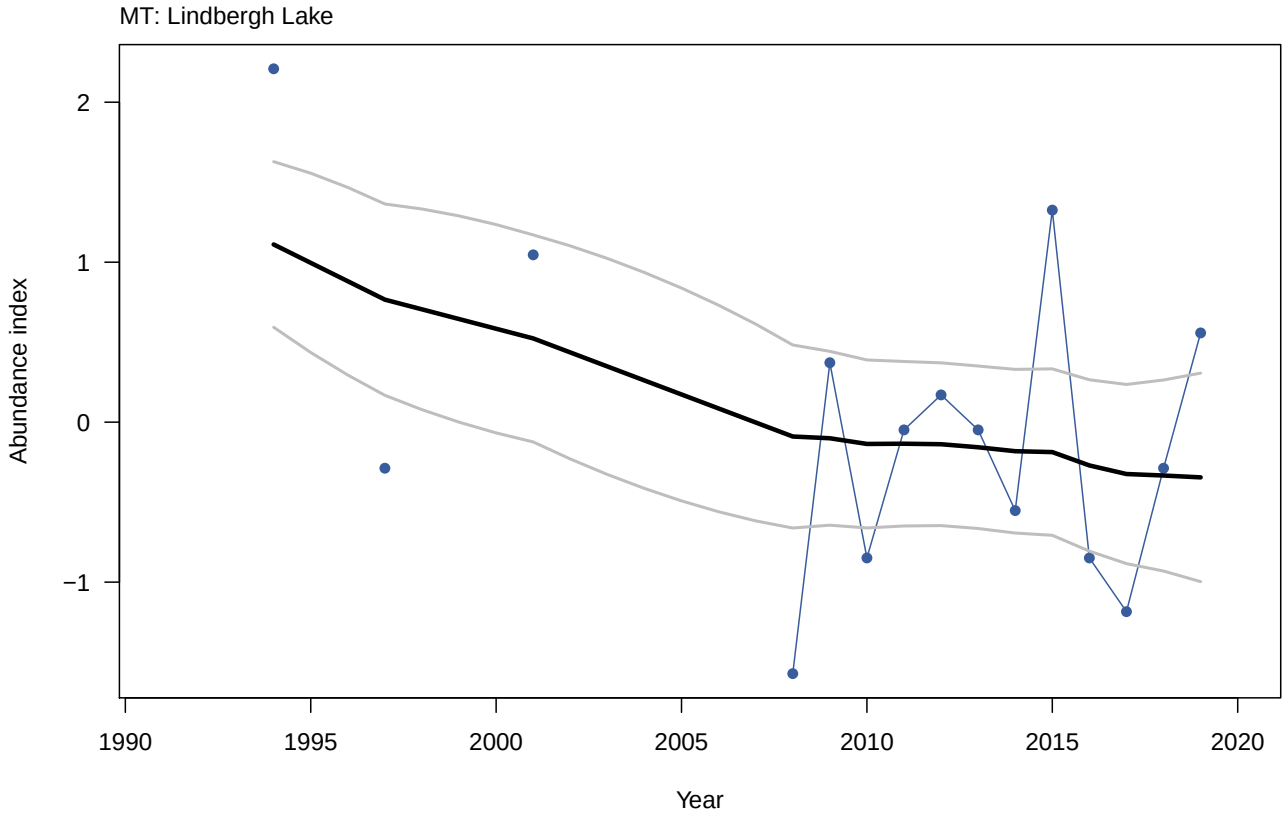
186


MT: Lake Koocanusa
Abundance index
2
1
0
−1
−2
−3
1990
1995
2000
2005
2010
2015
2020
Year

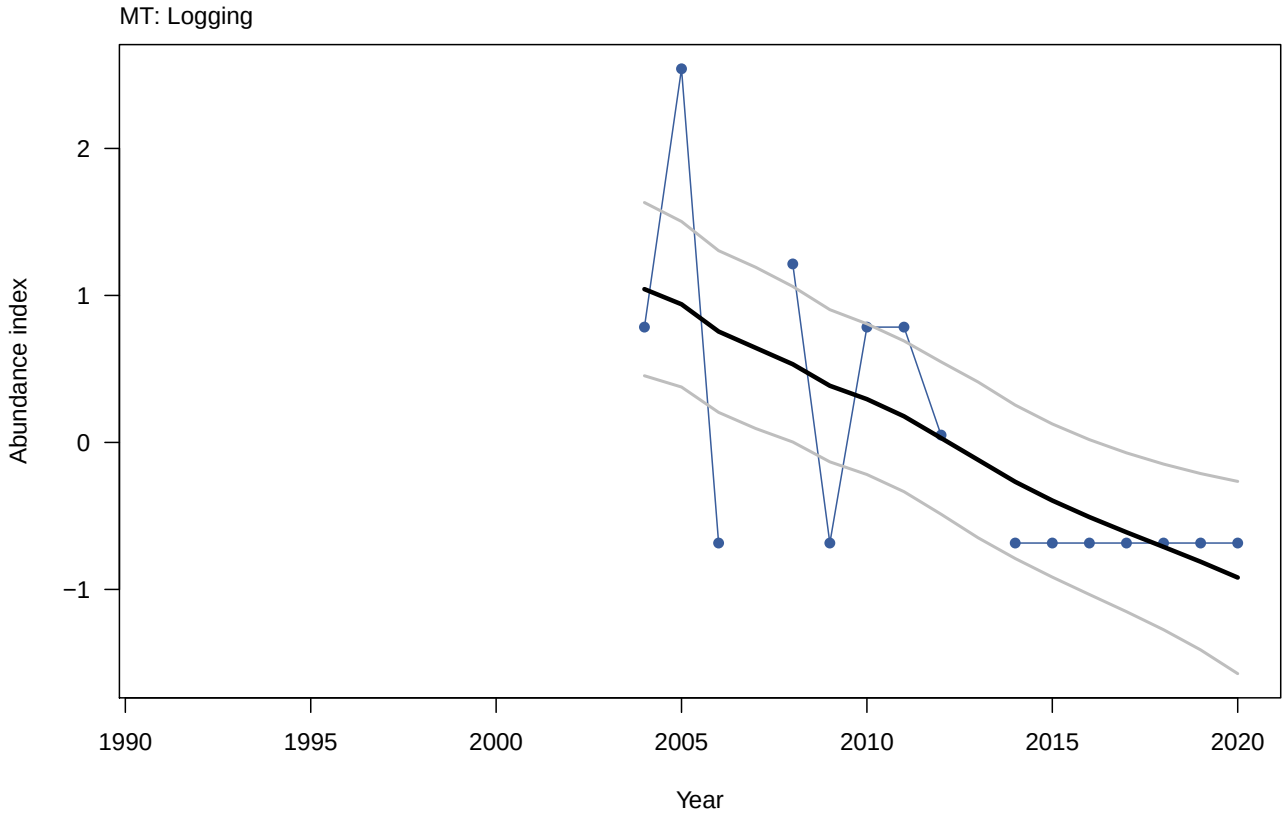
187


MT: Lake Pend Oreille
Abundance index
2
1
0
−1
−2
−3
1990
1995
2000
2005
2010
2015
2020
Year

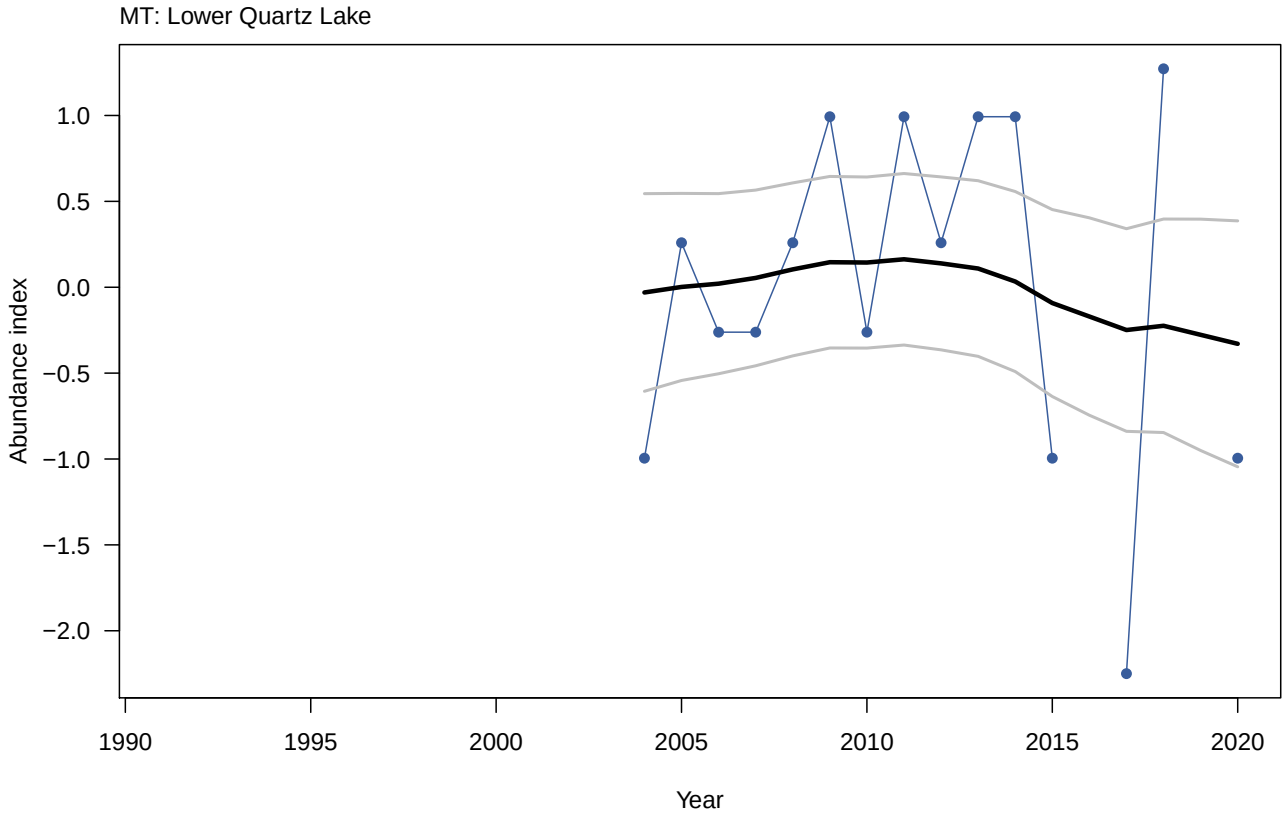
188


MT: Lindbergh Lake
Abundance index
2
1
0
−1
1990
1995
2000
2005
2010
2015
2020
Year

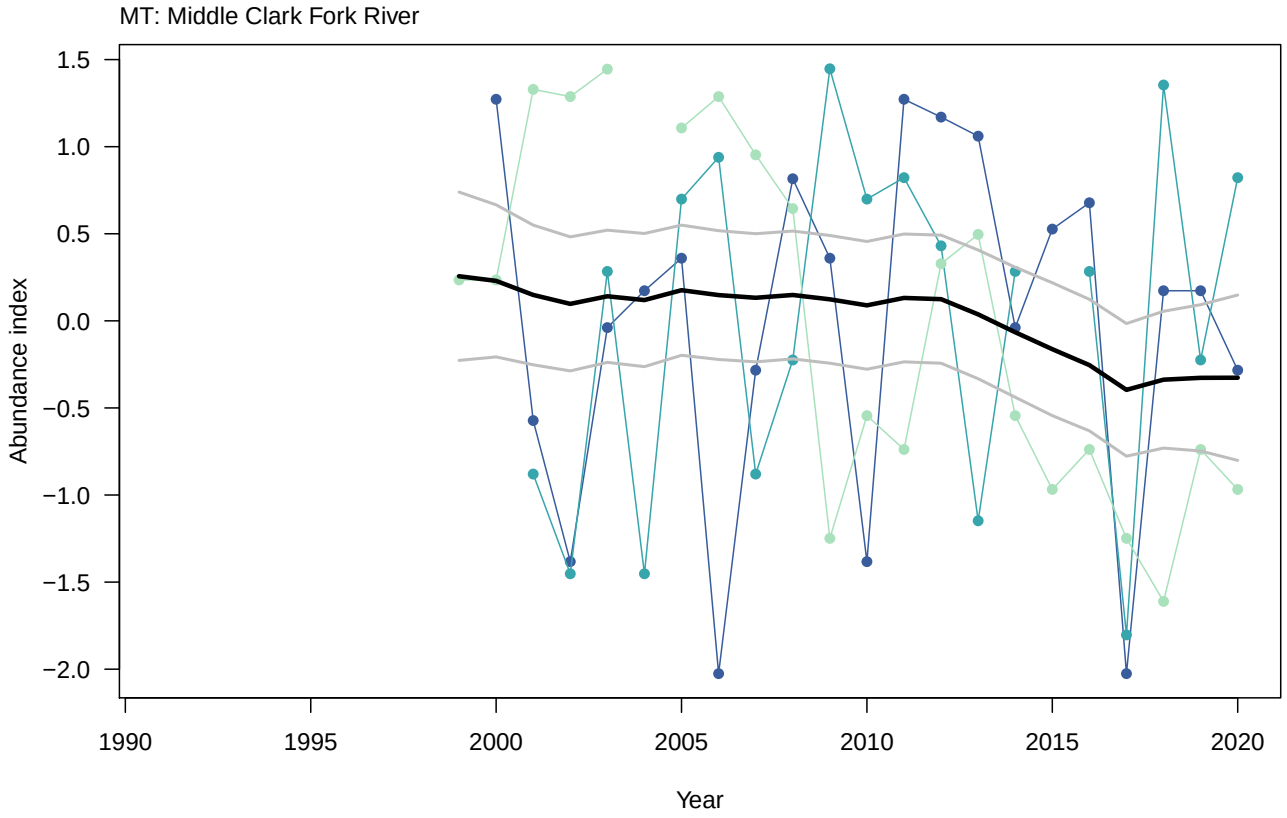
189


MT: Logging
Abundance index
2
1
0
−1
1990
1995
2000
2005
2010
2015
2020
Year

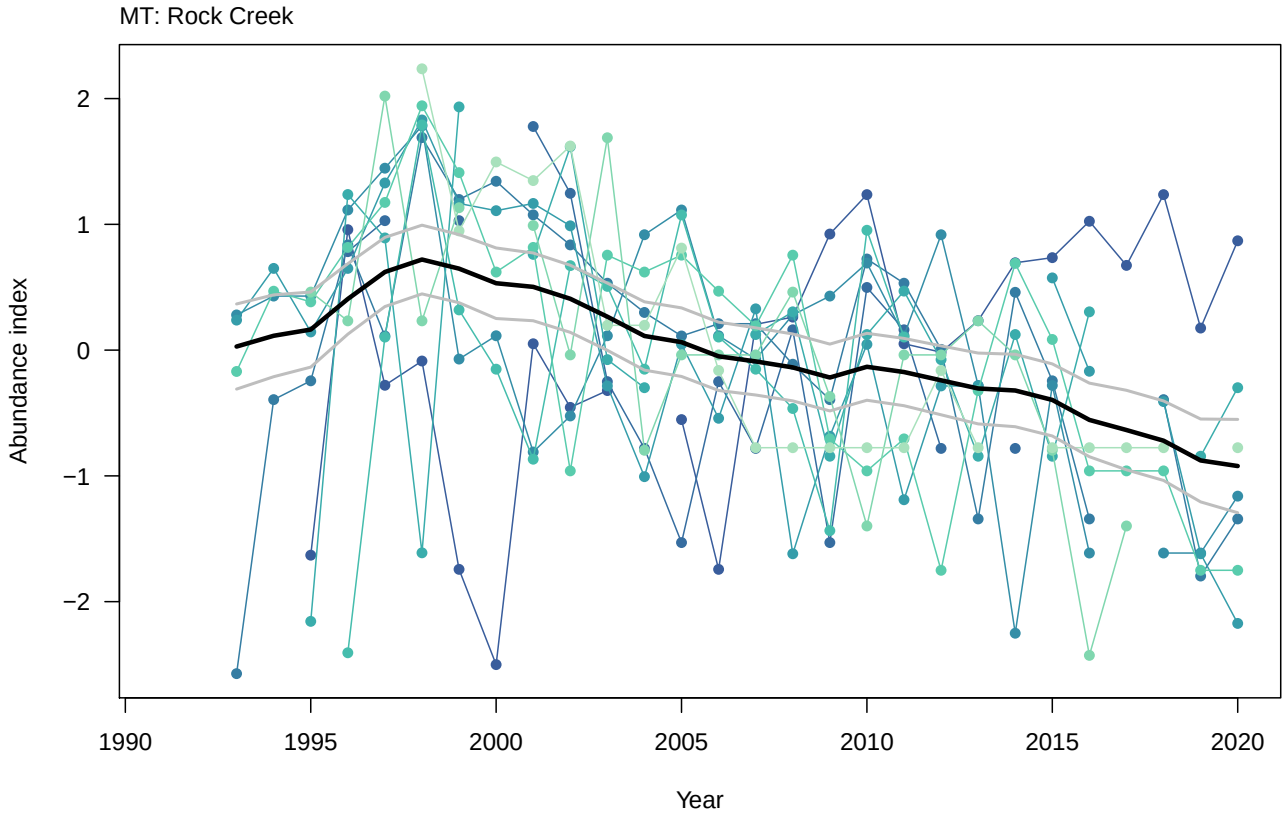
190


MT: Lower Quartz Lake
Abundance index
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
1990
1995
2000
2005
2010
2015
2020
Year

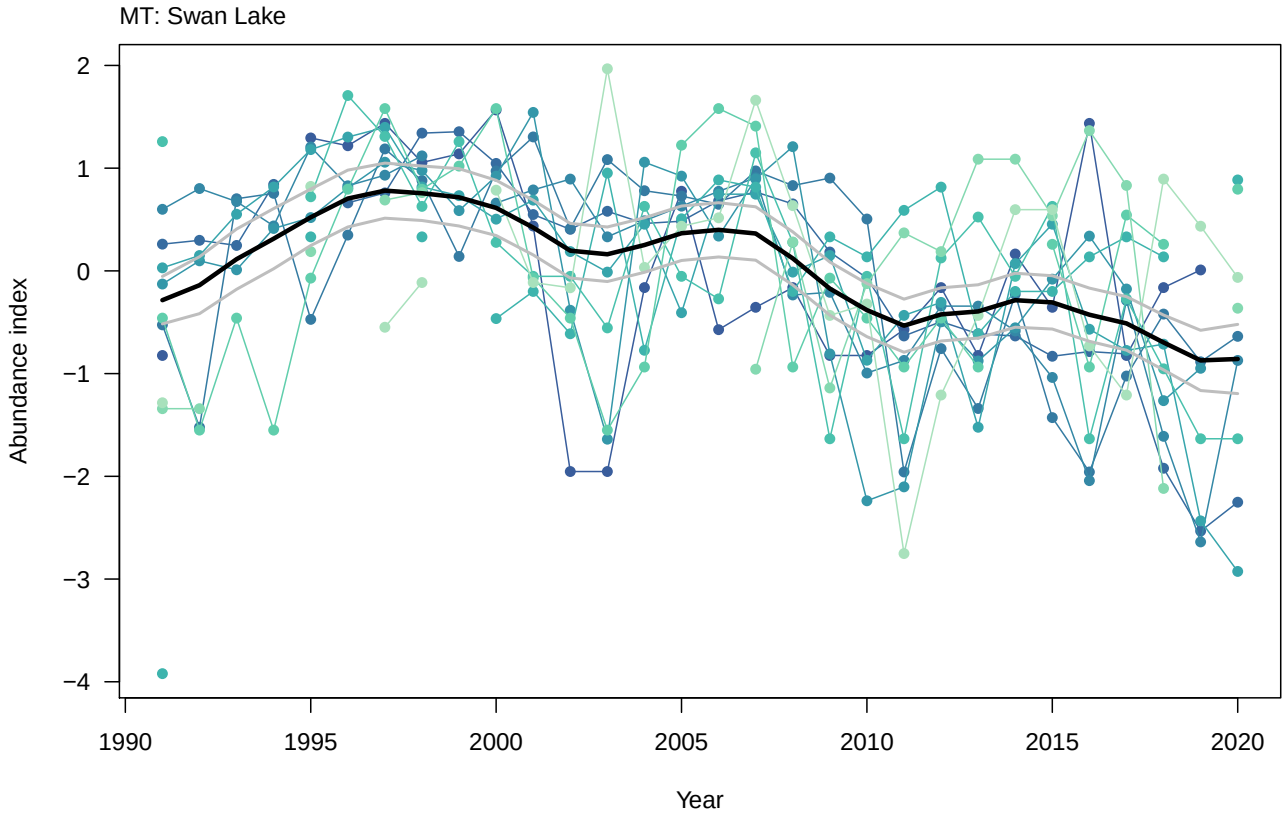
191


MT: Middle Clark Fork River
Abundance index
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
1990
1995
2000
2005
2010
2015
2020
Year

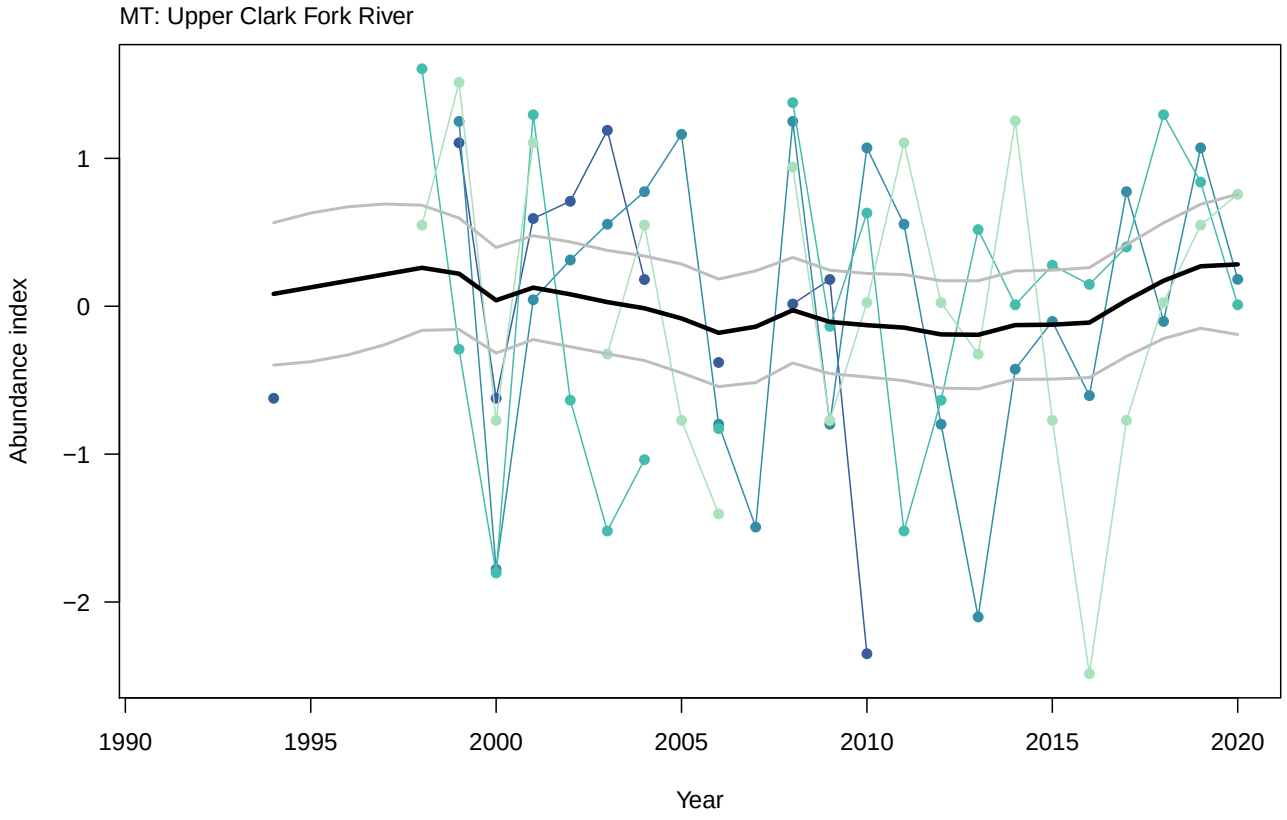
192


MT: Rock Creek
Abundance index
2
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

