Technical Memorandum

To: Columbia River CWR Project Team

From: Marcía Snyder, Nathan Schumaker, and Joe Ebersole

Date: August 16, 2020

Subject: HexSim migration corridor simulation model results

Background

To explore how cold water refuge (CWR) use influences fish fitness outcomes we developed a migration corridor simulation model in the HexSim modeling platform (Snyder et al. 2019) and used it to understand how CWR availability could potentially influence fish fitness in the Columbia River. HexSim is a dynamic, spatially-explicit individual-based modeling platform which has been frequently used to study the effect of landscape disturbance on a wide range of taxa (Schumaker and Brookes 2018). In HexSim, we developed a part probabilistic and part mechanistic model using the best available knowledge and data. The migration corridor simulation model tracks an individual's thermal exposure, energy consumption, and survival during migration. The model incorporates fish behavior, natural history, and bioenergetics and allows us to scale up from individual behaviors to population level effects. In the model, thermal conditions and fish behavior interact to determine overall fish exposure which is translated into fish fitness metrics.

The model runs on an hourly time step from July 1 to October 31. Individuals in the model migrate through the Columbia River passing through three hydropower structures starting upstream of the Bonneville dam and ending at the Snake River confluence. Swim speed and bioenergetic activity cost vary by location: hydropower tailrace, fish ladder, open reservoir, or cold water refuge. Actual fish must swim through some upstream section of the Columbia or Snake Rivers and up into adjacent tributaries to reach spawning grounds. The cost of doing so will vary depending on the individual's time of arriving at the confluence, remaining distance to and location of their spawning grounds. At present, our model cannot forecast the energetic cost of this segment of migration, and we do not have data sufficient to construct an analytic approximation. For more detailed information on model function, parameterization, and calibration see Snyder et al. 2019 and the associated Appendices.

Assumptions/Simplifications

In a system this complex there will be some simplifications based on limited understanding and availability of information. Simulation modeling is meant to approximate the important system drivers not be an exact replica. Following, we list a few important simplifications. However, this is not a comprehensive list of assumptions.

- Simulated fish do not distinguish between CWR based on quality. Warm, lower oxygen, small, or low substrate quality refuges are equally available and desirable to the fish in the model. While, temperature does not influence the selection of cold water refuges it does influence the outcome of the selection on fish fitness.

- Some fish behaviors, such as residence times in cold water refuges, are simulated probabilistically in the model and thus are simplifications of actual fish behavior.

- Simulated fish swim speeds are drawn from a distribution, but are fixed for any individual. Actual fish may adjust their swim speed in an attempt to lower exposure to high temperatures.

- Further, our bioenergetics equations do not take into account the fish swim speed, but instead account only for temperature and body size. We made the simplifying assumption that the possible thermal benefits of swimming faster were matched by the energetic cost of exerting extra energy.

- In addition, to simplifications to fish behavior and physiology, the simulated riverscape which includes temperature, volume, and depth maps, all have associated temporal and spatial uncertainties.

Experimental Approach

We used the model to explore how thermal conditions and the availability of CWR influenced fish fitness measures. These experiments were designed to assess the potential of CWRs to improve the condition of the migrating salmon and trout. We simulated the migration performance of four fish populations under differing thermal conditions.

To simulate differing thermal conditions, we varied either the temperature of the Columbia River or the availability of CWRs, or both. We created hourly thermal conditions for the experiments based on two different temperature time series for the current Columbia River. One is based on a long-term average of recent temperatures (average from 1992-2016) and the other is based on more recent temperatures (2017). The more recent temperature condition, from 2017, is not an average and therefore has a greater range of values than the long-term average. The future Columbia River year 2040 conditions were created by adding 1 °C to the current temperature time series for the Columbia River. The historic Columbia River conditions were created by subtracting 2 °C from the current temperature time series for the Columbia River.

Table 1. Table summarizing the temperature conditions of the scenarios run in the HexSim migration corridor simulations.

	CWR available	*CWR not available*
Current Columbia River temperature long term average (1992-2016)	Historic	Historic
	Current	Current
	Future Year 2040	Future Year 2040
Current Columbia River temperature recent condition (2017)	Current	Current
	Future Year 2040	Future Year 2040
	Additional CWRs Added	

Our experiments examined how the availability of CWRs can influence fish condition at the Snake River confluence by simulating thermalscapes under historic, current, and predicted future Columbia River temperatures with CWRs and with CWRs unavailable. Additionally, we evaluated how additional CWRs in the reaches of the migration corridor with low quantities of coldwater refuges (John Day and McNary

pools) would influence fish conditions. Additionally, we simulated an uncertainty analysis of the relationship between acute temperature stress and survivorship.

The four populations we simulated are specified in the model using distinct entry time and initial weight distributions:

1. Tucannon Summer Steelhead
2. Grande Ronde Summer Steelhead
3. Snake River Fall Chinook salmon
4. Hanford Reach Fall Chinook salmon

Table 2. Entry time and initial weight distributions as specified in HexSim migration corridor simulation model. Distributions were summarized from Jepson et al. 2010, Keefer et al. 2009, and Keefer (unpub) data.

	Mean weight (g)	Standard deviation Weight (g)	Median run timing	Standard deviation run timing (d)
Tucannon Summer Steelhead	4836	1060	July 17	15
Grande Ronde Summer Steelhead	5092	1674	August 5	15
Snake River Fall Chinook salmon	4279	2088	September 3	6.5
Hanford Reach Fall Chinook salmon	5320	2720	September 10	8

For simulations with the Columbia River temperature based on year 2017 only Grande River summer steelhead and Snake River Fall Chinook Salmon populations were modeled.

Results

The following figures and tables summarize some of the results from these experiments. For each scenario, populations were simulated separately because volume of cold water does not seem to be limiting use of the majority of cold water refuges. Simulated fish condition outputs are typically depicted as a distribution of values. Results are organized by population, i.e. all results for Grande Ronde River steelhead from the six scenarios based on Columbia River long-term average are analyzed and displayed together. For each population and scenario, cumulative temperature exposure, then, energy remaining, acute mortality, and exit dates are summarized. First included are results from the Columbia River long term average scenarios. Then, we append, summary results, for the four scenarios based on the Columbia River year 2017 temperatures.

Sections
Long-term average Columbia River temperatures:
      1. Cumulative degree days summary results for Tucannon River summer steelhead under long-

term average temperatures for the Columbia River

2. Energy use, CWR use, and survivorship results for Tucannon River summer steelhead under long-term average temperatures for the Columbia River

3. Cumulative degree days summary results for Grande Ronde River summer steelhead under long-term average temperatures for the Columbia River

4. Energy use, CWR use, and survivorship results for Grande Ronde River summer steelhead under long-term average temperatures for the Columbia River

5. Cumulative degree days summary results for Snake River Fall Chinook Salmon under long-term average temperatures for the Columbia River

6. Energy use, CWR use, and survivorship results for Snake River Fall Chinook Salmon under long-term average temperatures for the Columbia River

7. Cumulative degree days summary results for Hanford Reach Fall Chinook Salmon under long-term average temperatures for the Columbia River

8. Energy use, CWR use, and survivorship results for Hanford Reach Fall Chinook Salmon under long-term average temperatures for the Columbia River

Year 2017 Columbia River temperatures:

9. Cumulative degree days summary results for Grande Ronde River summer steelhead under year 2017 temperatures for the Columbia River

10. Energy