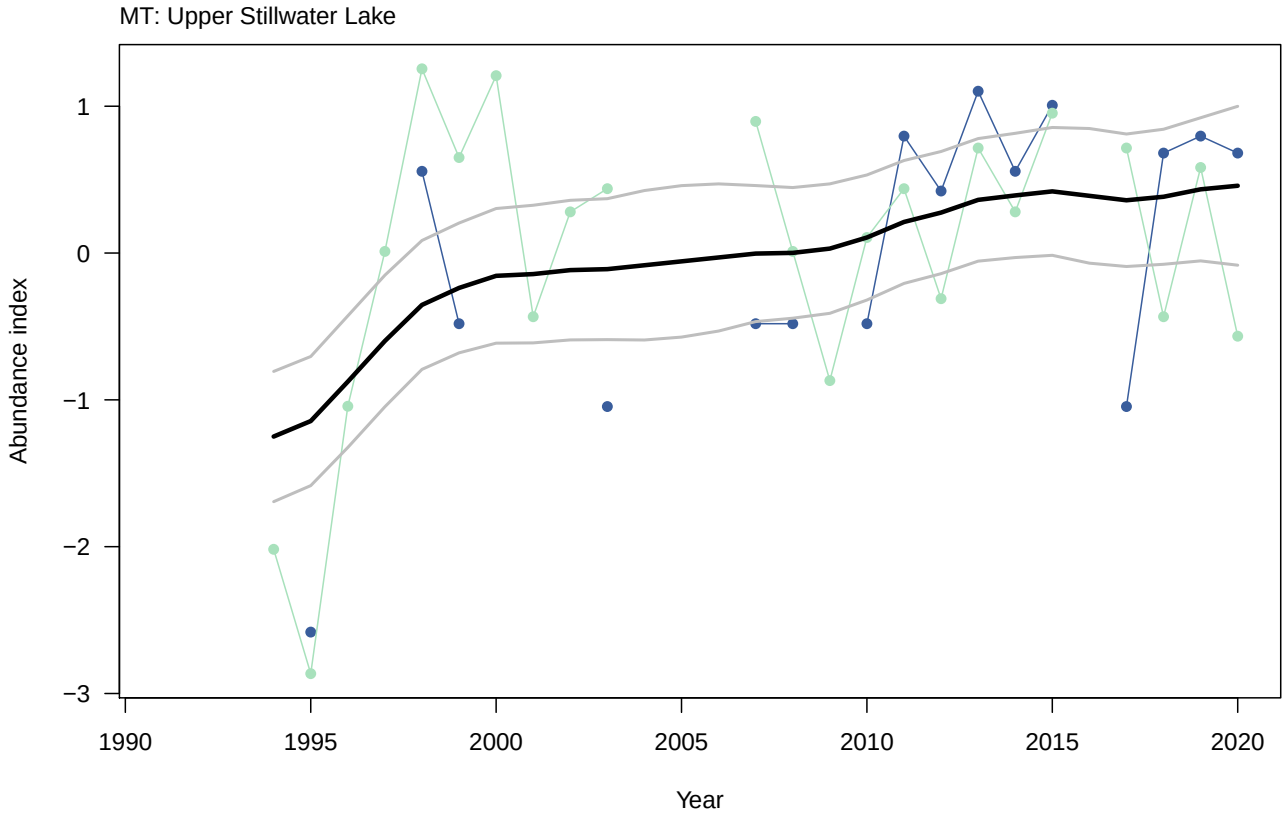
193


MT: Swan Lake
Abundance index
2
1
0
−1
−2
−3
−4
1990
1995
2000
2005
2010
2015
2020
Year

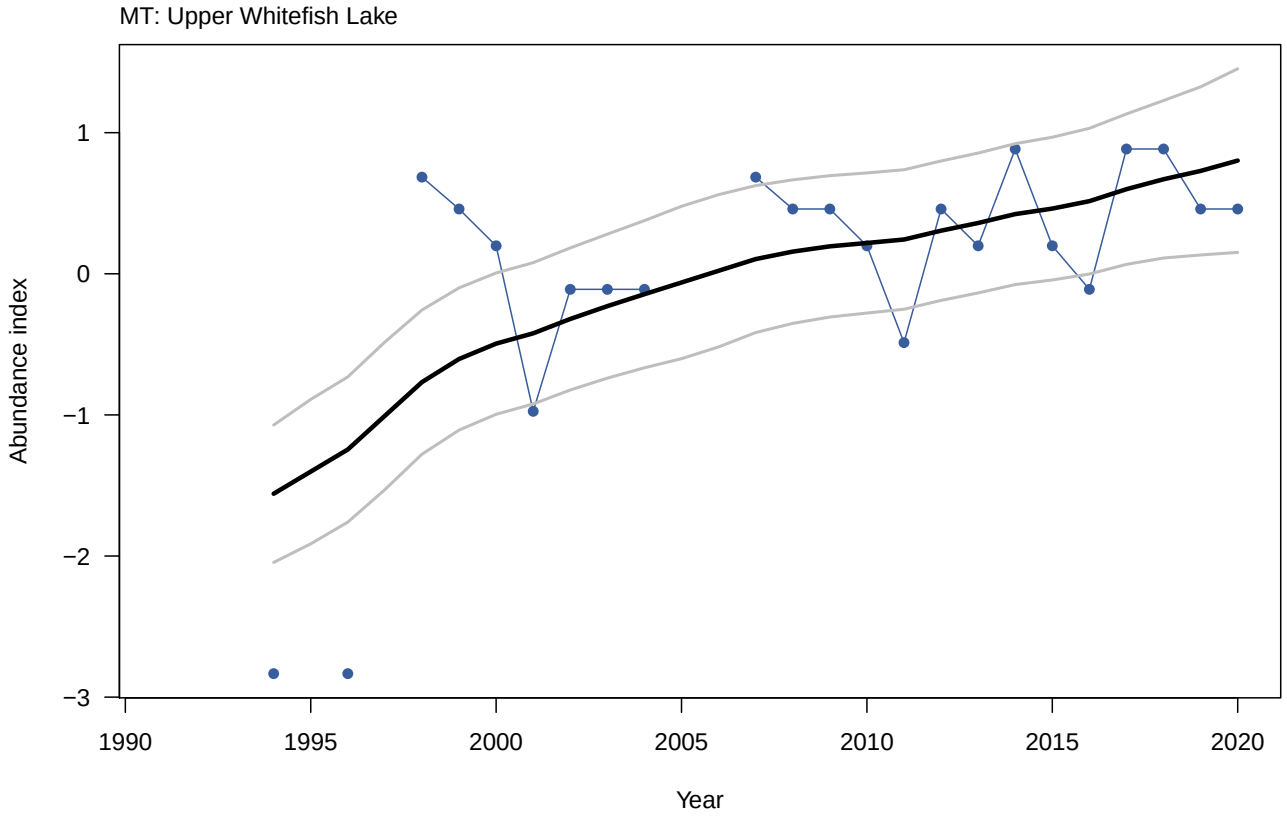
194


MT: Upper Clark Fork River
Abundance index
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

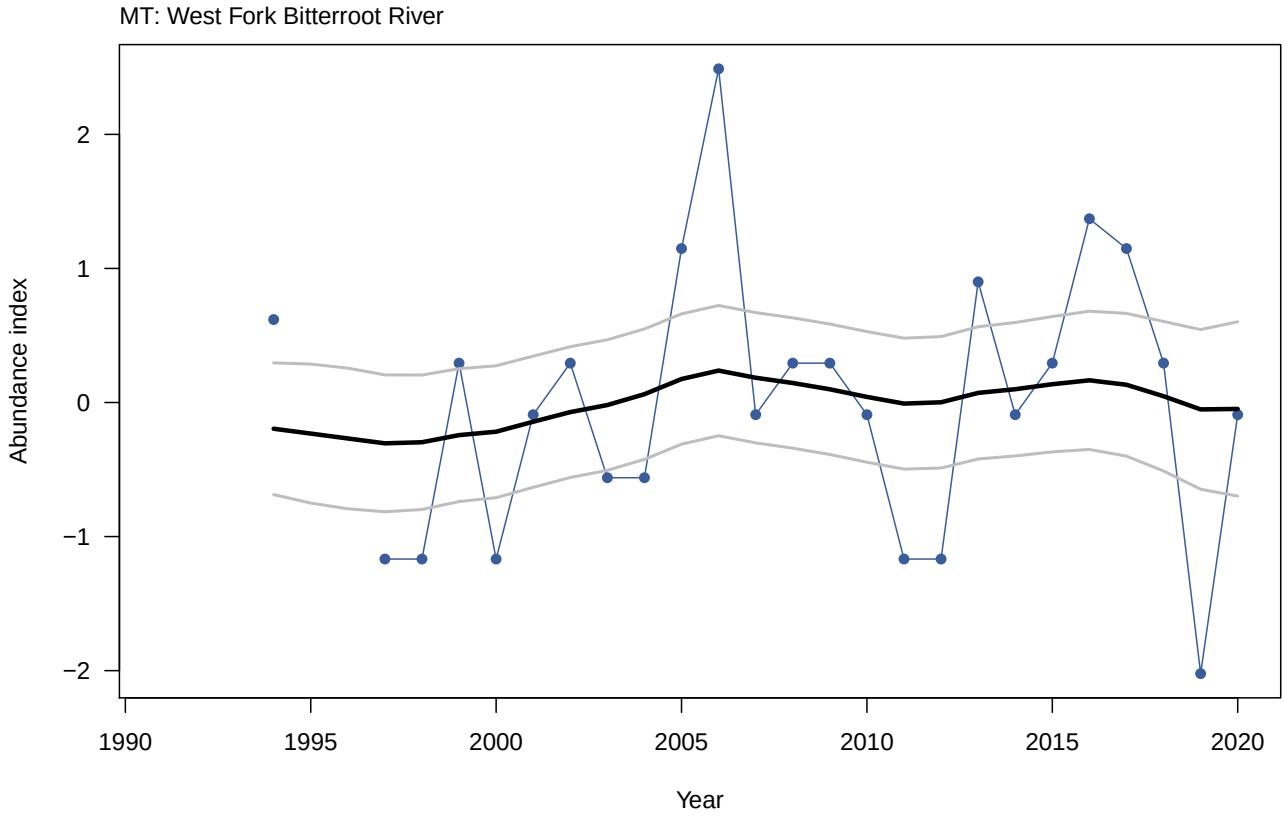
195


MT: Upper Stillwater Lake
Abundance index
1
0
−1
−2
−3
1990
1995
2000
2005
2010
2015
2020
Year

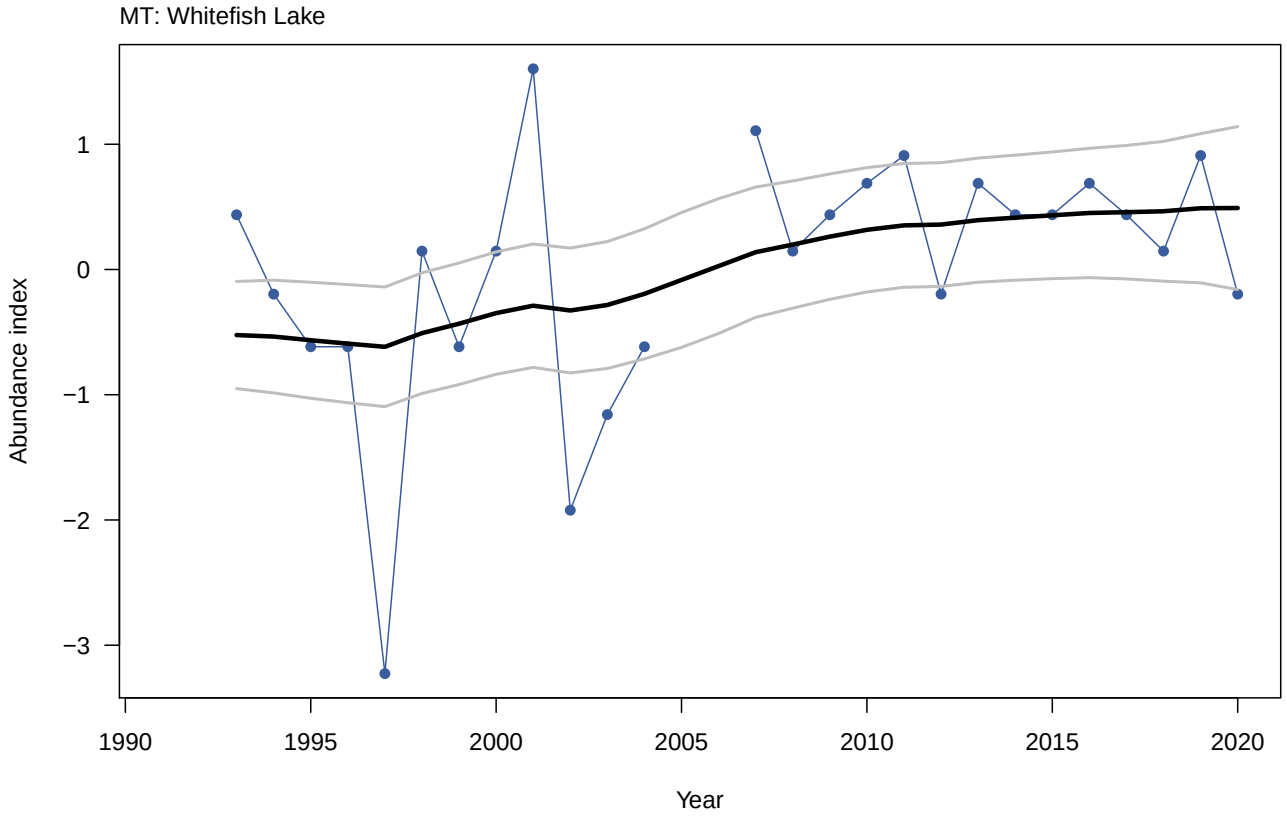
196


MT: Upper Whitefish Lake
Abundance index
1
0
−1
−2
−3
1990
1995
2000
2005
2010
2015
2020
Year

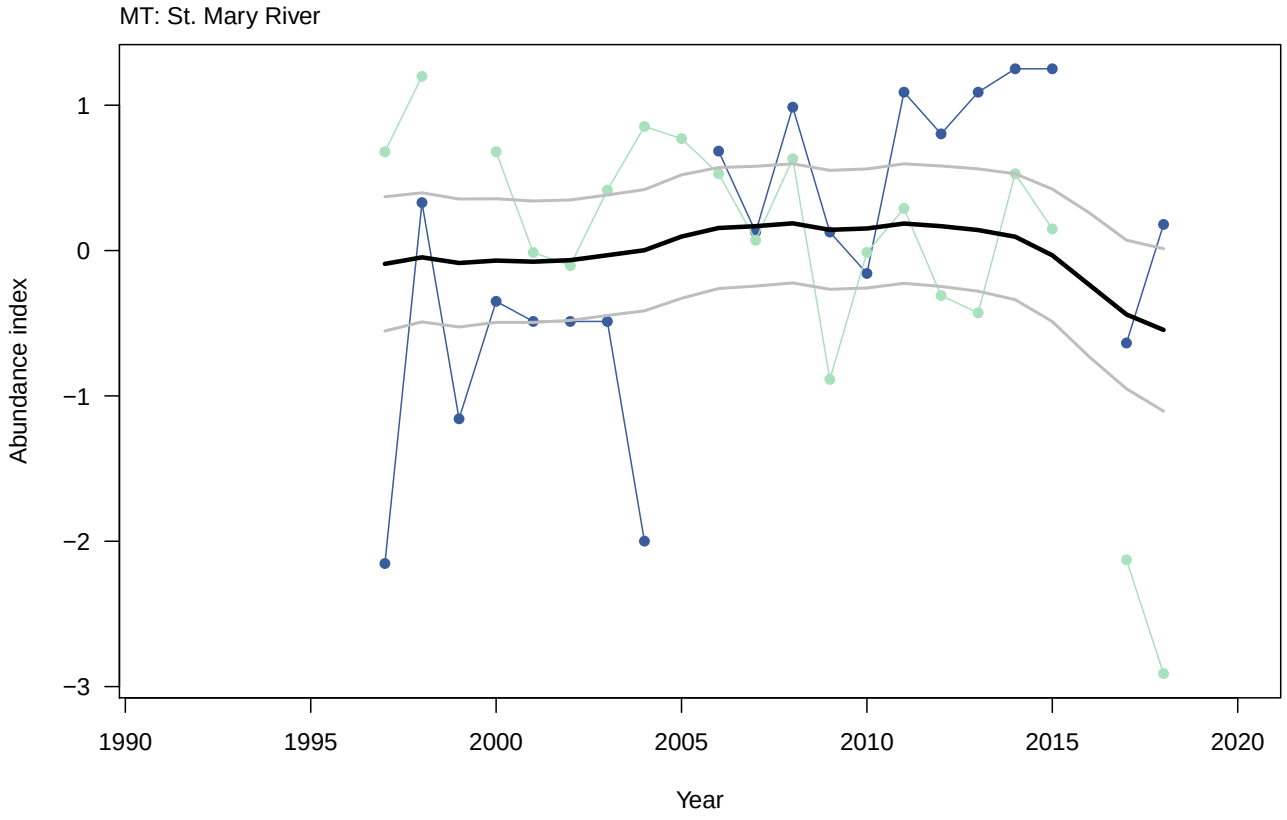
197


MT: West Fork Bitterroot River
Abundance index
2
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

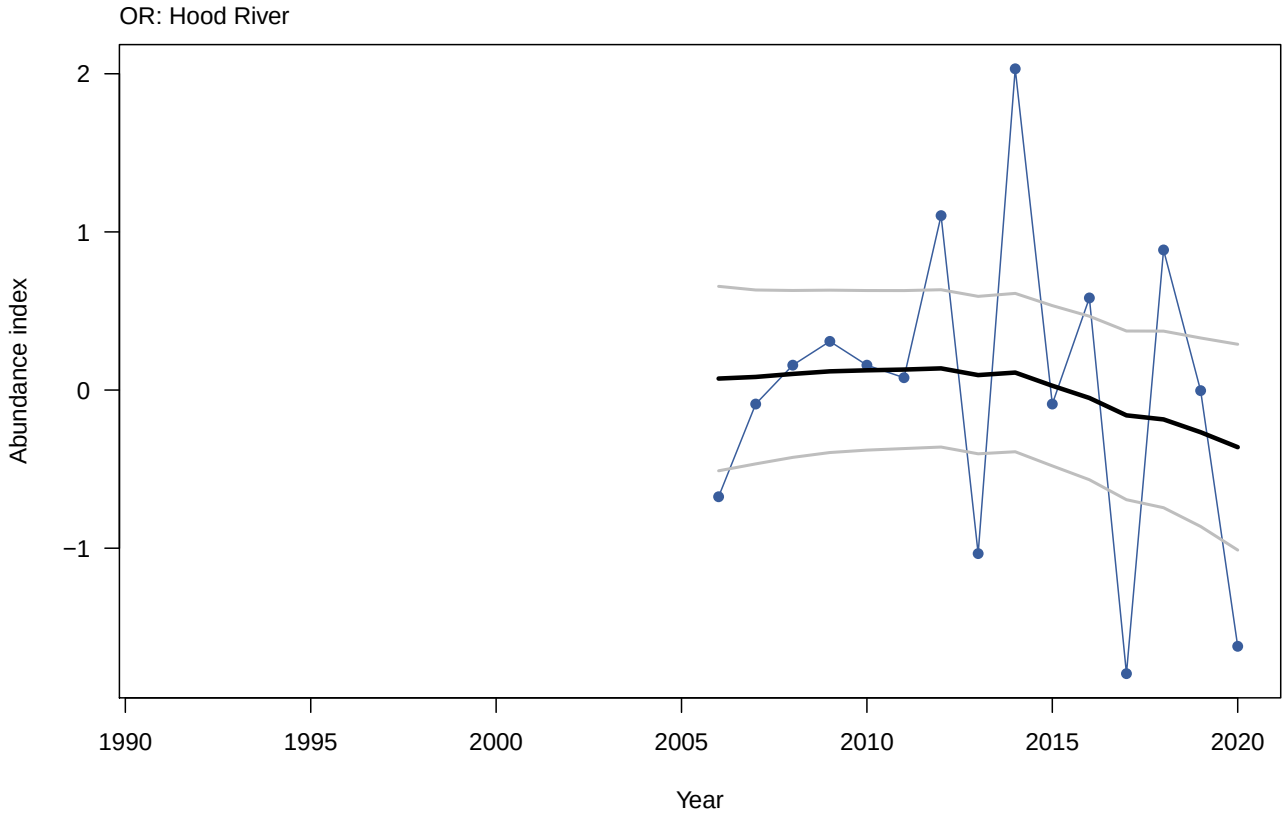
198


MT: Whitefish Lake
Abundance index
1
0
−1
−2
−3
1990
1995
2000
2005
2010
2015
2020
Year

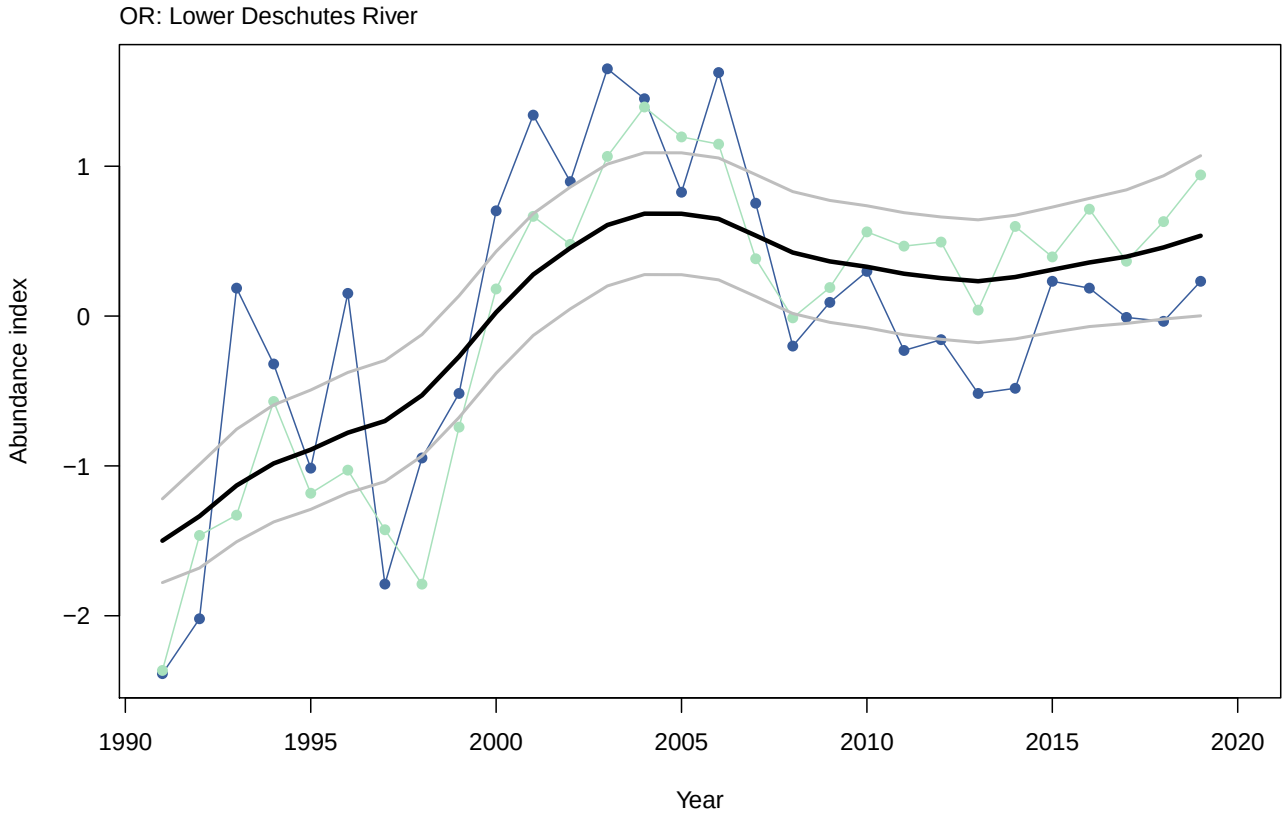
199


MT: St. Mary River
Abundance index
1
0
−1
−2
−3
1990
1995
2000
2005
2010
2015
2020
Year

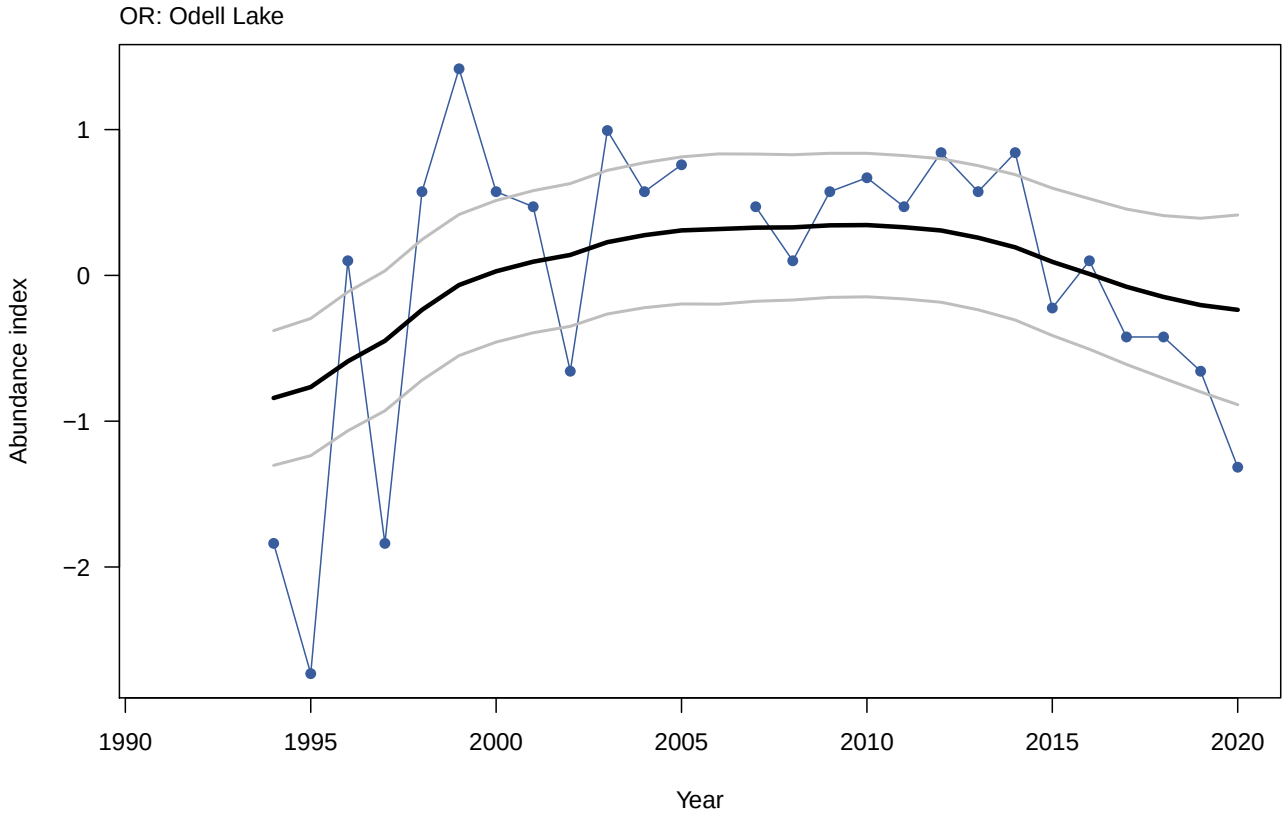
200


OR: Hood River
Abundance index
2
1
0
−1
1990
1995
2000
2005
2010
2015
2020
Year

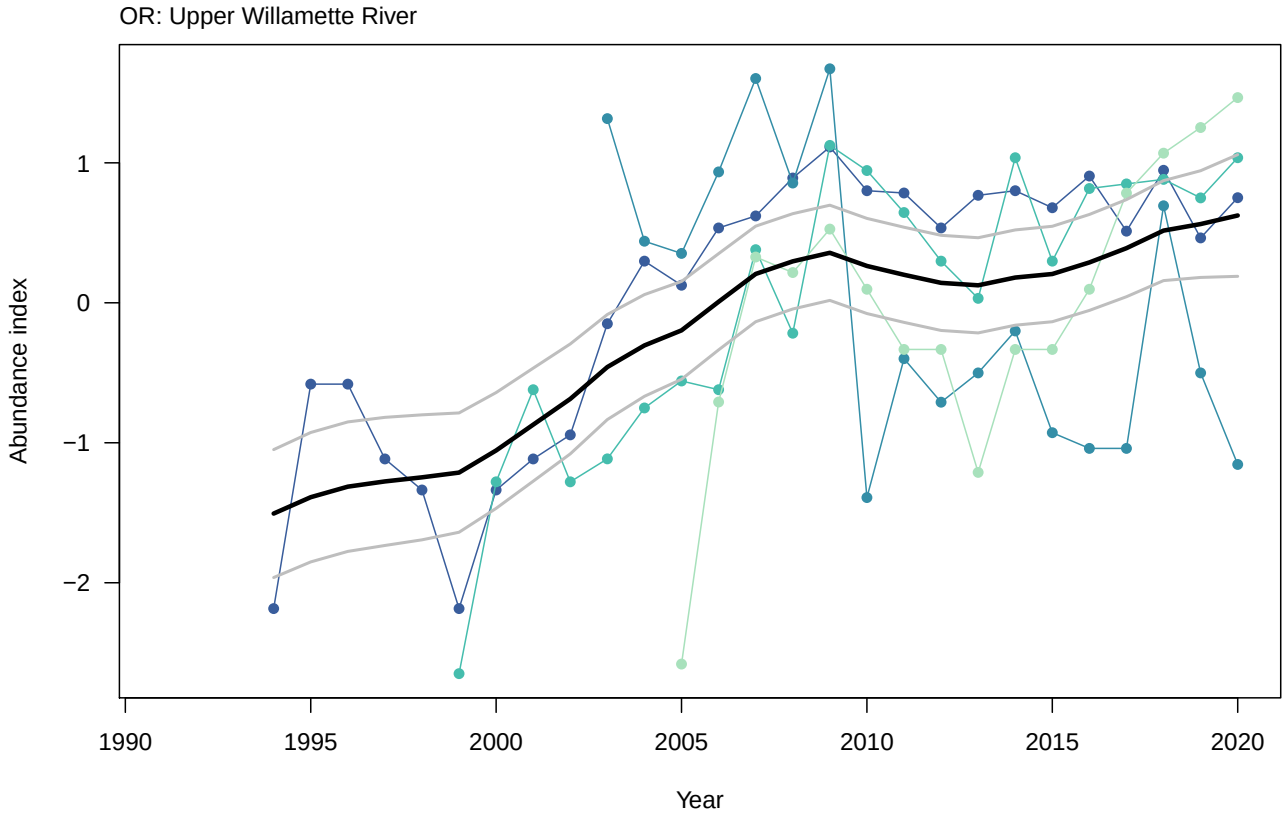
201


OR: Lower Deschutes River
Abundance index
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

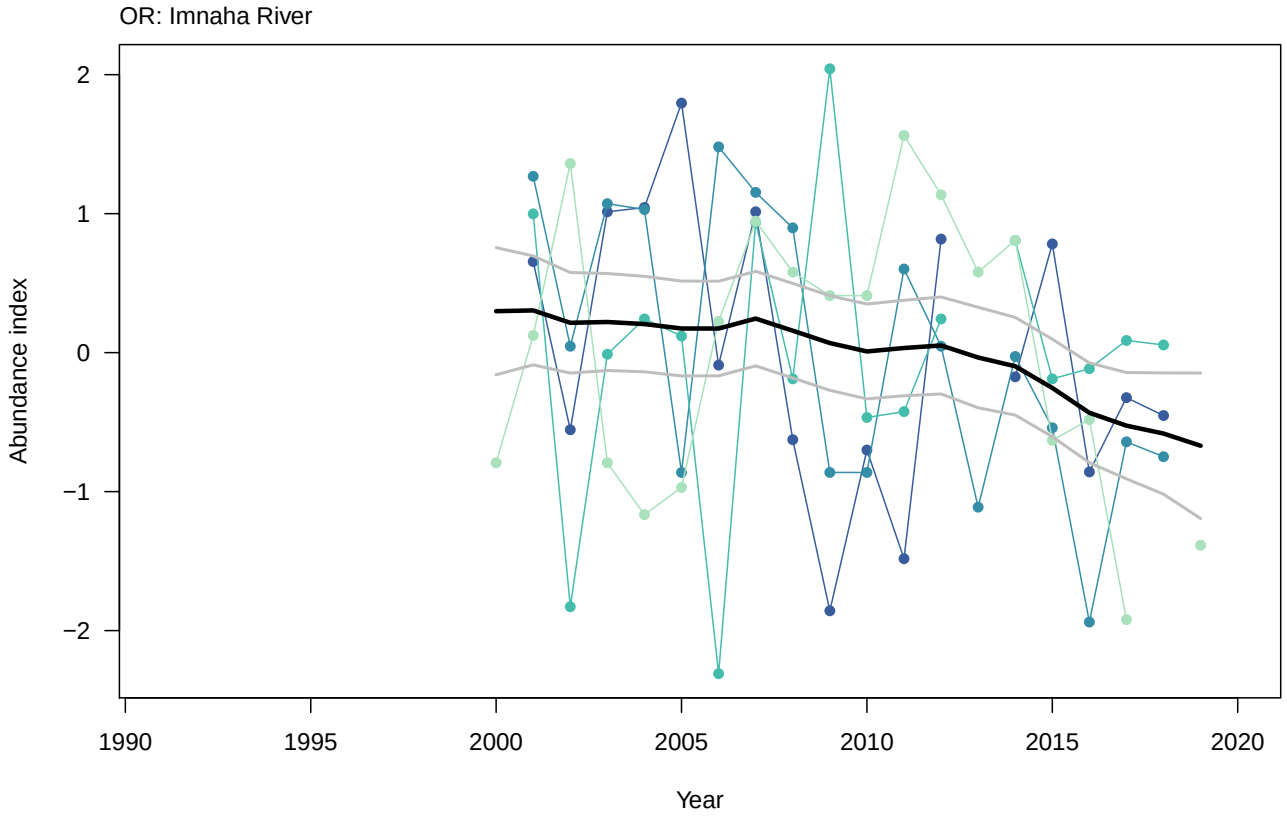
202


OR: Odell Lake
Abundance index
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

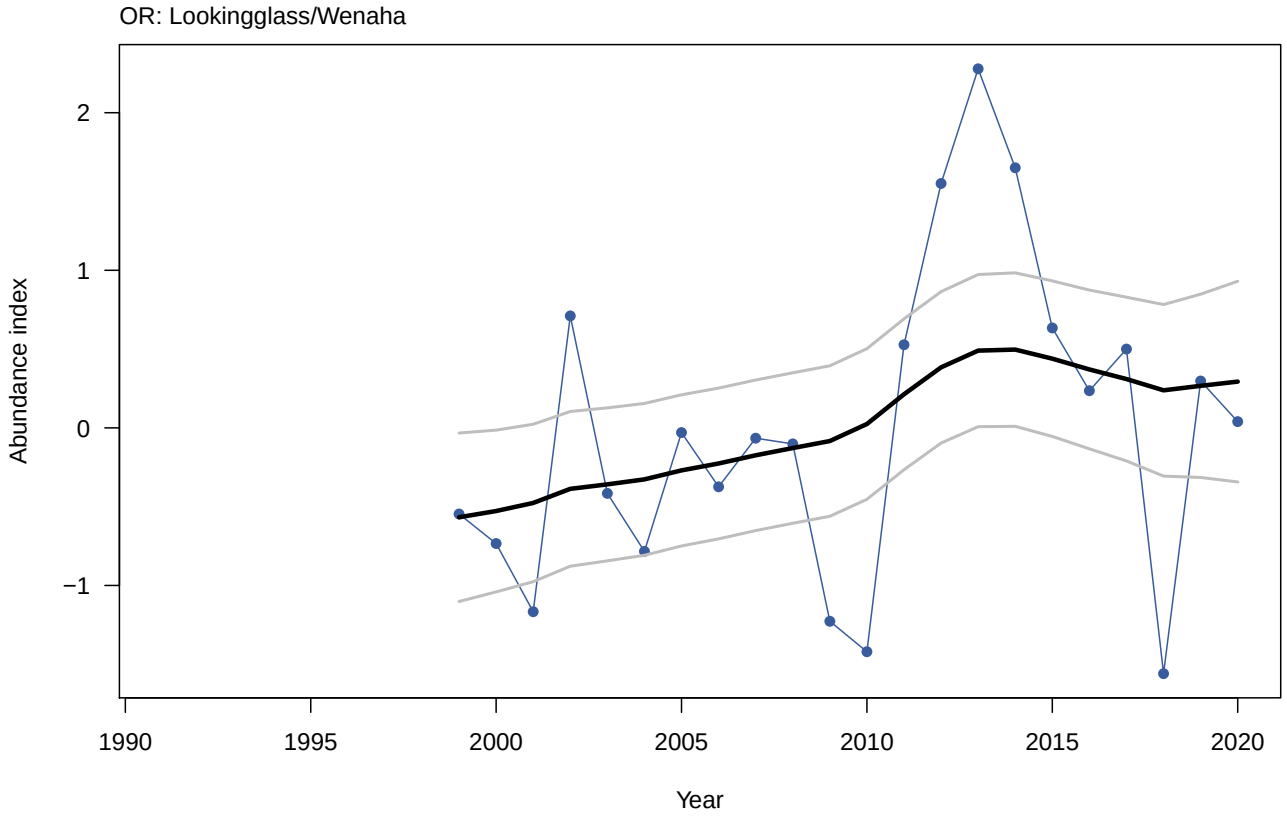
203


OR: Upper Willamette River
Abundance index
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

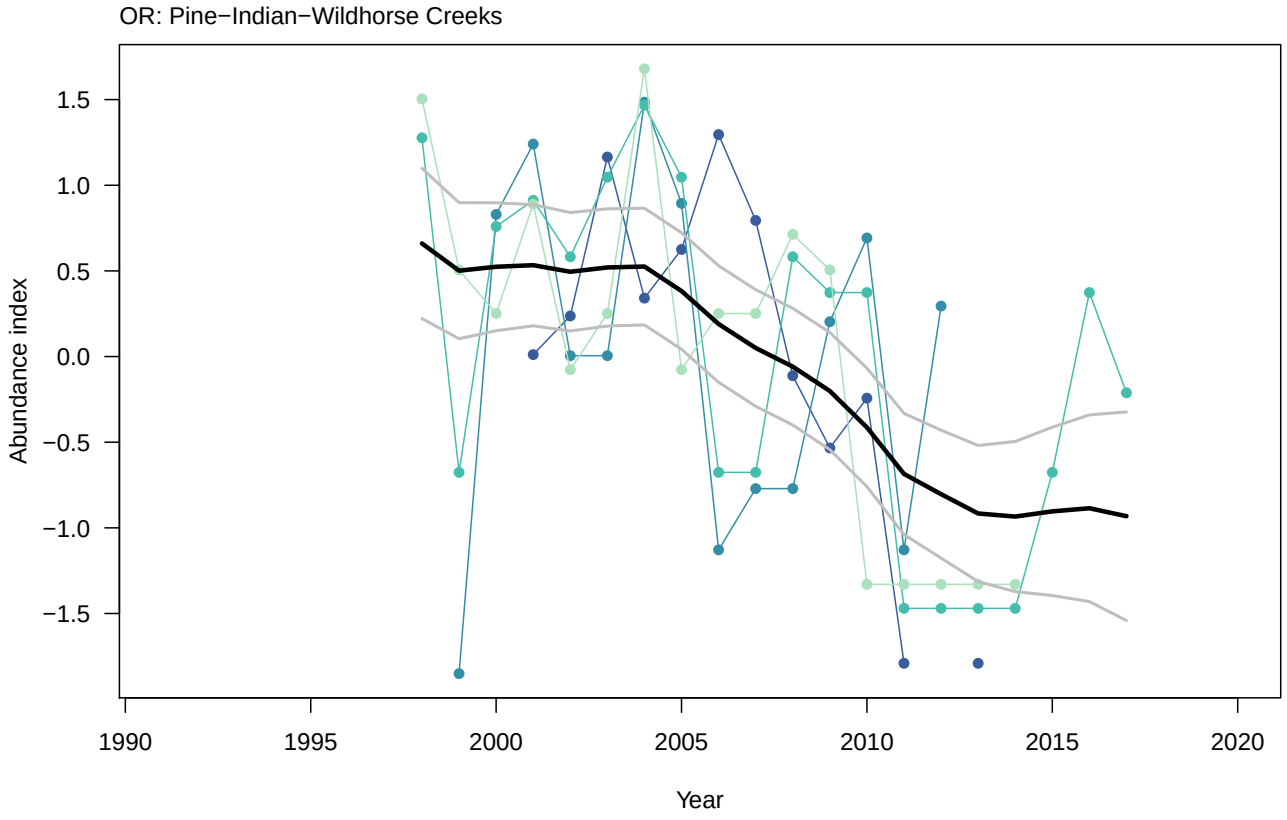
204


OR: Imnaha River
Abundance index
2
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

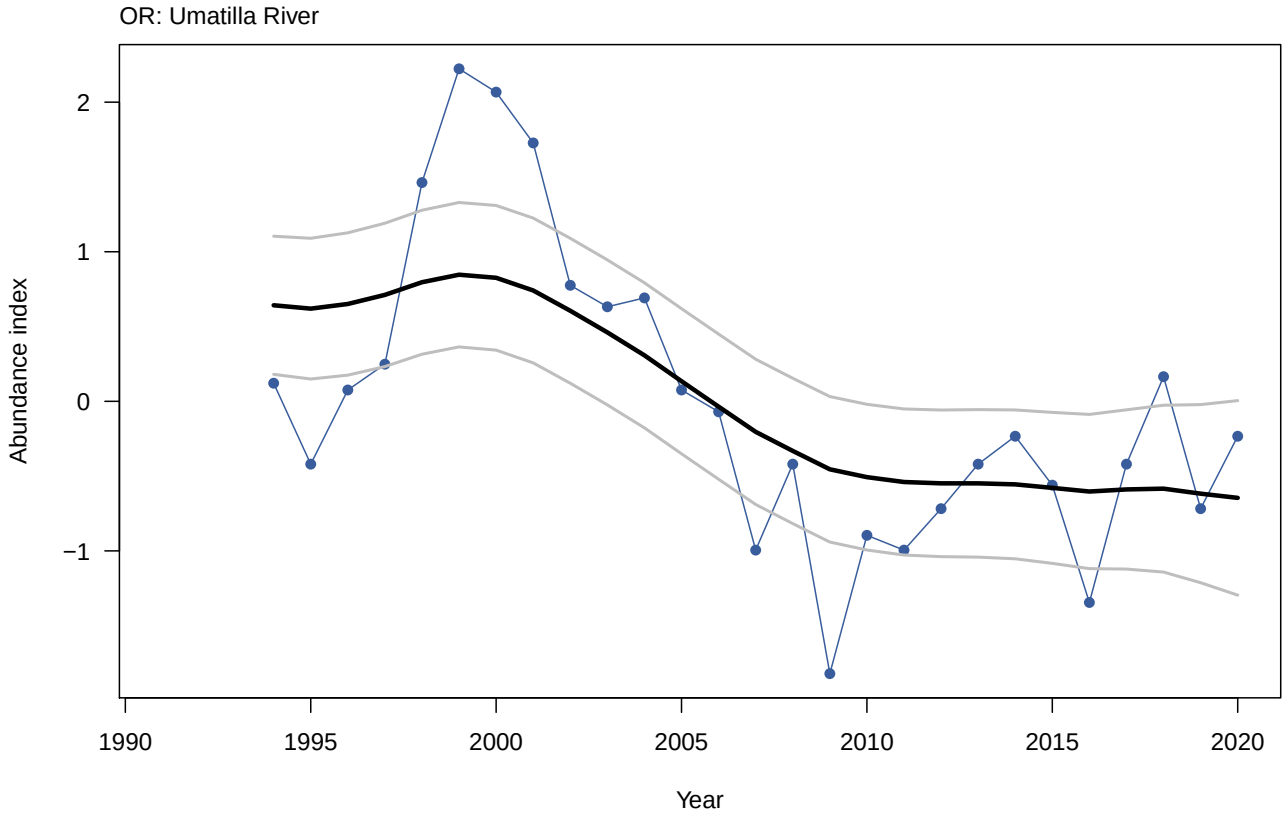
205


OR: Lookingglass/Wenaha
Abundance index
2
1
0
−1
1990
1995
2000
2005
2010
2015
2020
Year

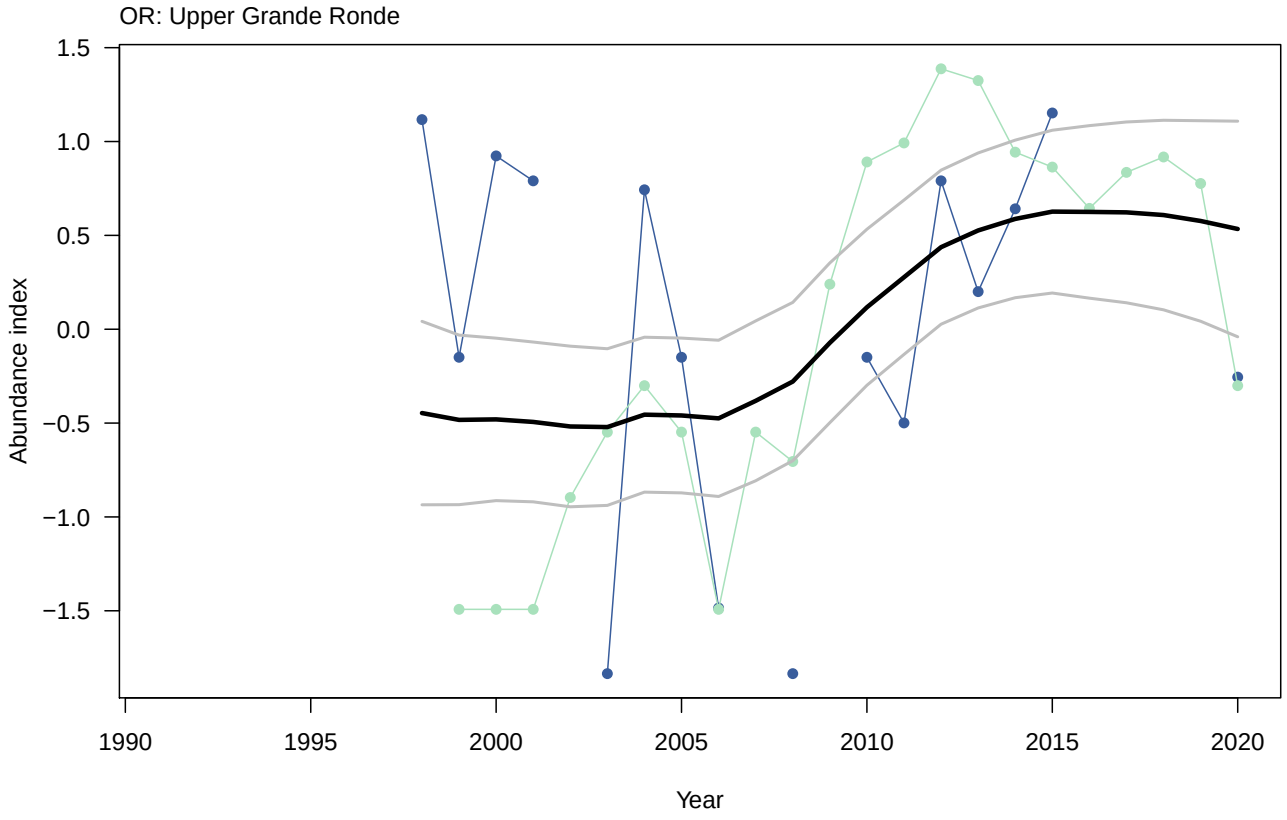
206


OR: Pine−Indian−Wildhorse Creeks
Abundance index
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
1990
1995
2000
2005
2010
2015
2020
Year

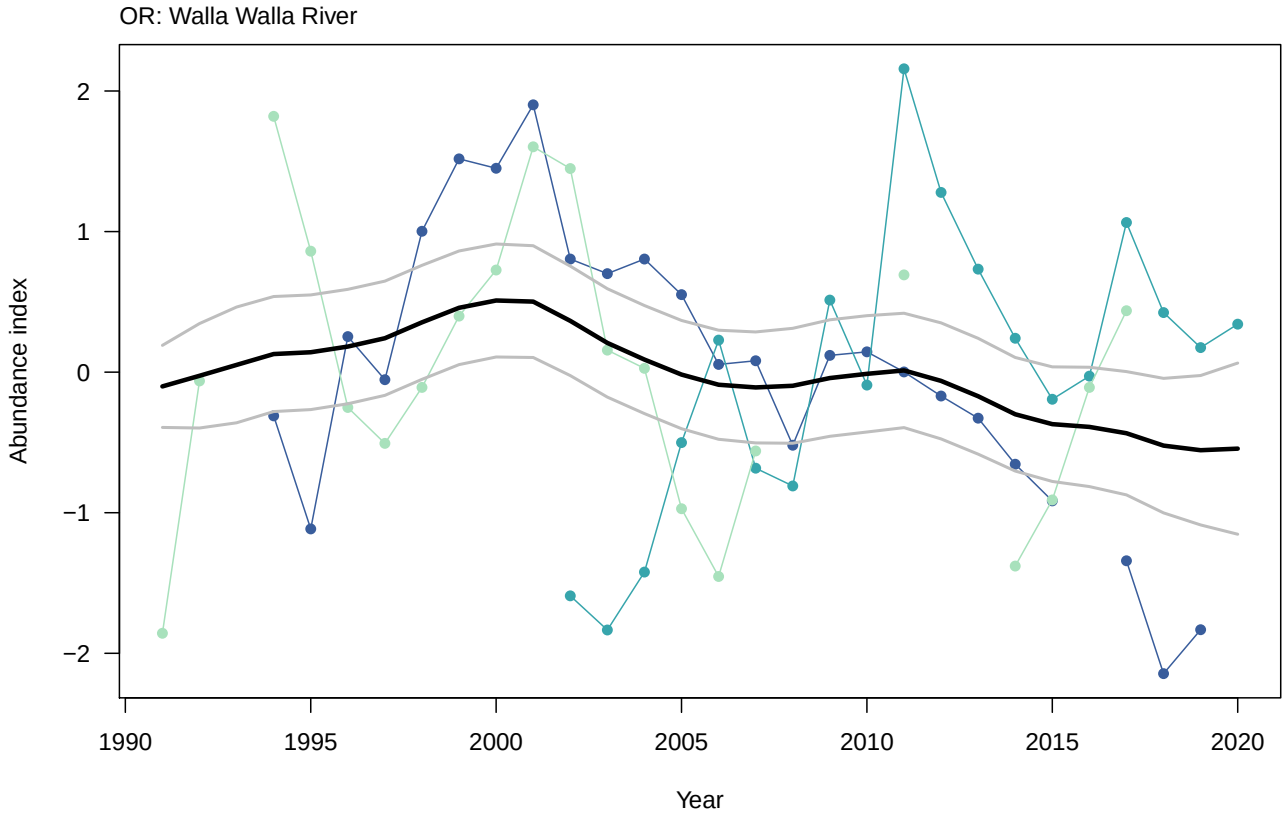
207


OR: Umatilla River
Abundance index
2
1
0
−1
1990
1995
2000
2005
2010
2015
2020
Year

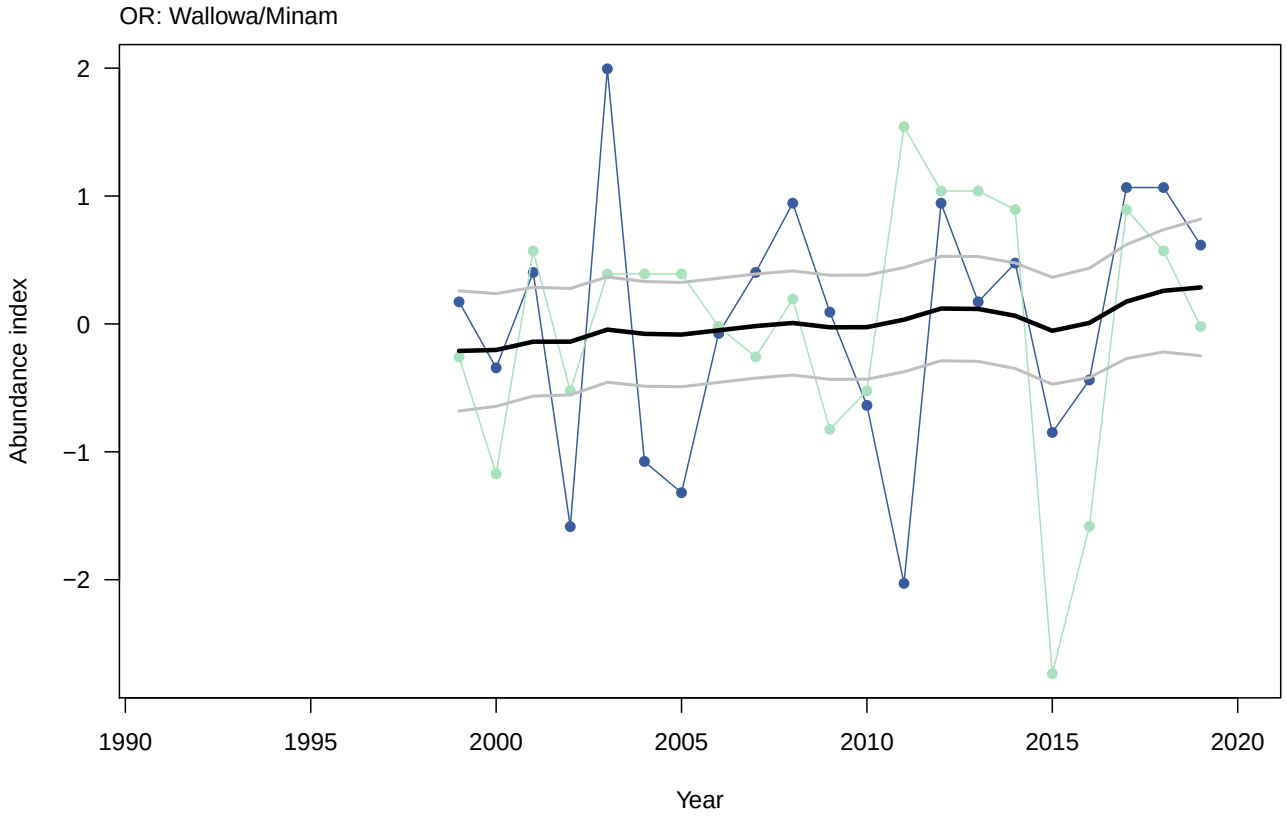
208


OR: Upper Grande Ronde
Abundance index
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
1990
1995
2000
2005
2010
2015
2020
Year

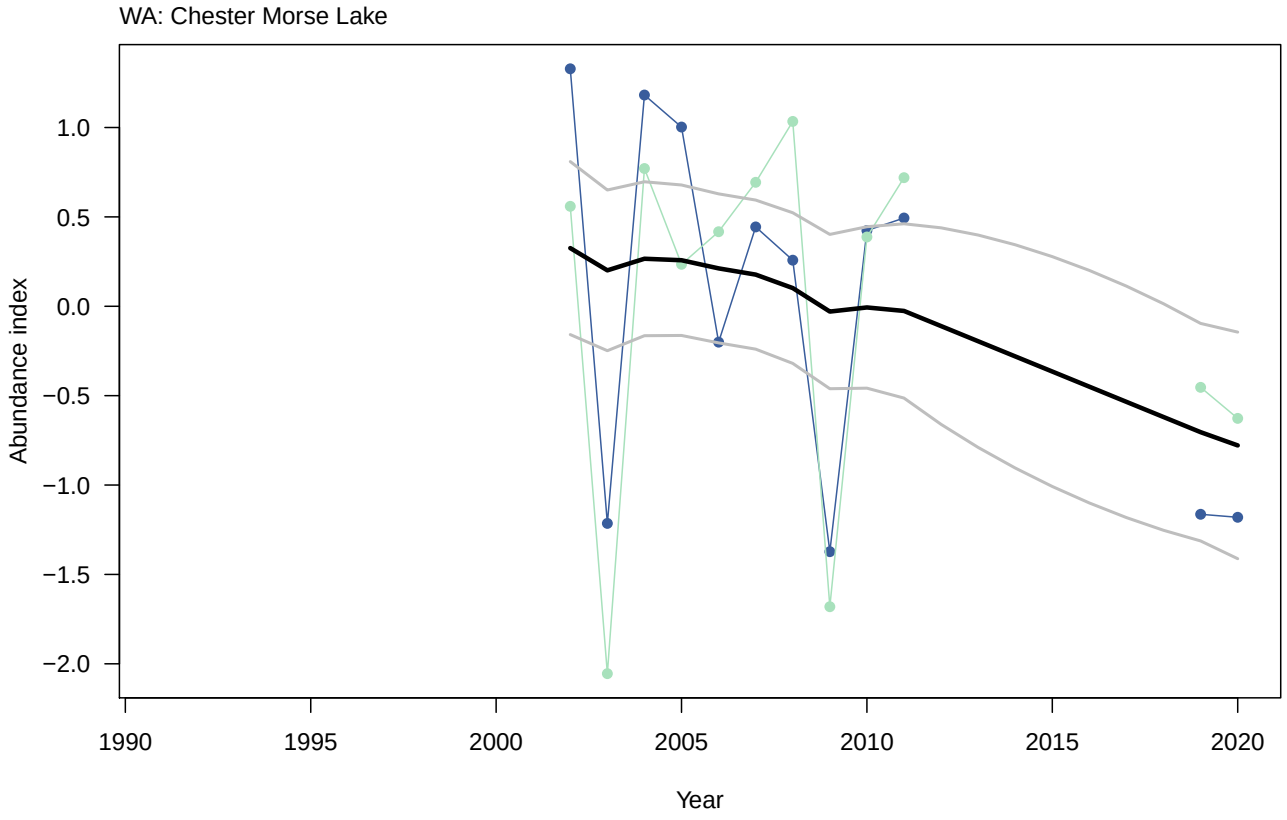
209


OR: Walla Walla River
Abundance index
2
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

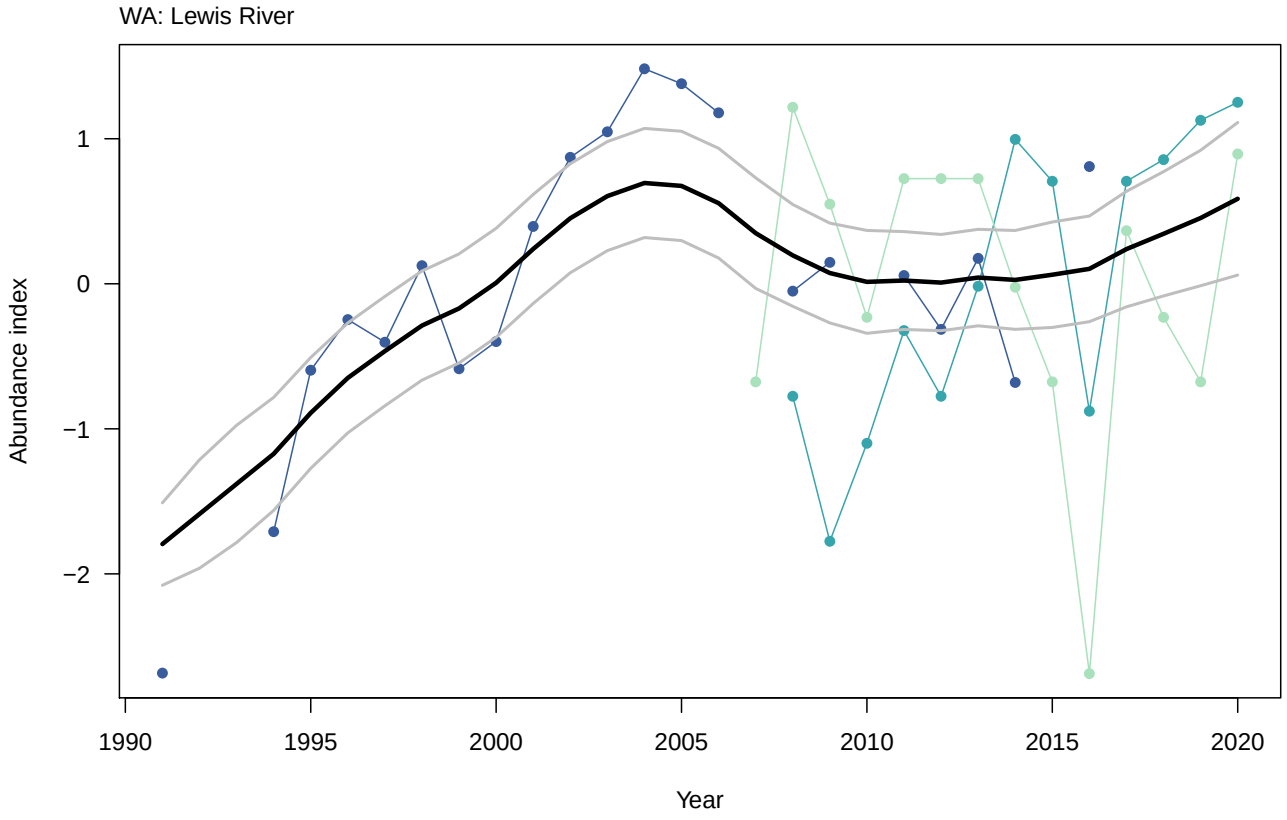
210


OR: Wallowa/Minam
Abundance index
2
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

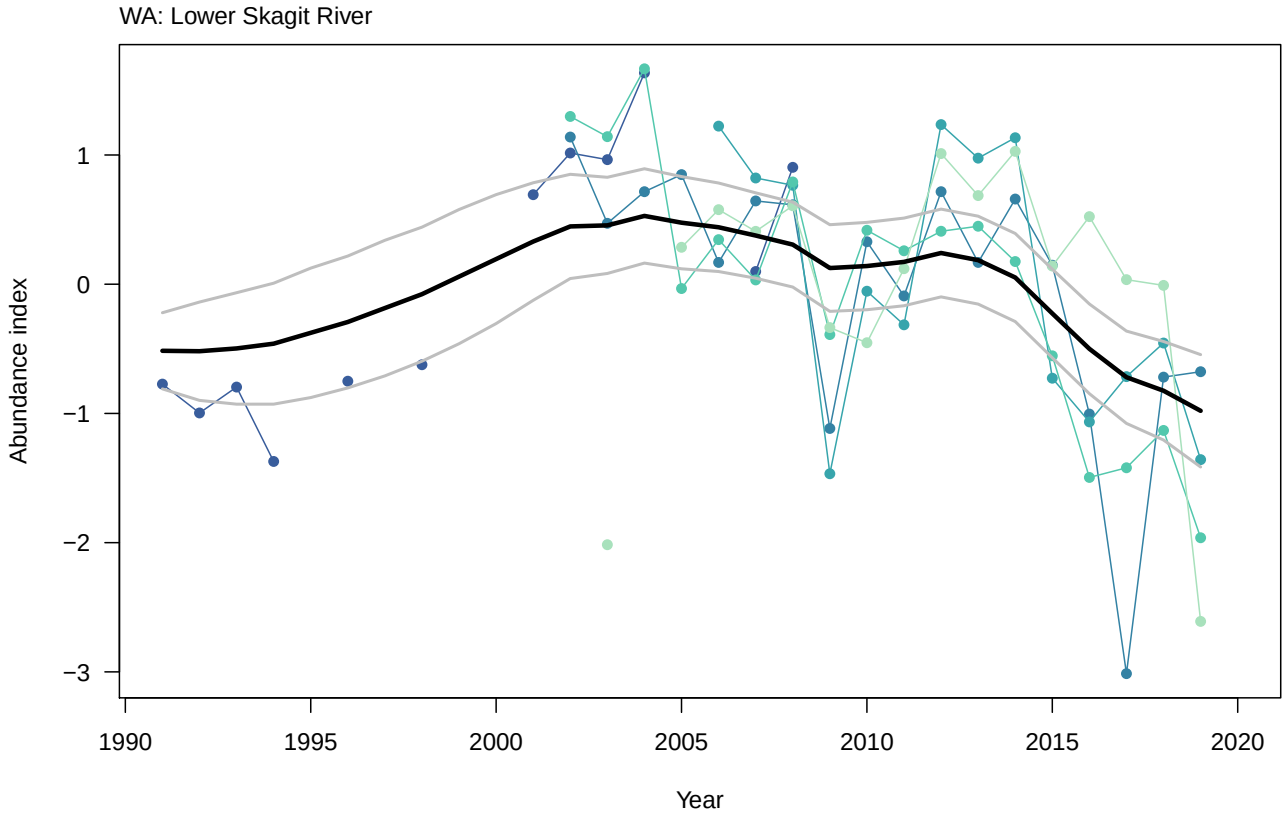
211


WA: Chester Morse Lake
Abundance index
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
1990
1995
2000
2005
2010
2015
2020
Year

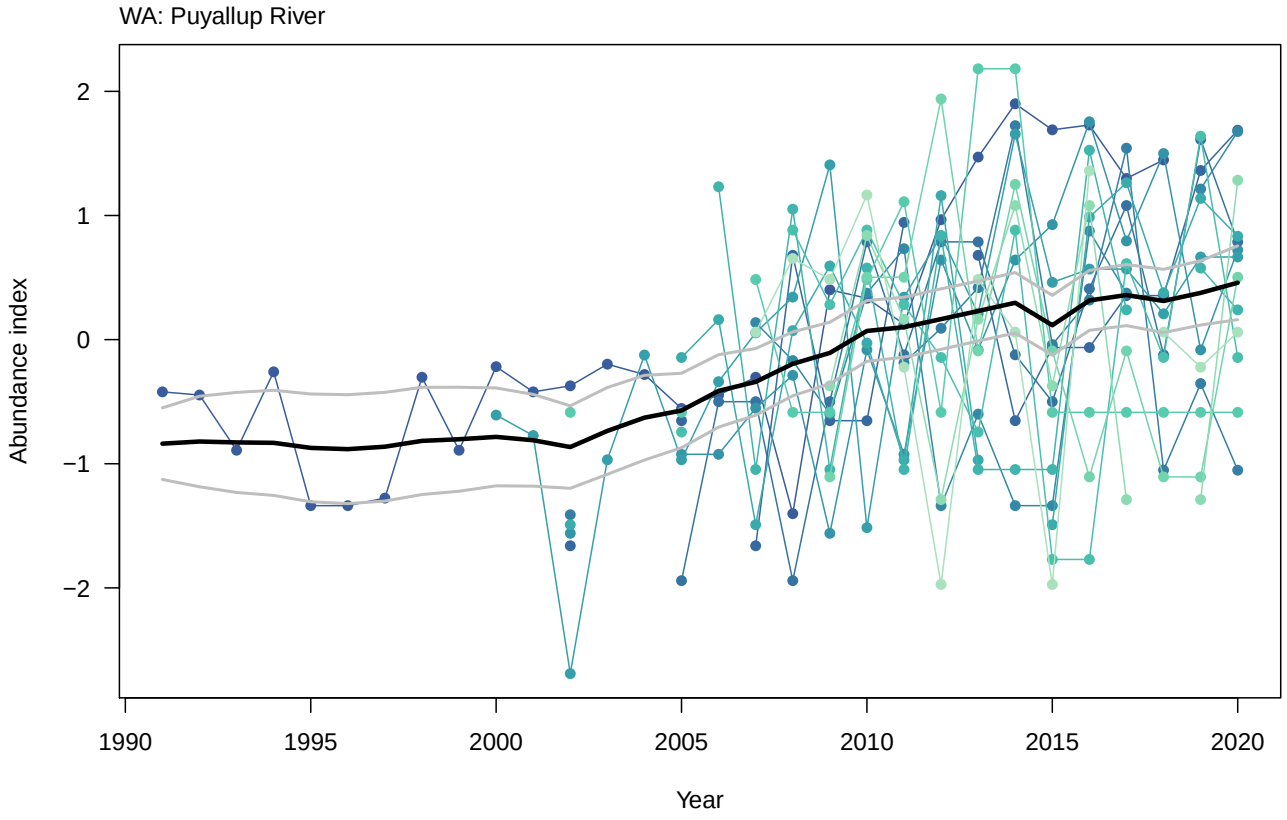
212


WA: Lewis River
Abundance index
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

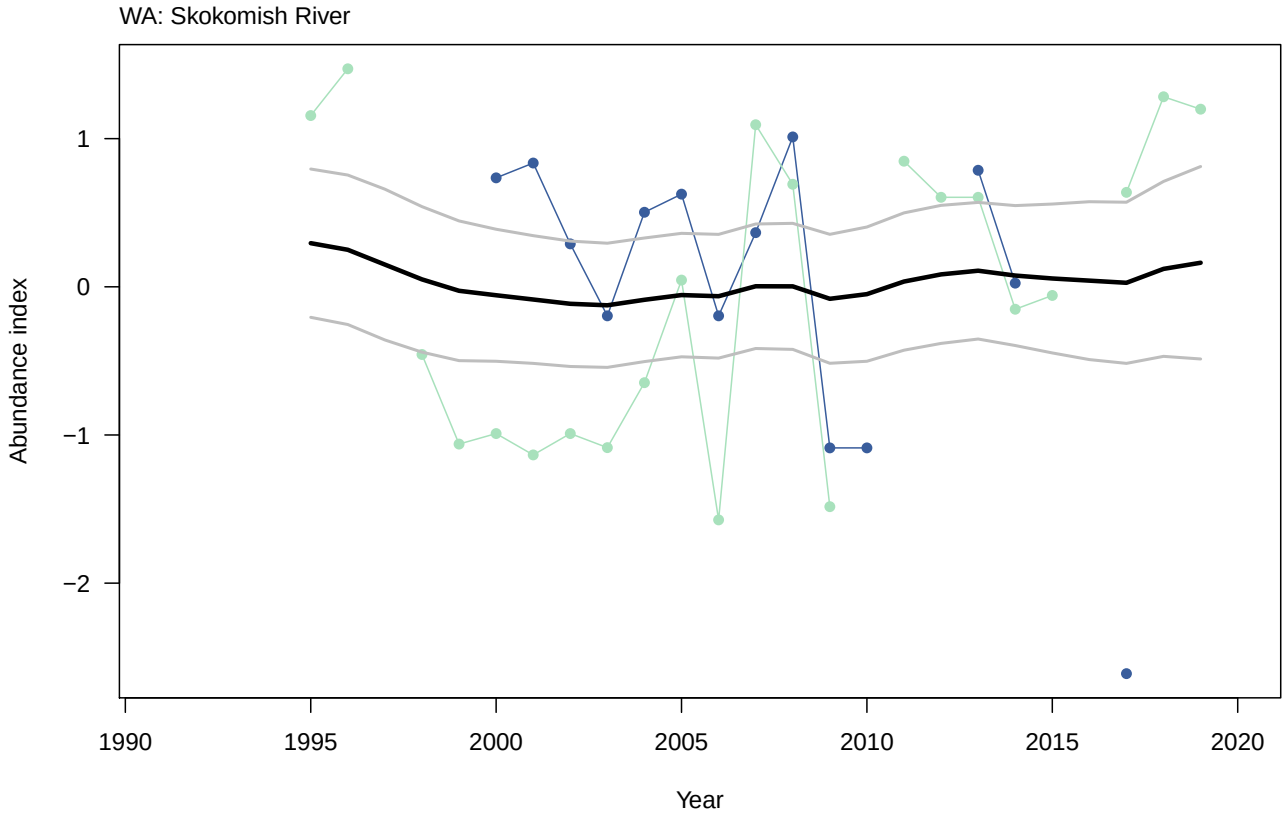
213


WA: Lower Skagit River
Abundance index
1
0
−1
−2
−3
1990
1995
2000
2005
2010
2015
2020
Year

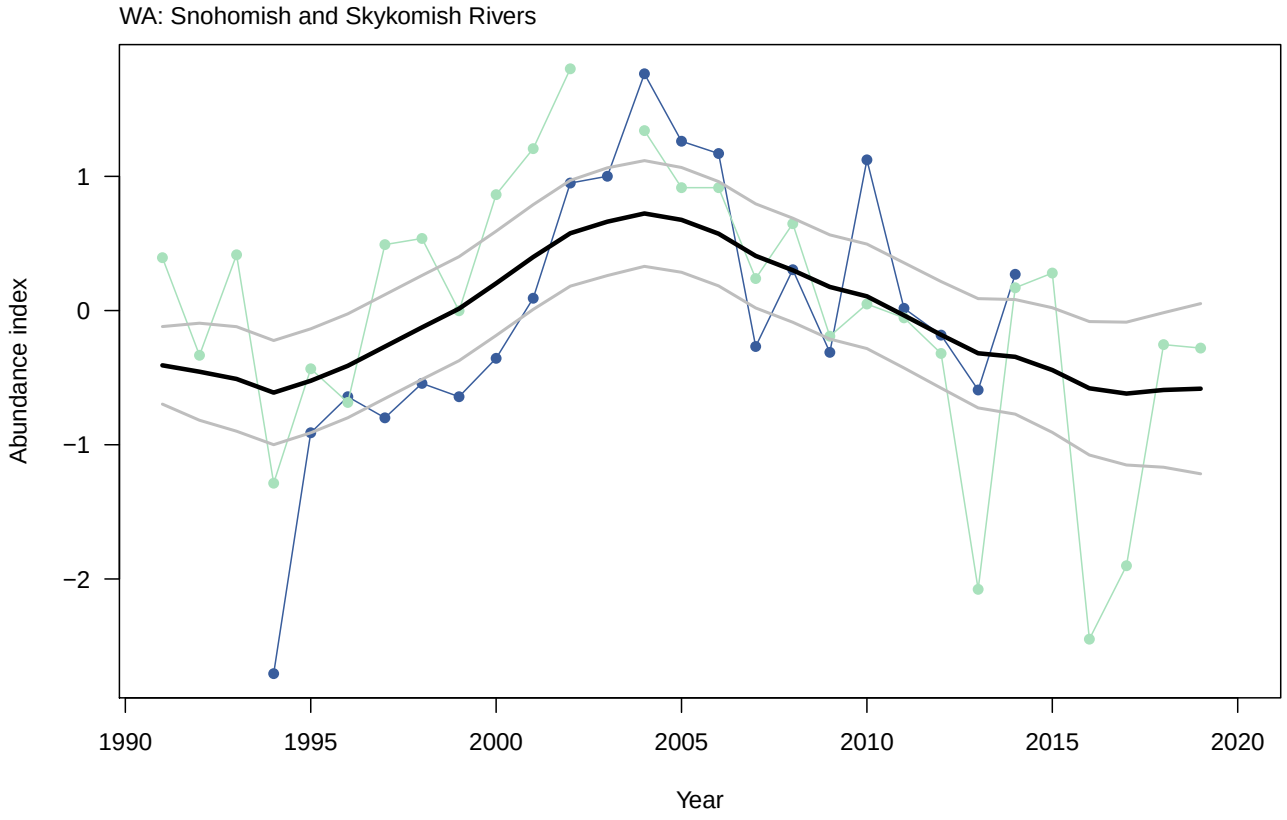
214


WA: Puyallup River
Abundance index
2
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

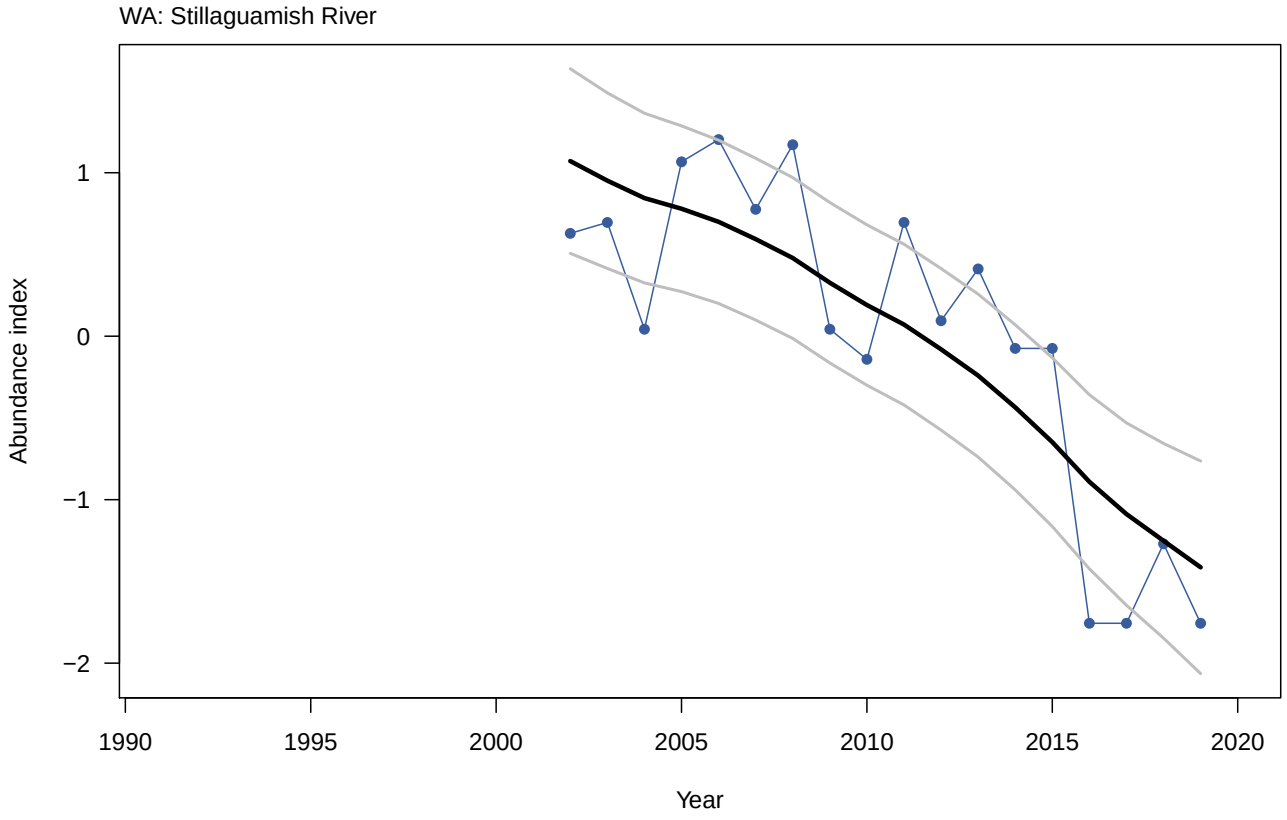
215


WA: Skokomish River
Abundance index
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

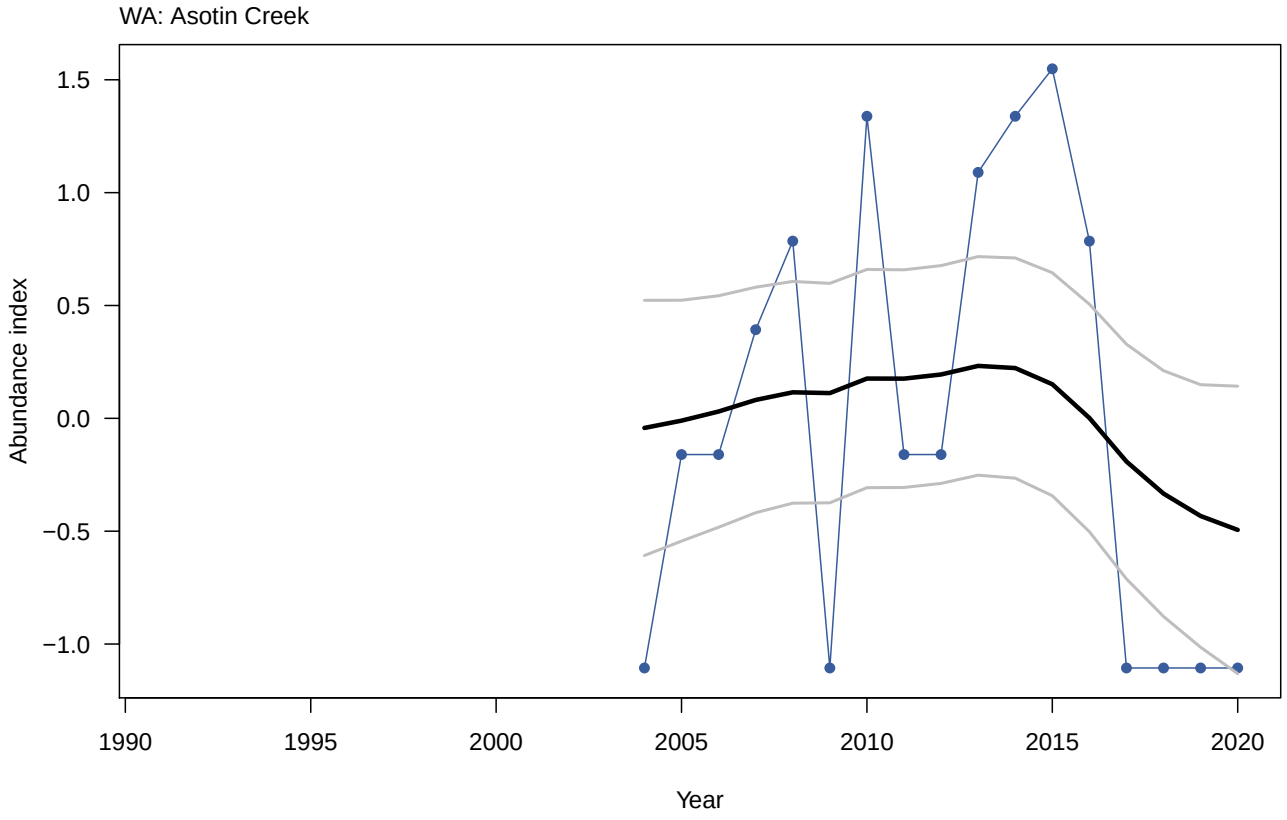
216


WA: Snohomish and Skykomish Rivers
Abundance index
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

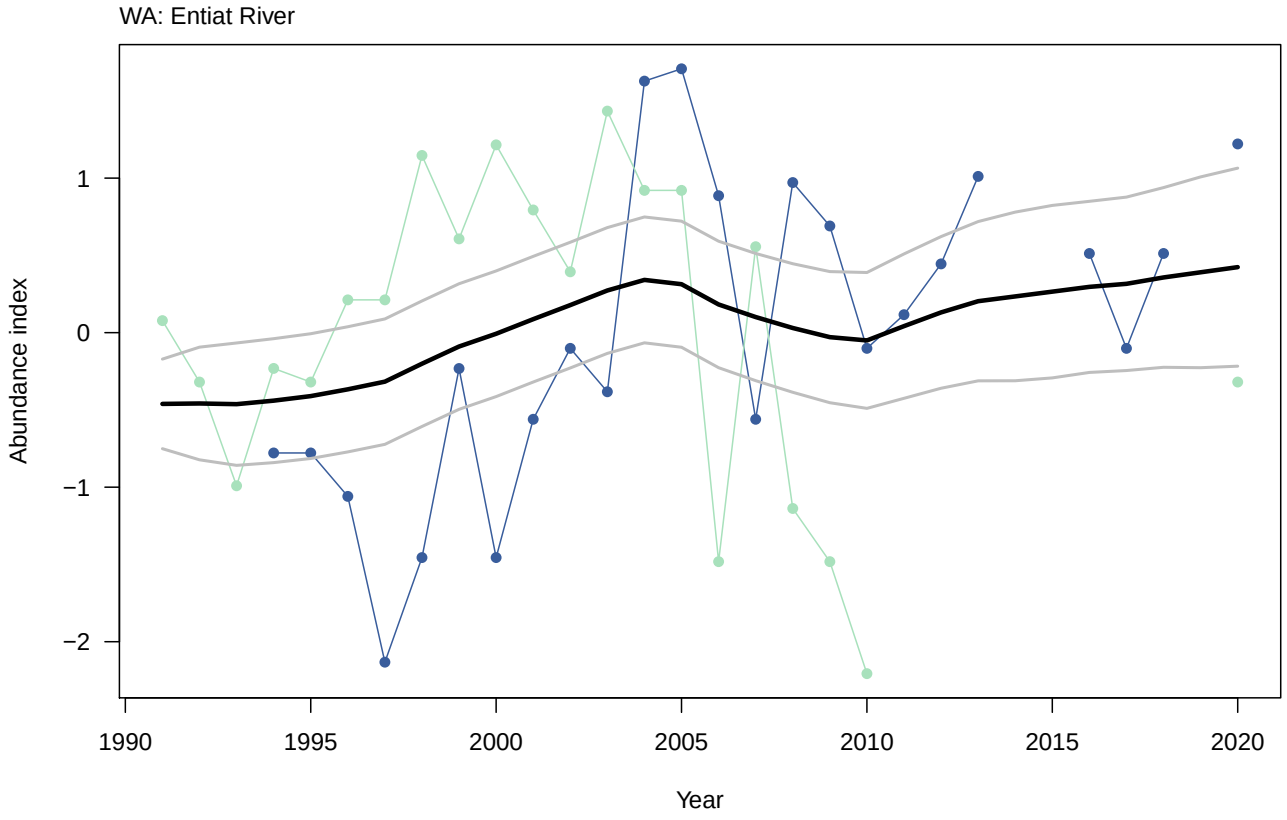
217


WA: Stillaguamish River
Abundance index
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

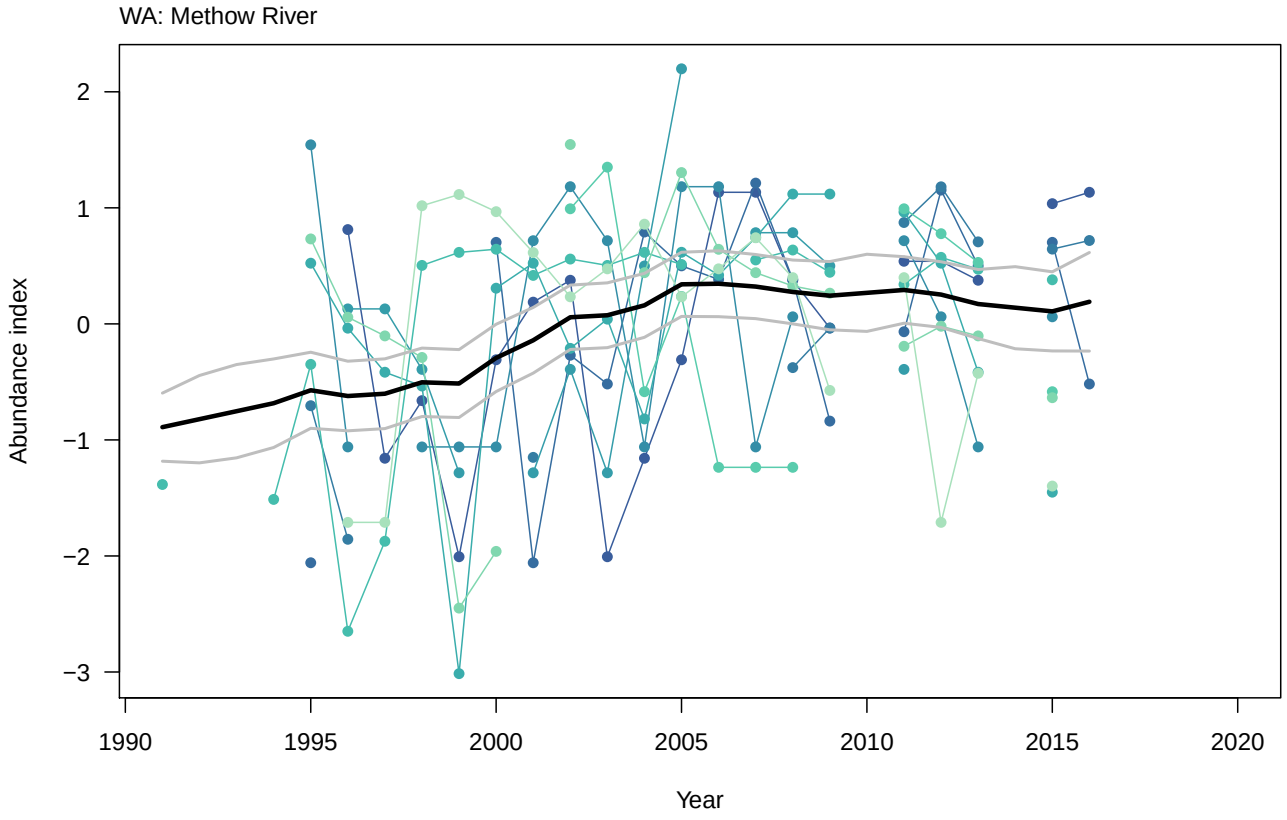
218


WA: Asotin Creek
Abundance index
1.5
1.0
0.5
0.0
−0.5
−1.0
1990
1995
2000
2005
2010
2015
2020
Year

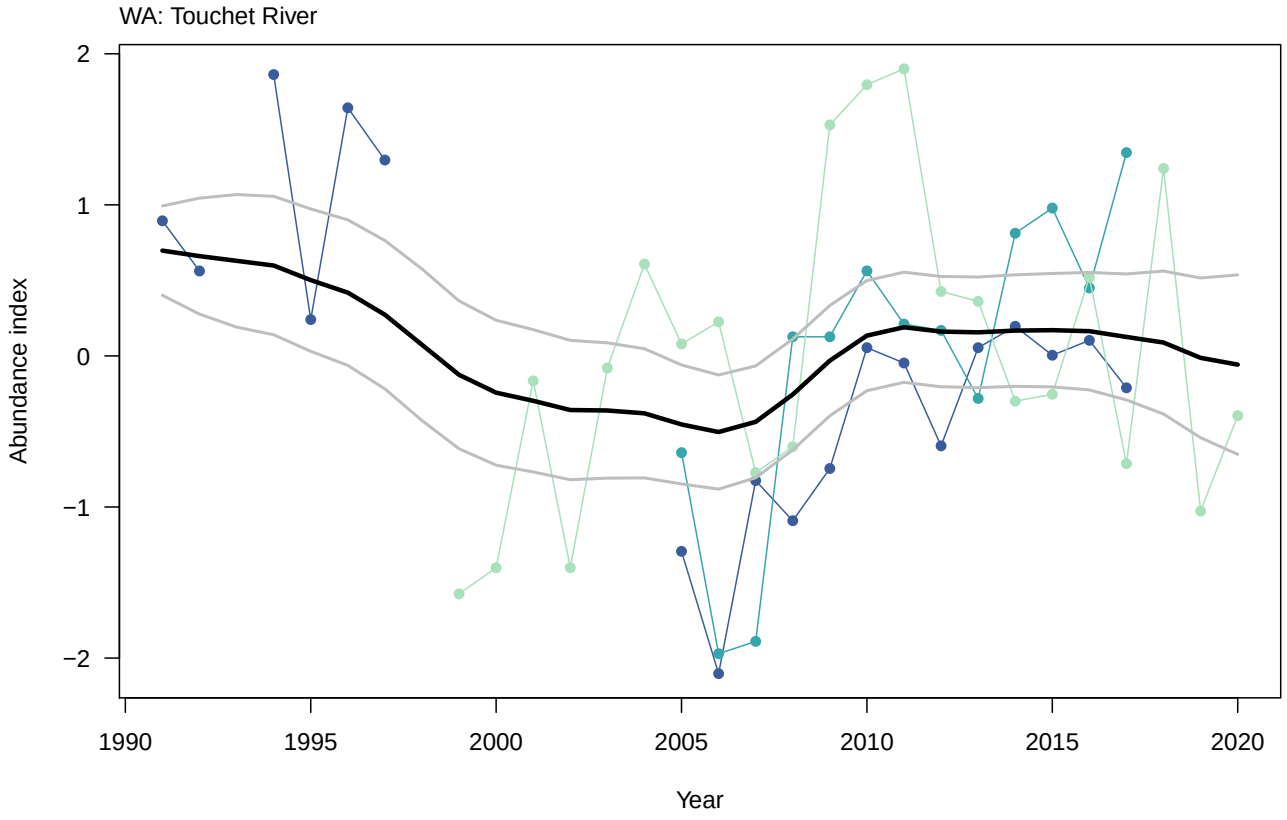
219


WA: Entiat River
Abundance index
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

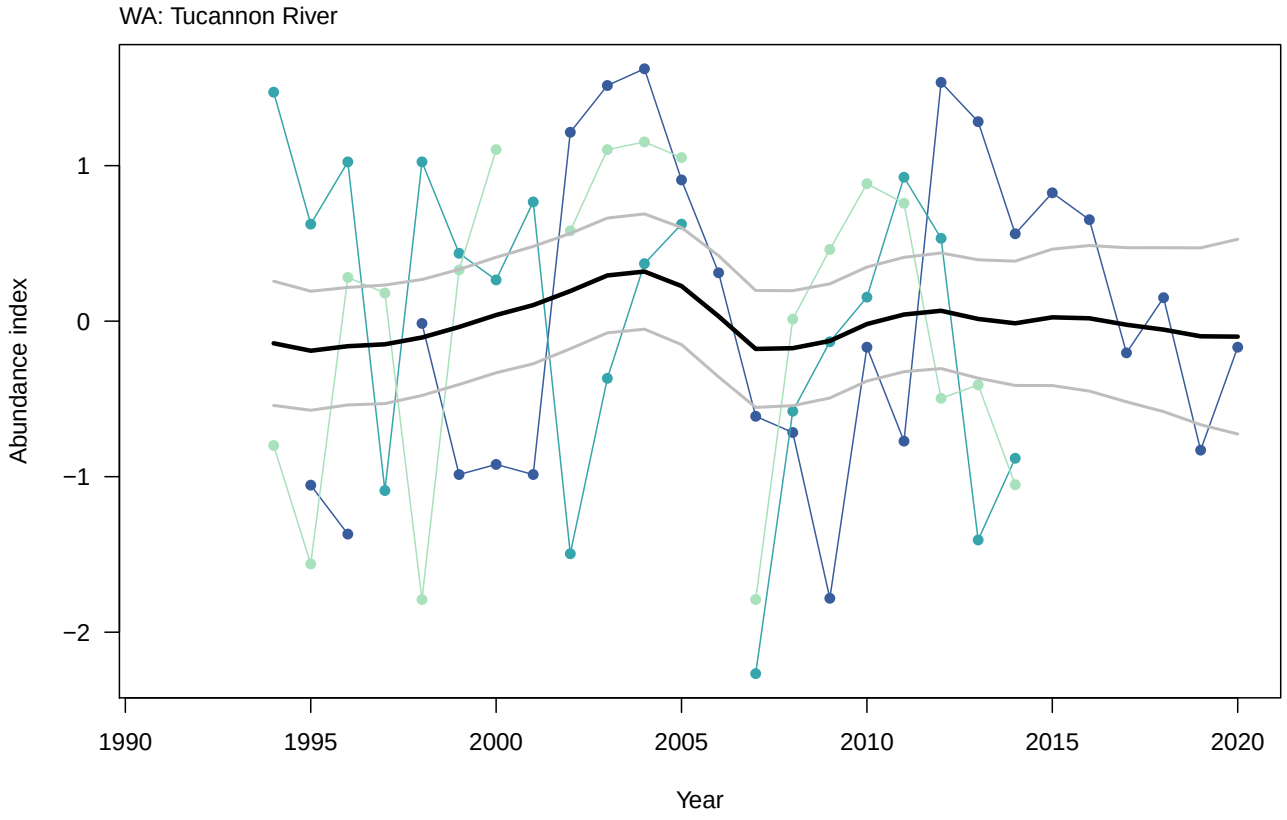
220


WA: Methow River
Abundance index
2
1
0
−1
−2
−3
1990
1995
2000
2005
2010
2015
2020
Year

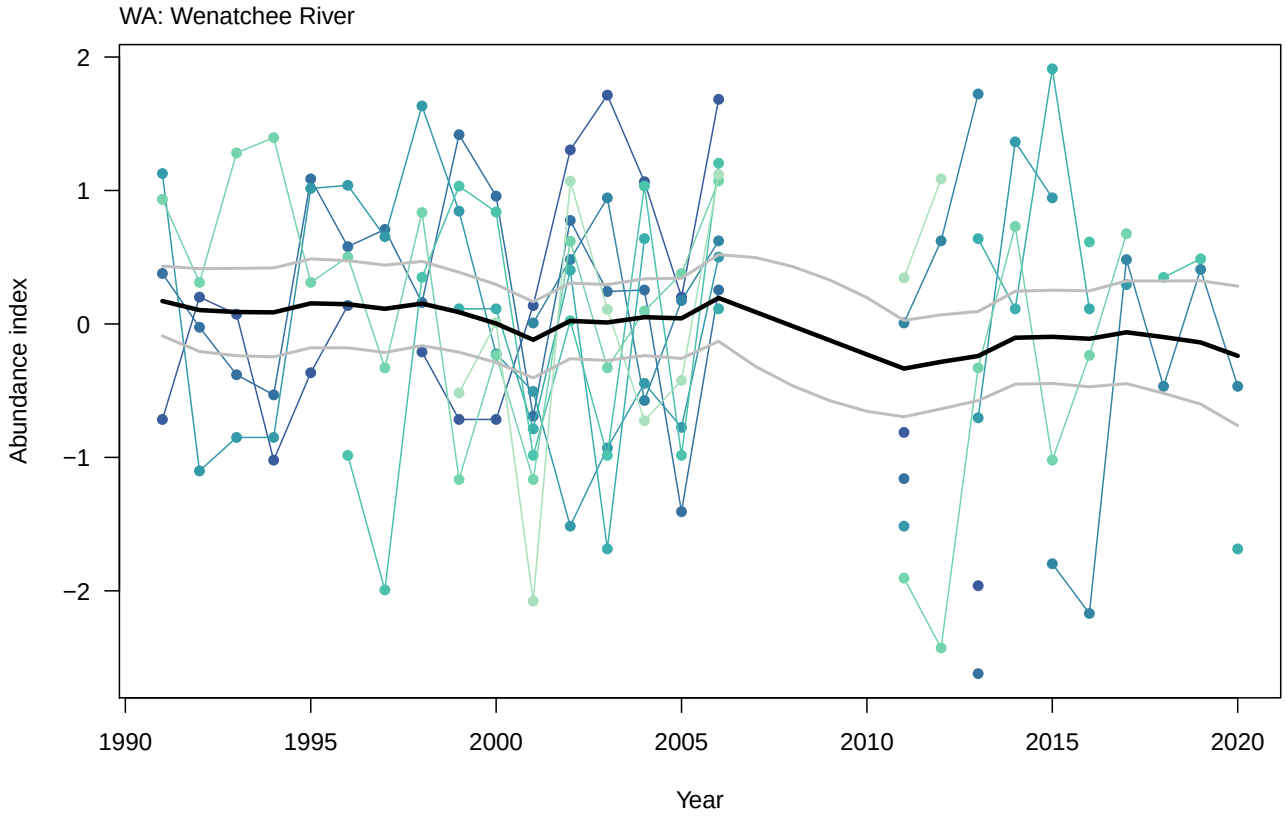
221


WA: Touchet River
Abundance index
2
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

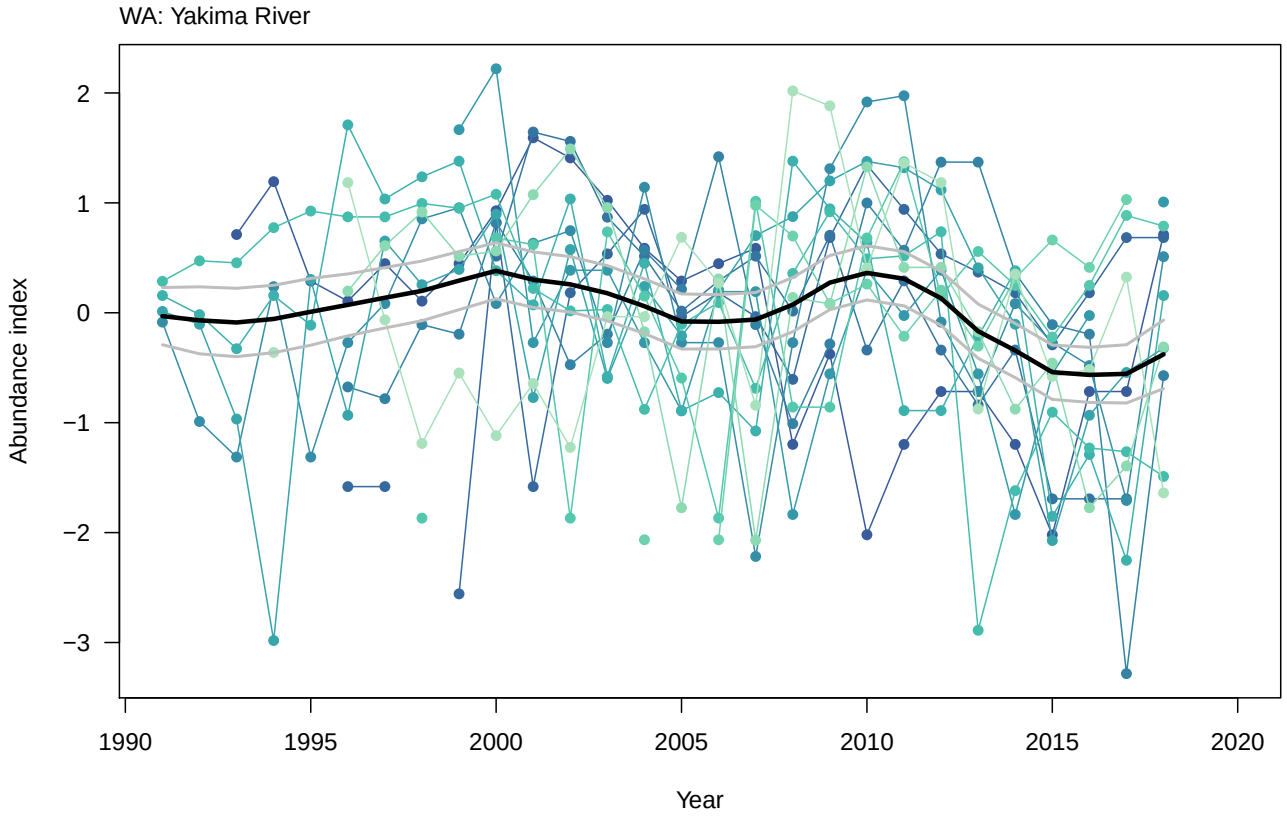
222


WA: Tucannon River
Abundance index
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

223


WA: Wenatchee River
Abundance index
2
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

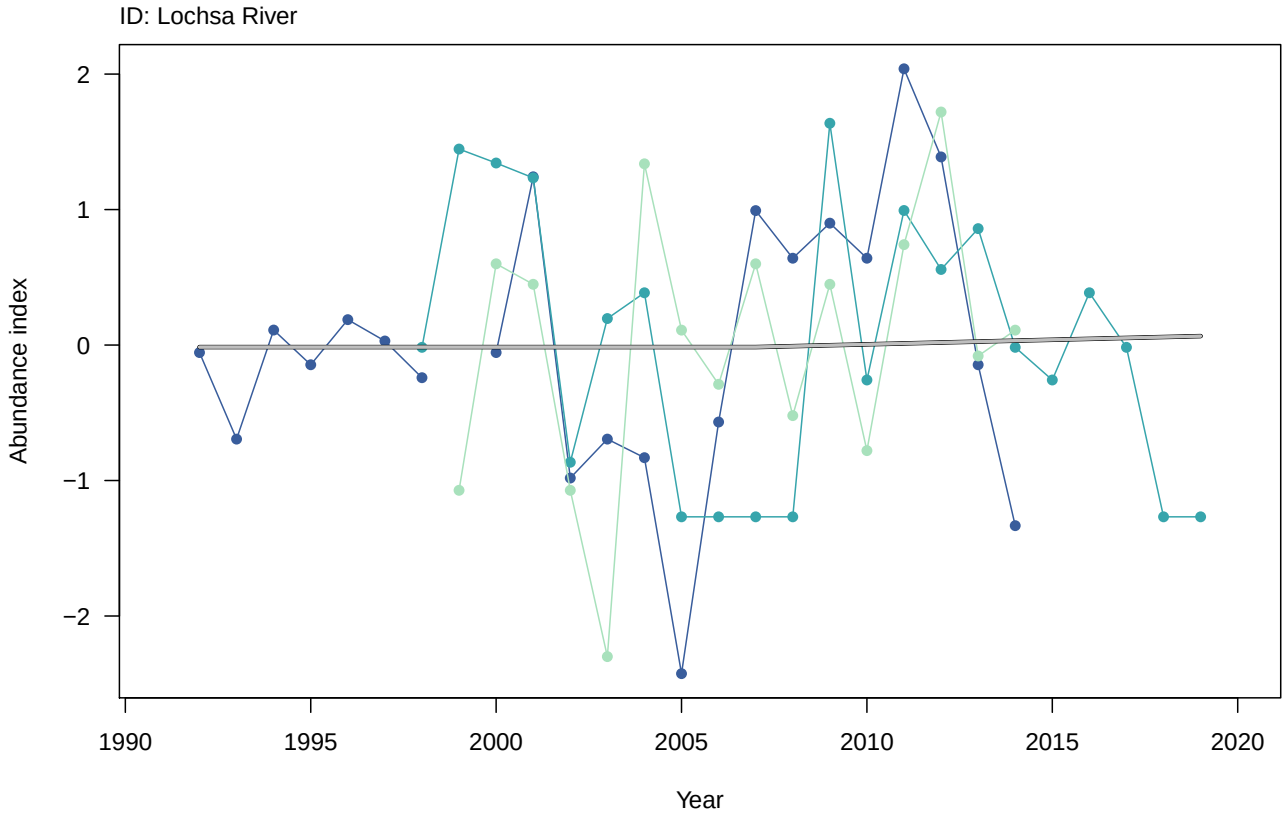
224


WA: Yakima River
Abundance index
2
1
0
−1
−2
−3
1990
1995
2000
2005
2010
2015
2020
Year

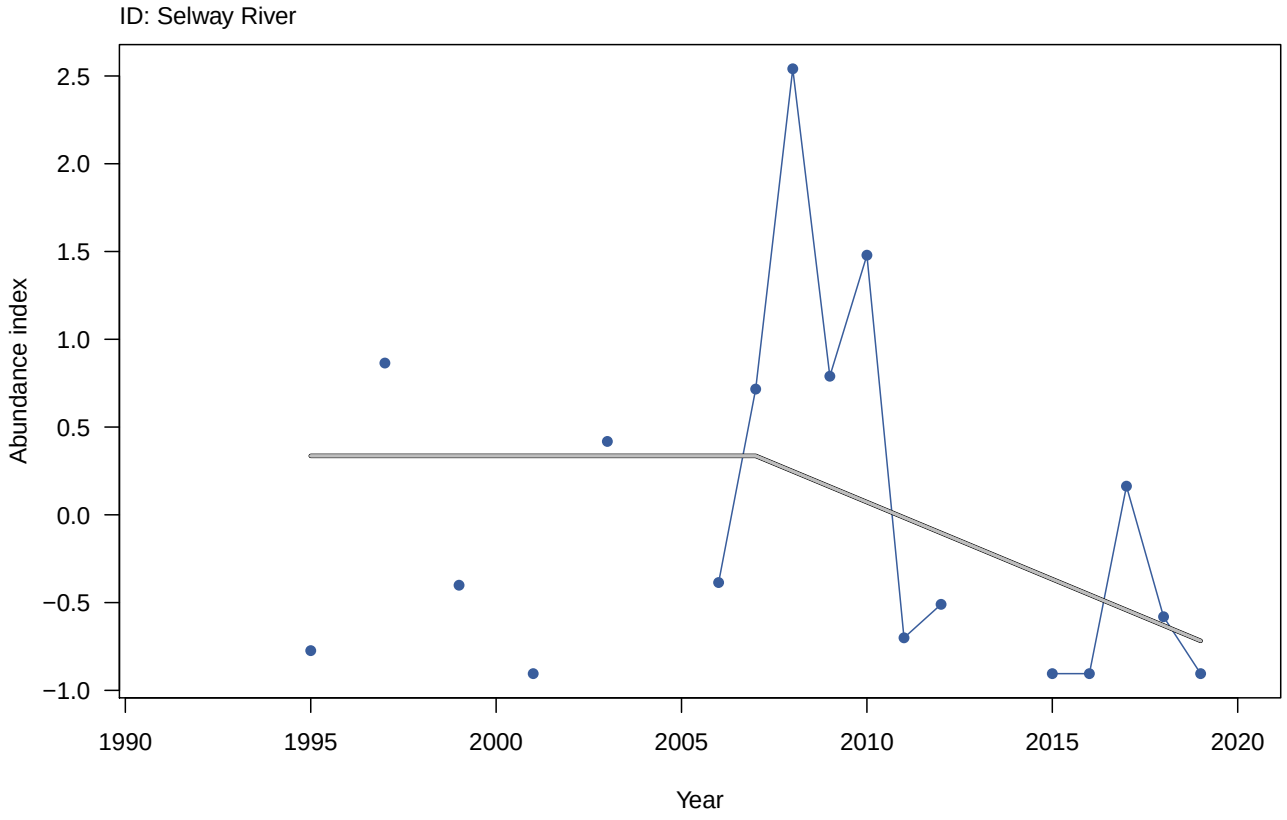
Appendix B

The following pages contain plots of standardized indices of log-abundance for juveniles over time by core area (i.e., location indicated on plots by `State: Core area`). Fitted trend lines (black) and associated 90% confidence intervals (gray) are also shown.

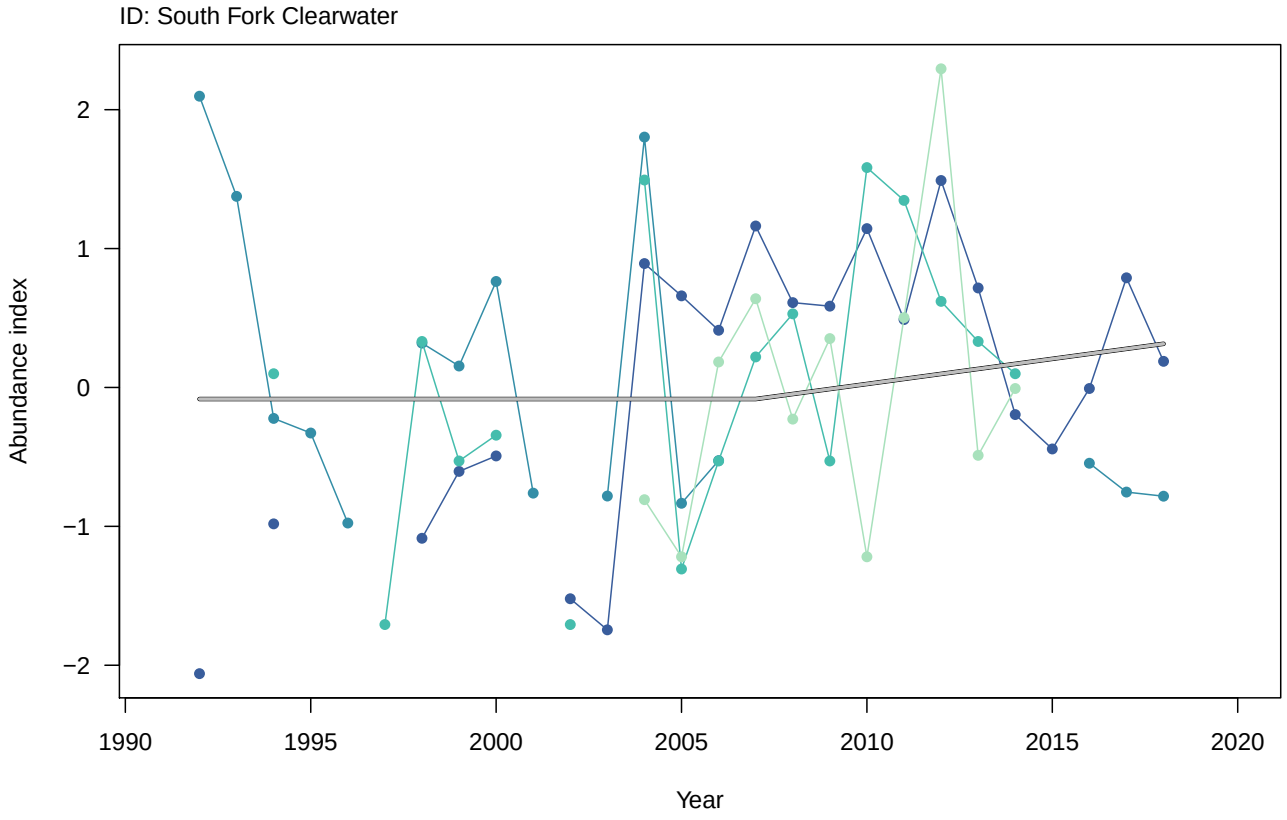
229


ID: Lochsa River
Abundance index
2
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

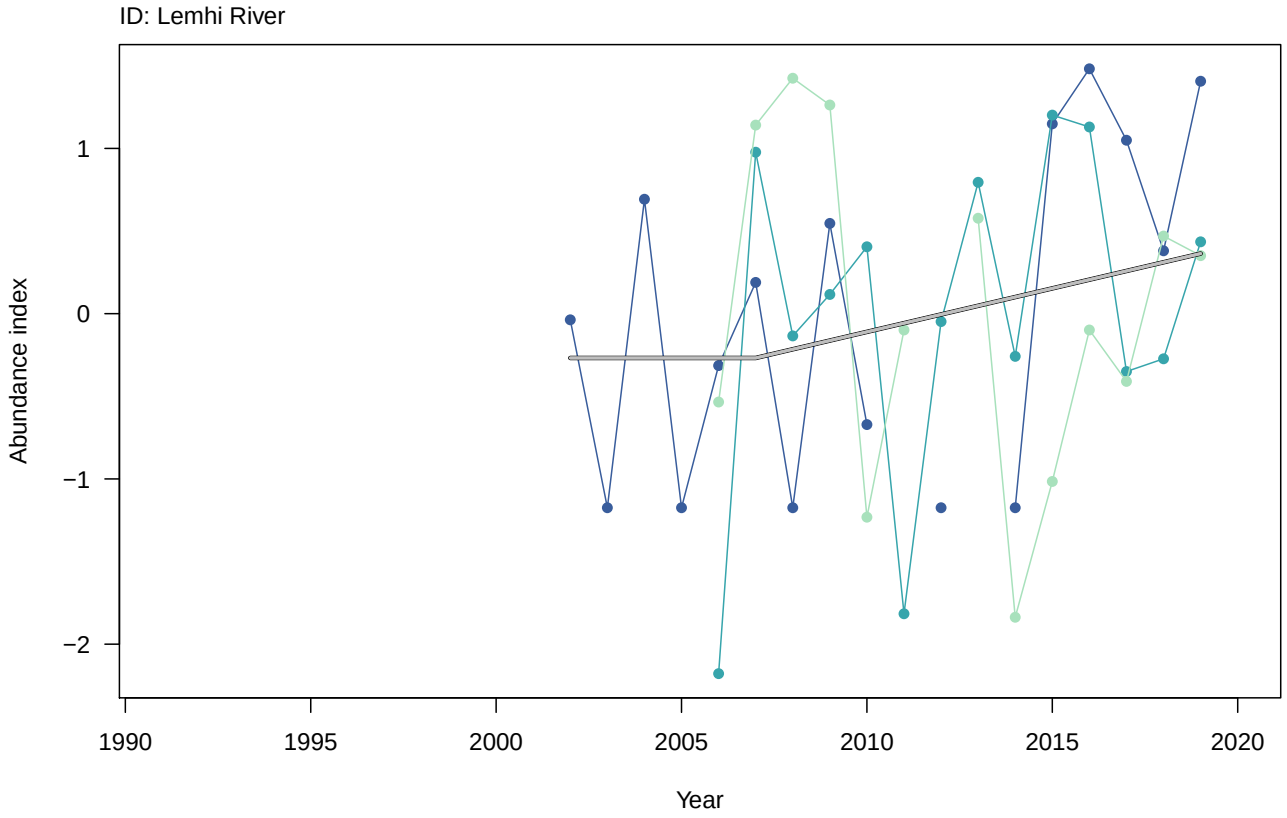
230


ID: Selway River
Abundance index
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
1990
1995
2000
2005
2010
2015
2020
Year

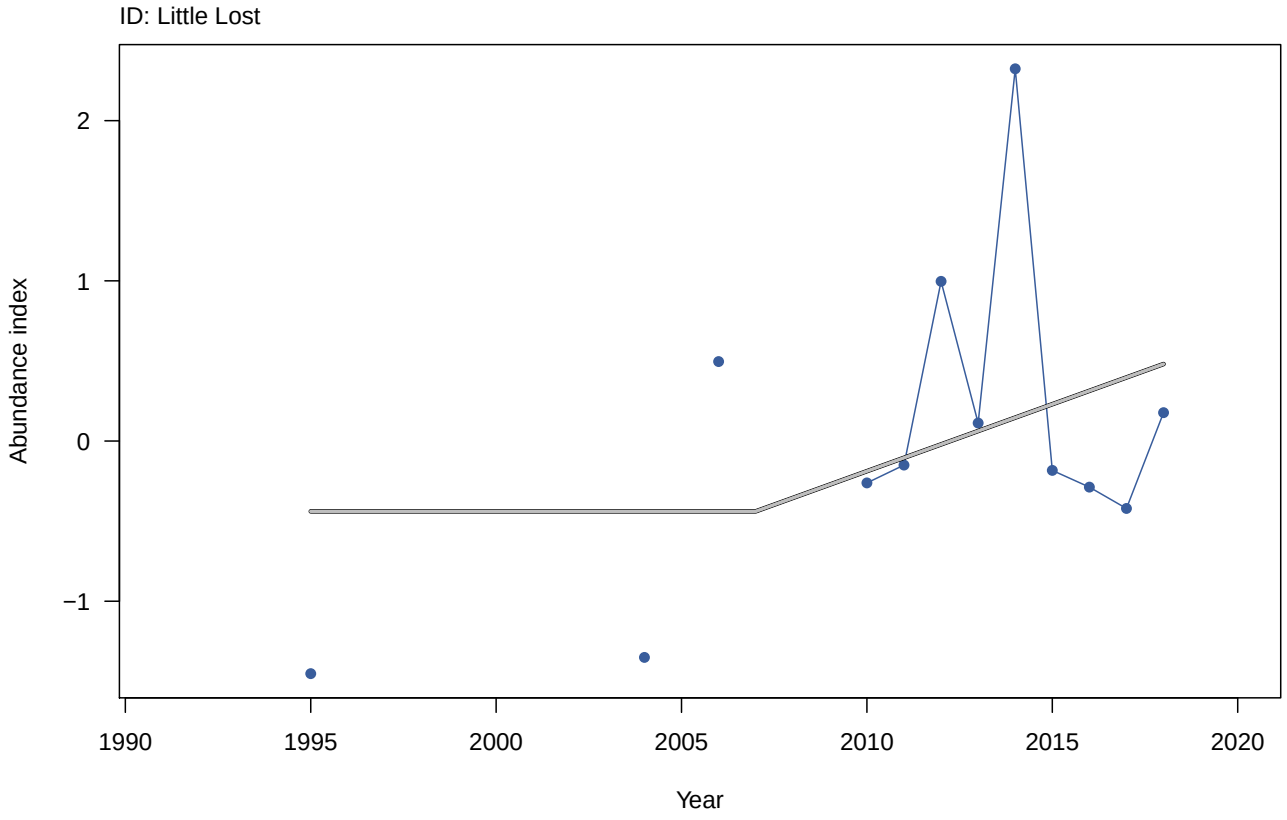
231


ID: South Fork Clearwater
Abundance index
2
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

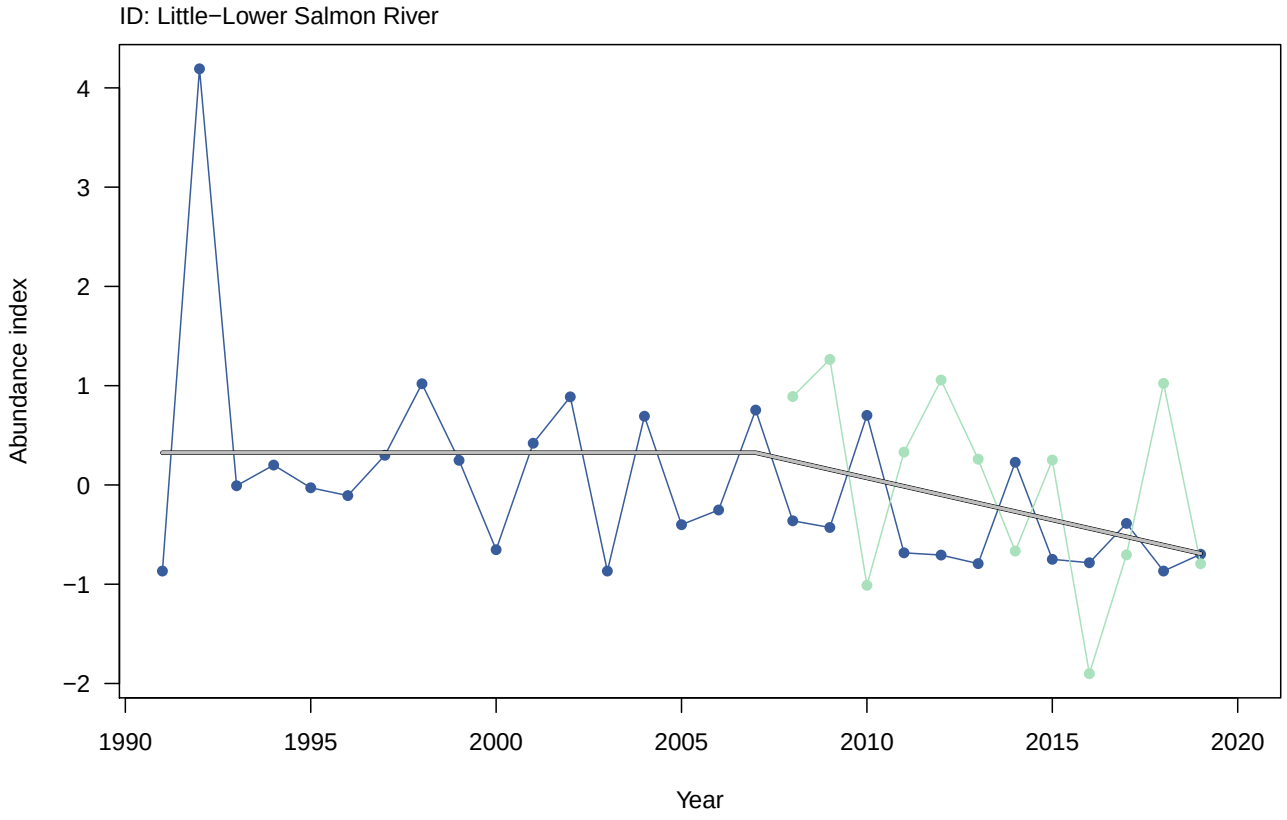
232


ID: Lemhi River
Abundance index
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

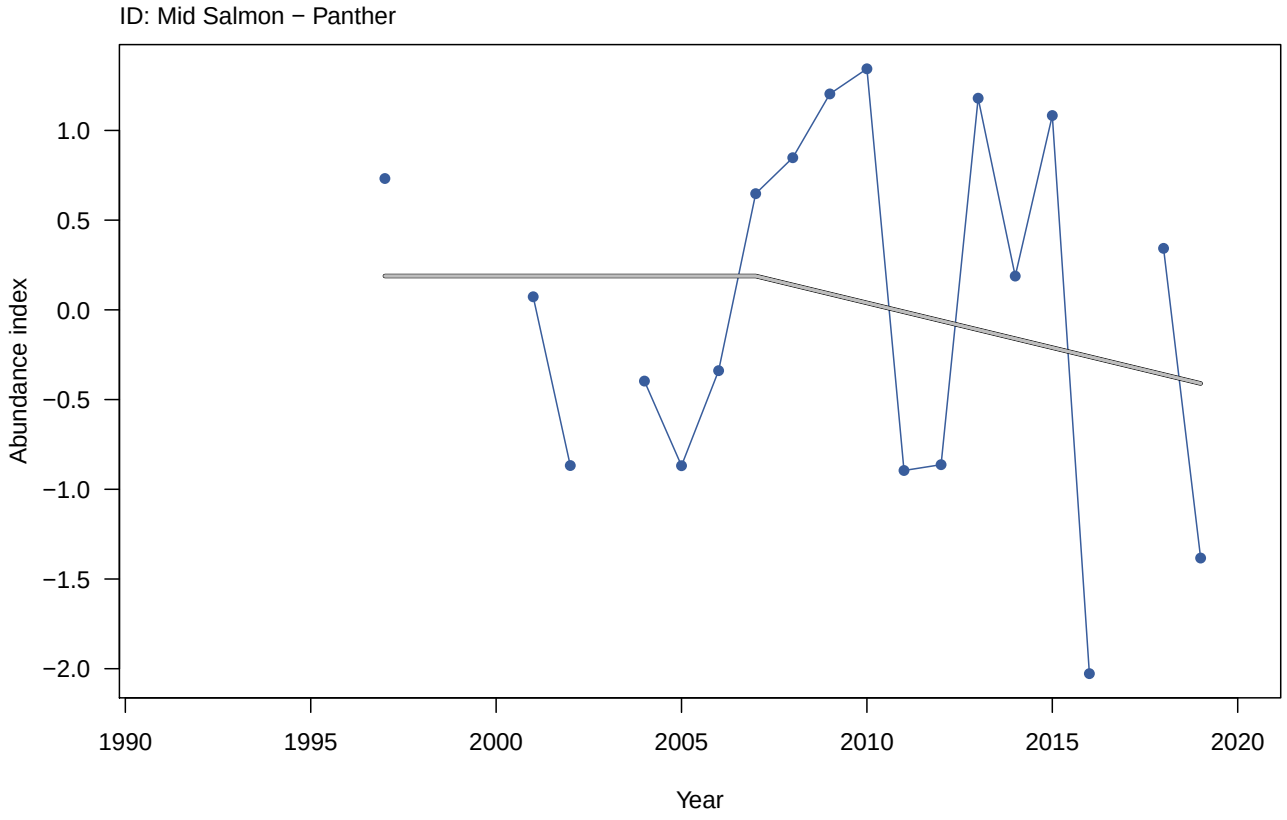
233


ID: Little Lost
Abundance index
2
1
0
−1
1990
1995
2000
2005
2010
2015
2020
Year

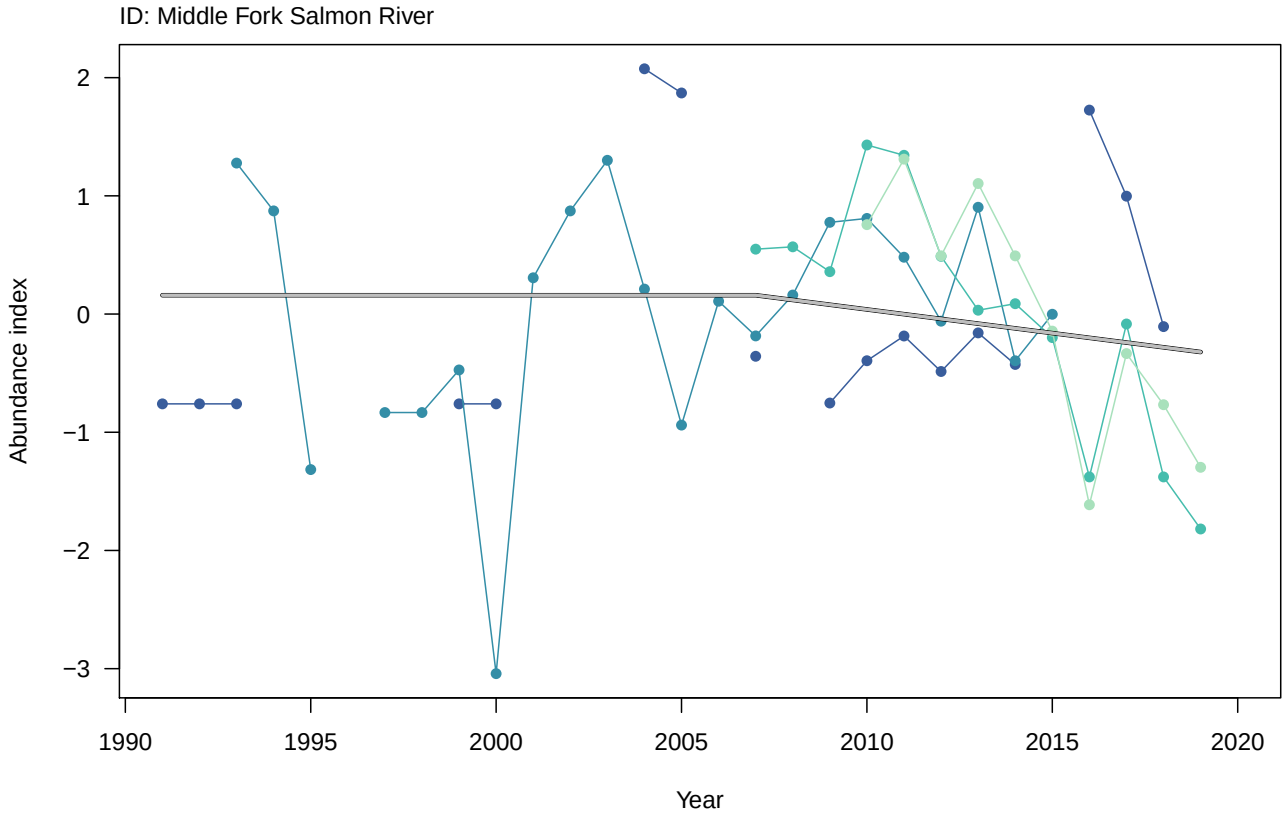
234


ID: Little−Lower Salmon River
Abundance index
4
3
2
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

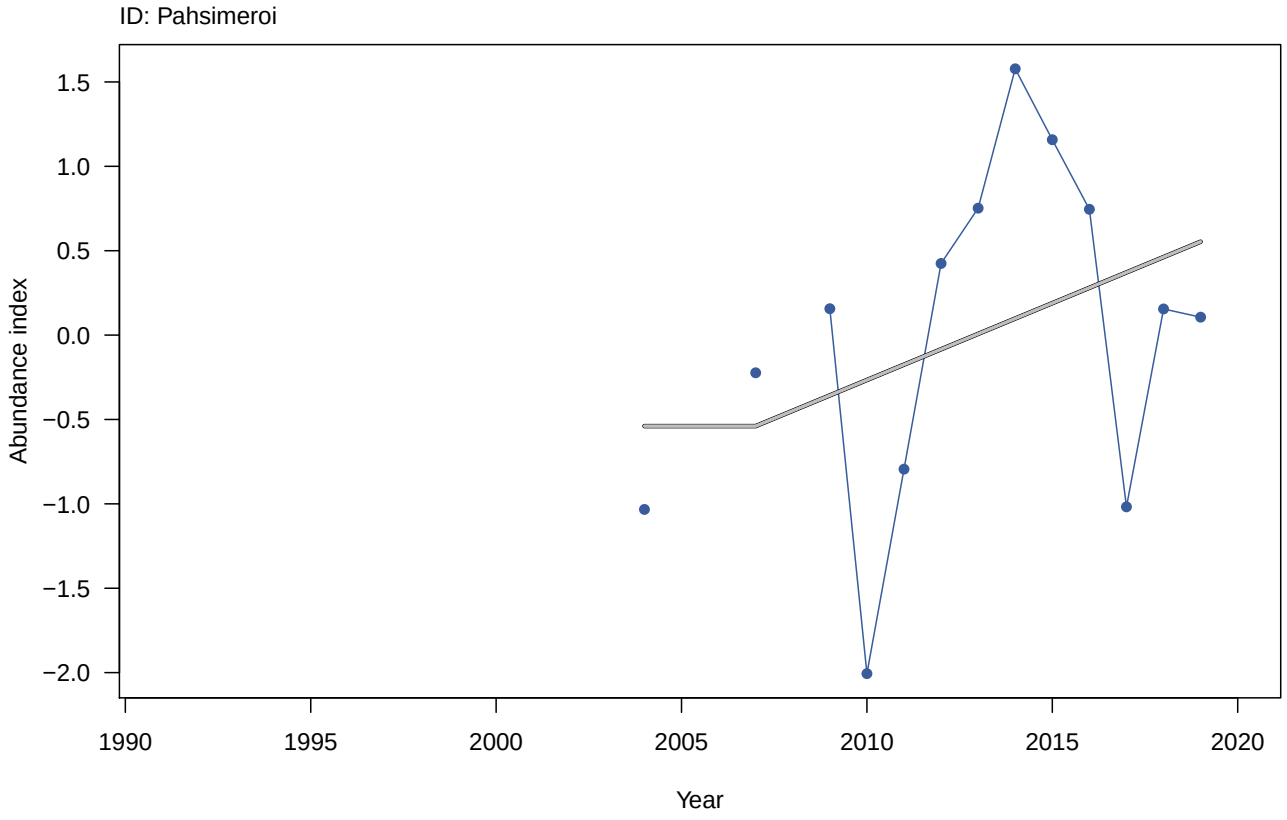
235


ID: Mid Salmon − Panther
Abundance index
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
1990
1995
2000
2005
2010
2015
2020
Year

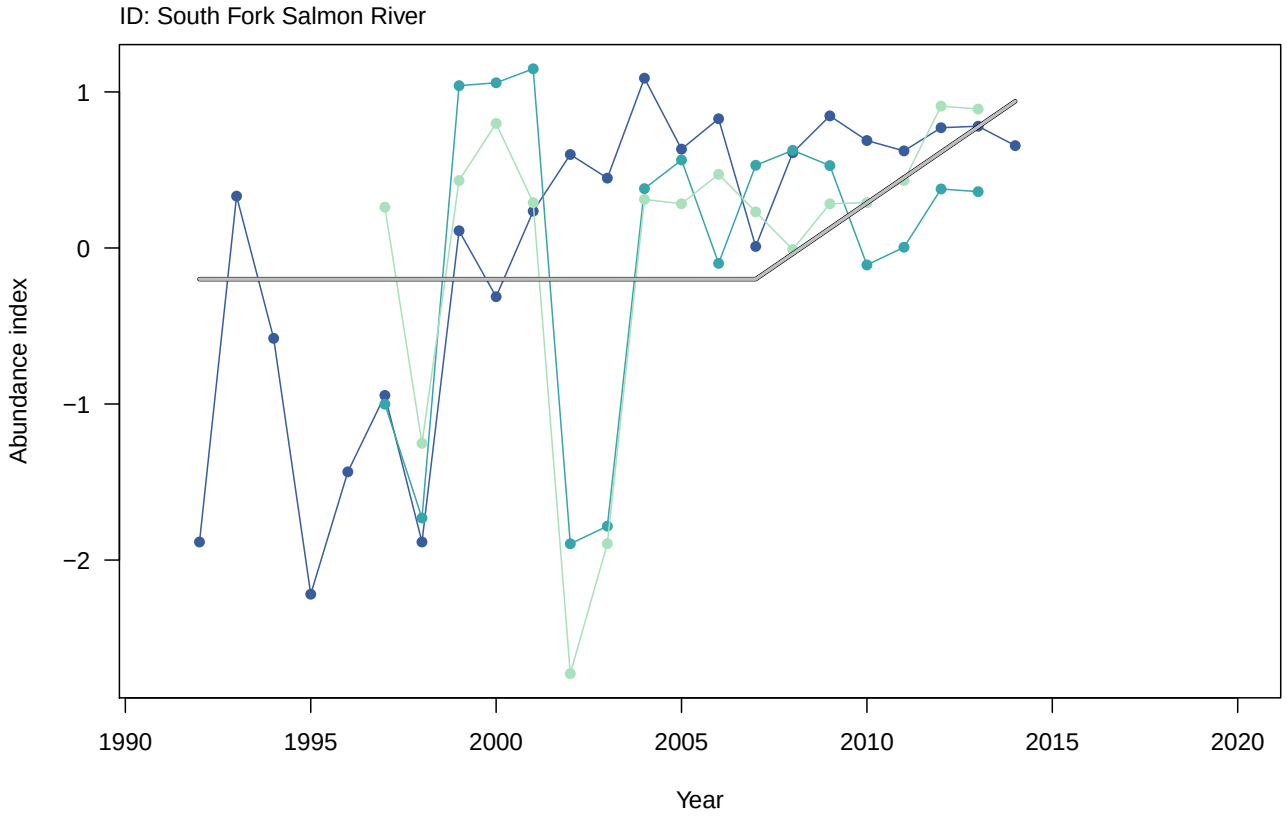
236


ID: Middle Fork Salmon River
Abundance index
2
1
0
−1
−2
−3
1990
1995
2000
2005
2010
2015
2020
Year

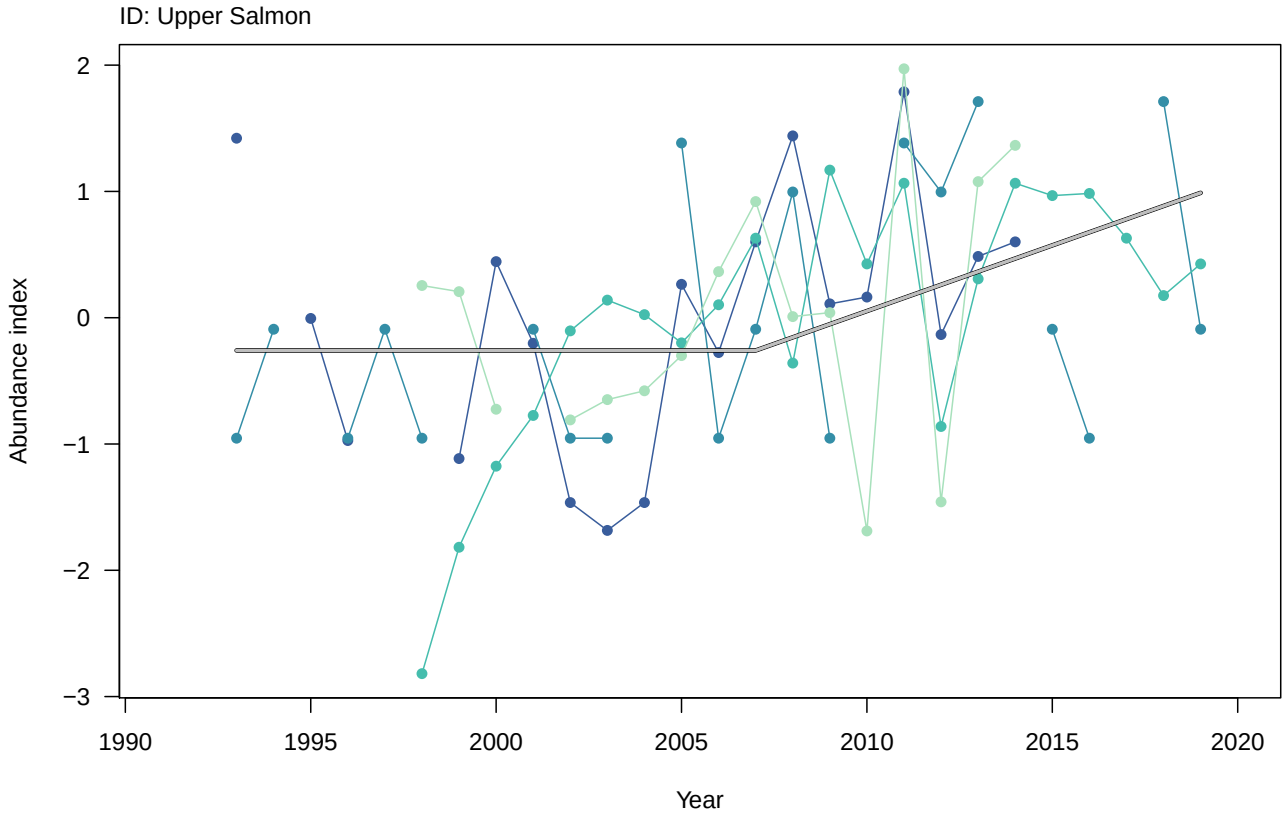
237


ID: Pahsimeroi
Abundance index
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
1990
1995
2000
2005
2010
2015
2020
Year

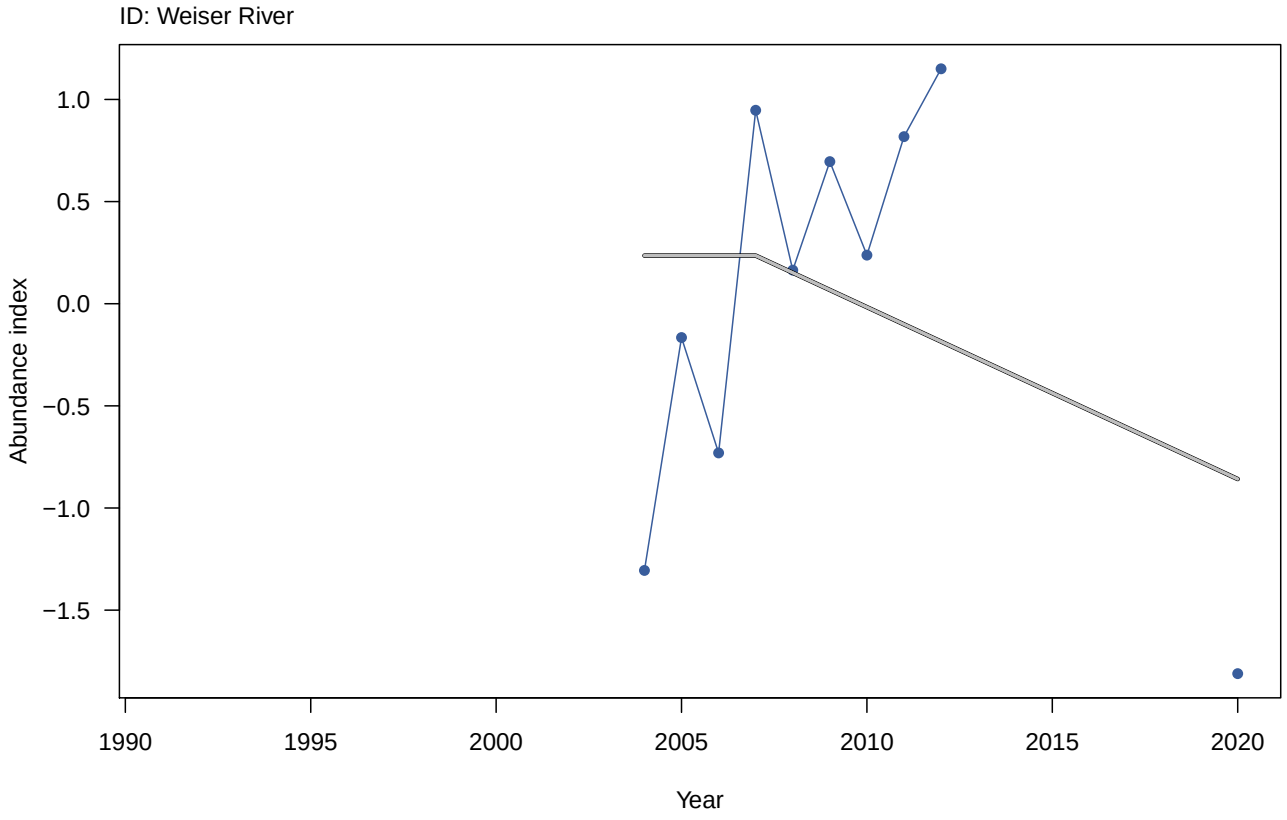
238


ID: South Fork Salmon River
Abundance index
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

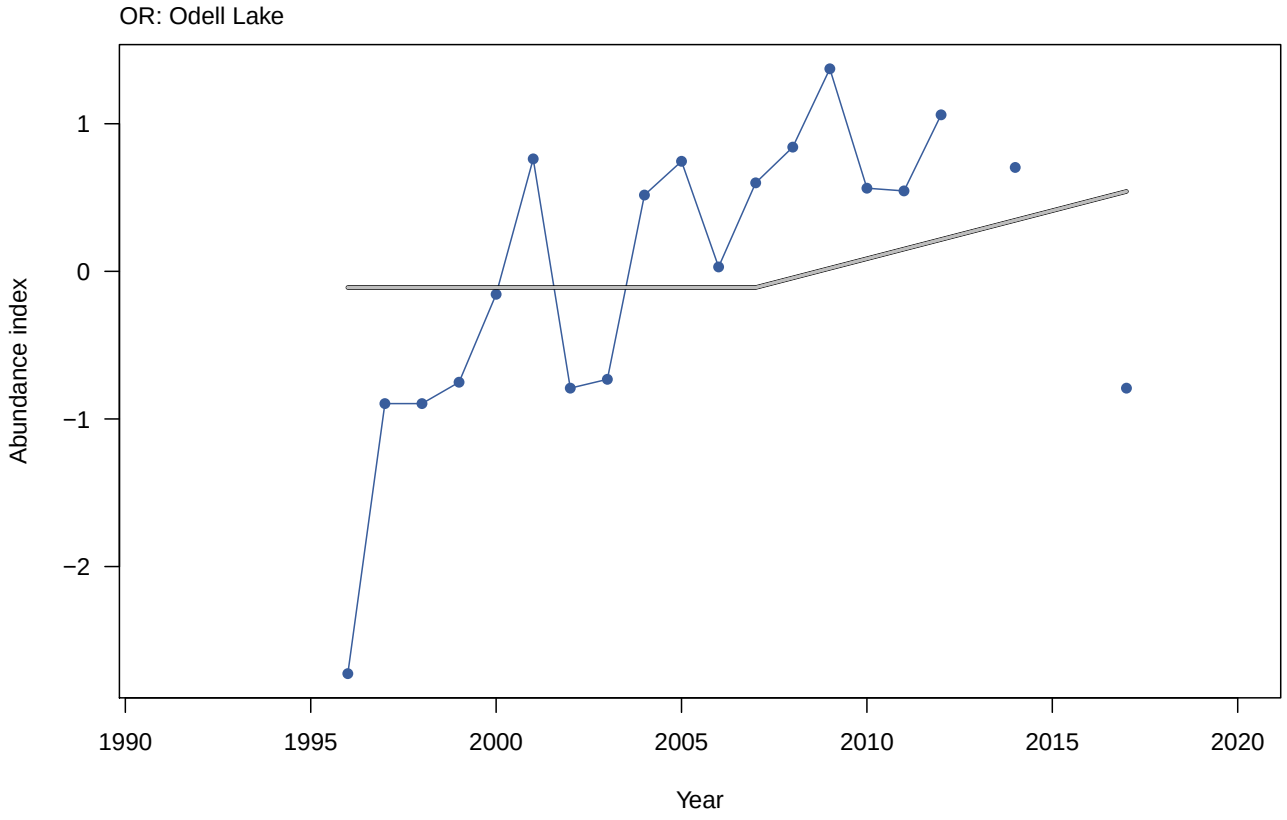
239


ID: Upper Salmon
Abundance index
2
1
0
−1
−2
−3
1990
1995
2000
2005
2010
2015
2020
Year

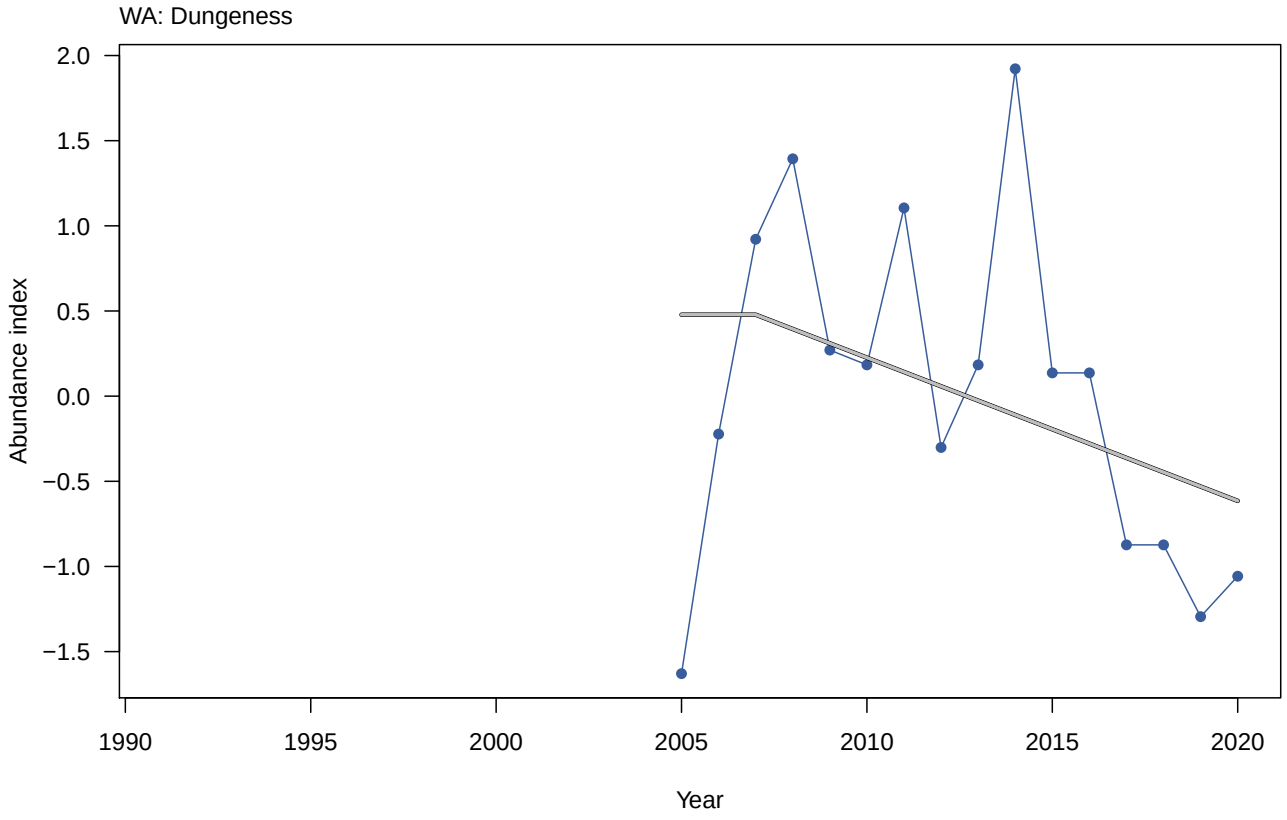
240


ID: Weiser River
Abundance index
1.0
0.5
0.0
−0.5
−1.0
−1.5
1990
1995
2000
2005
2010
2015
2020
Year

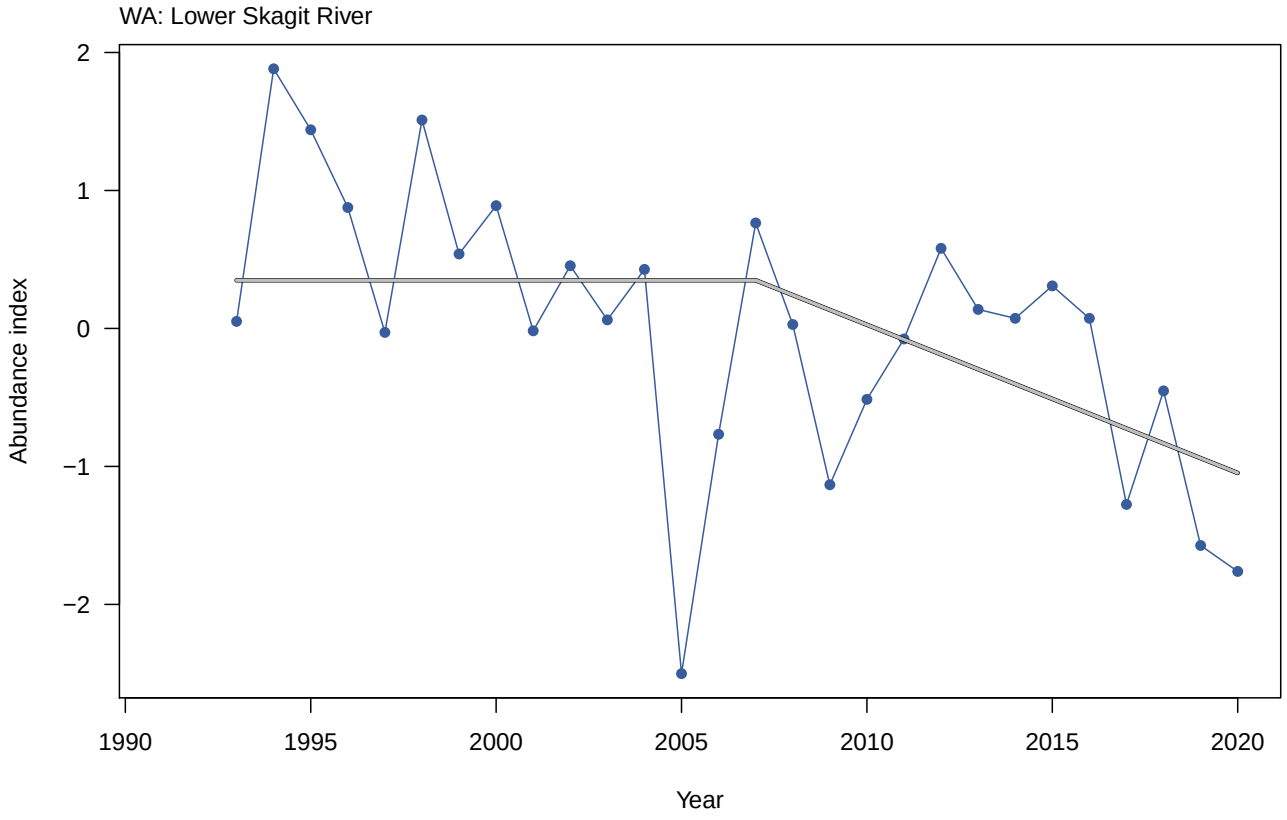
241


OR: Odell Lake
Abundance index
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

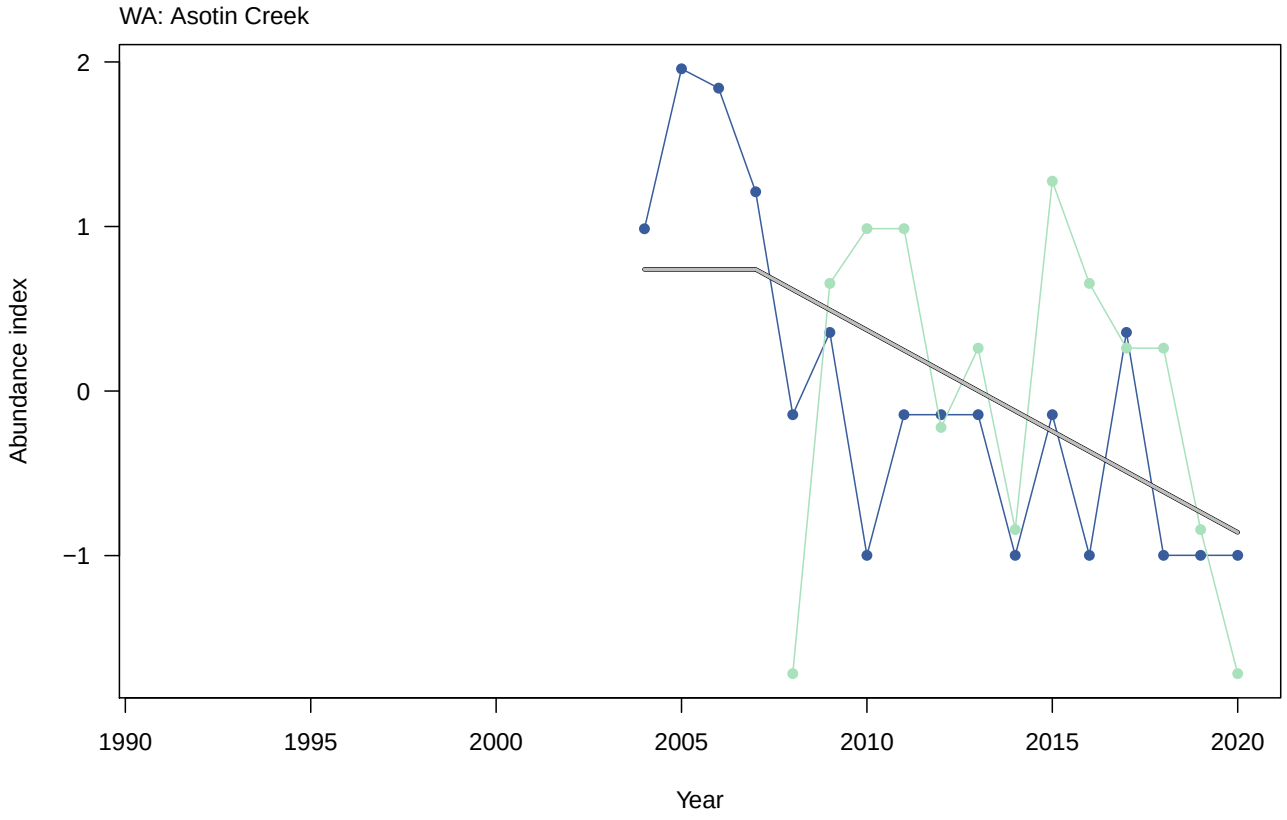
242


WA: Dungeness
Abundance index
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
1990
1995
2000
2005
2010
2015
2020
Year

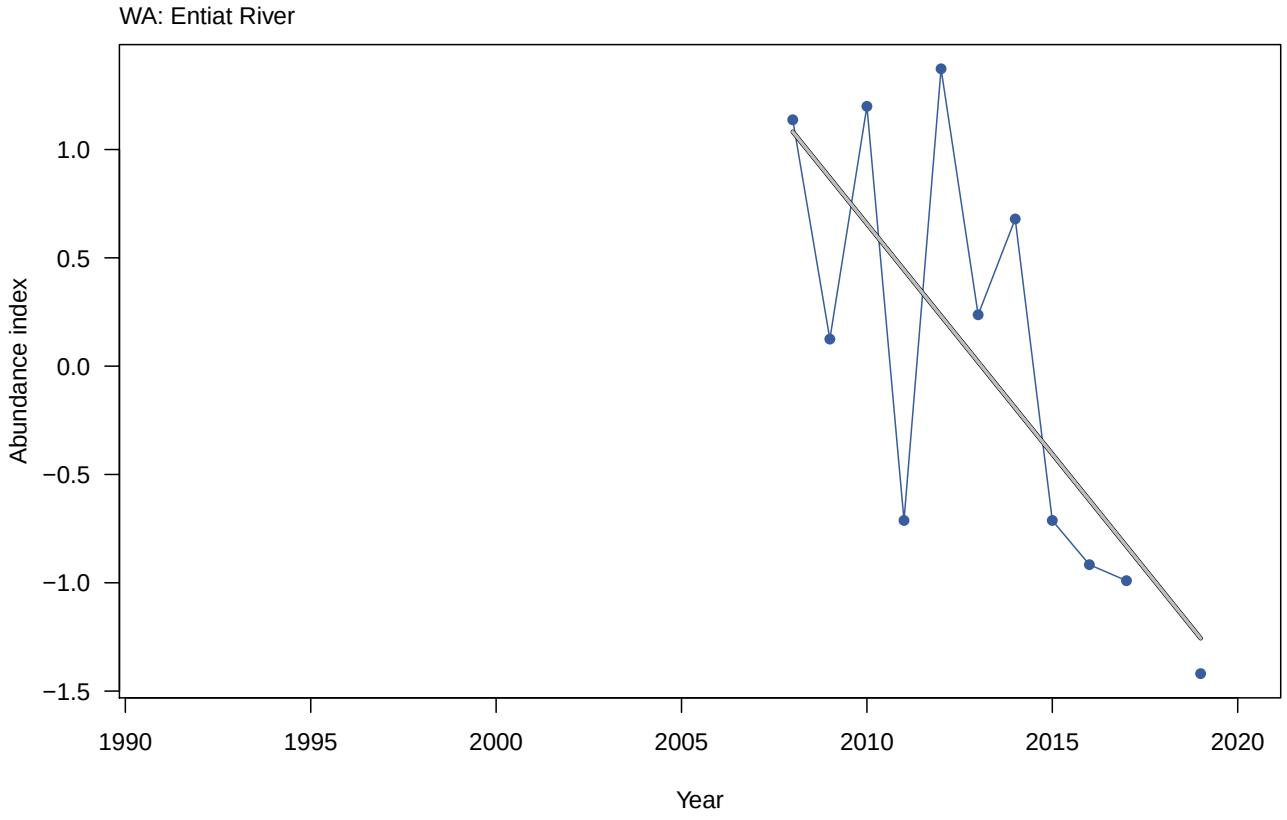
243


WA: Lower Skagit River
Abundance index
2
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year

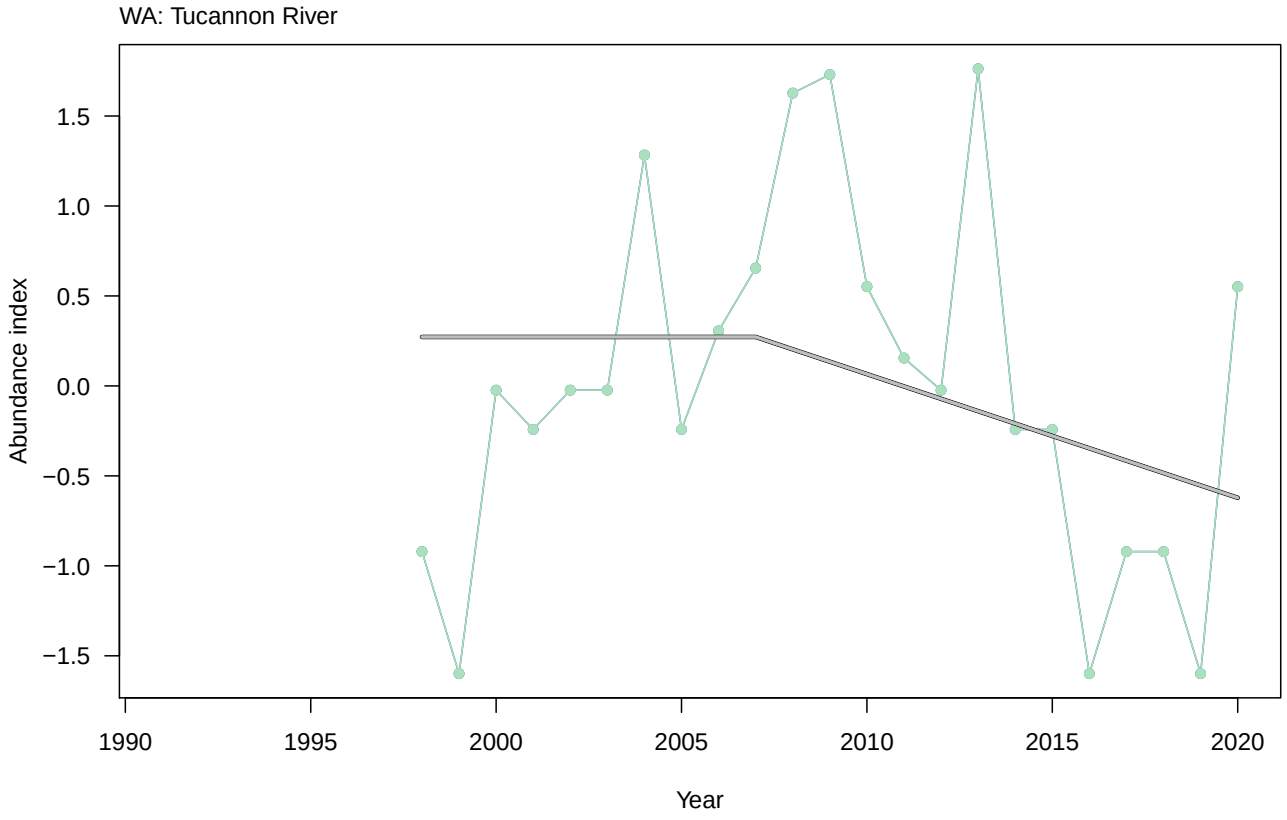
244


WA: Asotin Creek
Abundance index
2
1
0
−1
1990
1995
2000
2005
2010
2015
2020
Year

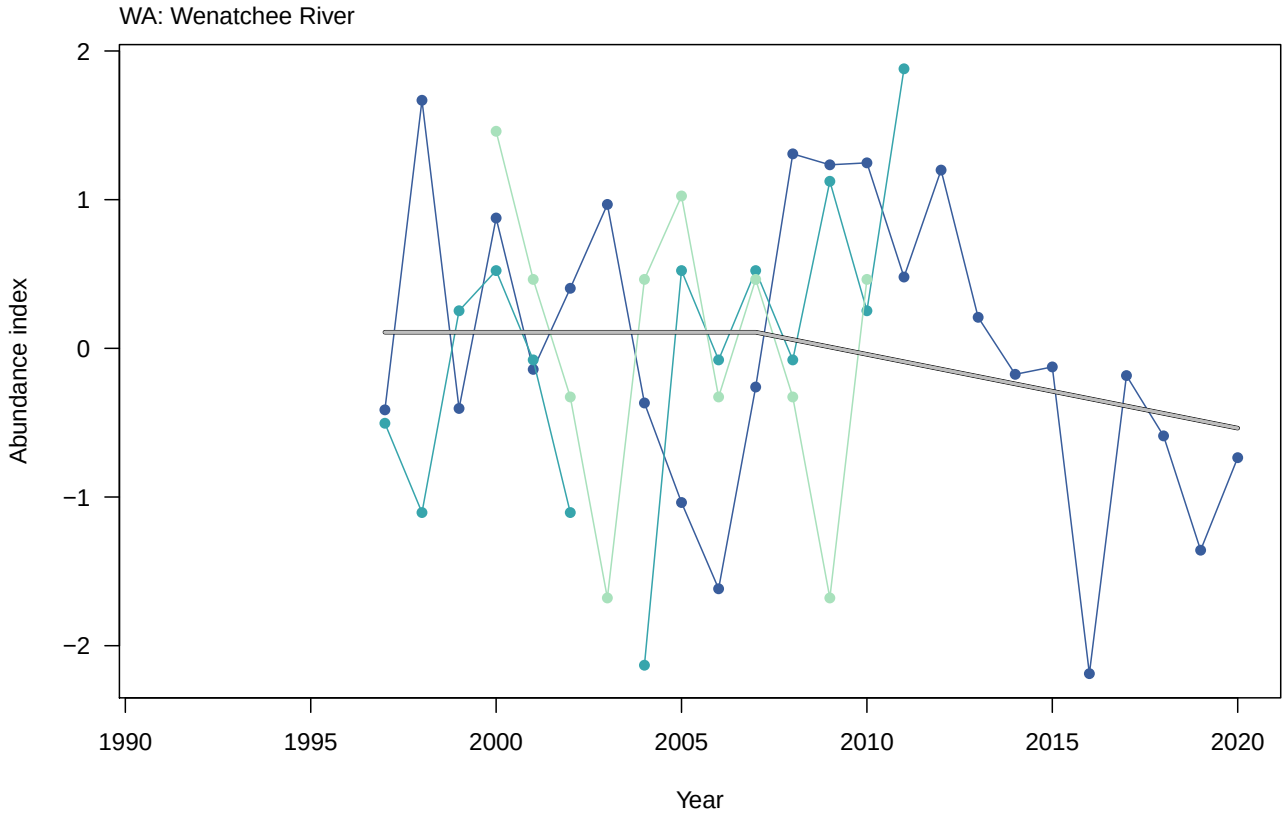
245


WA: Entiat River
Abundance index
1.0
0.5
0.0
−0.5
−1.0
−1.5
1990
1995
2000
2005
2010
2015
2020
Year

246


WA: Tucannon River
Abundance index
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
1990
1995
2000
2005
2010
2015
2020
Year

247


WA: Wenatchee River
Abundance index
2
1
0
−1
−2
1990
1995
2000
2005
2010
2015
2020
Year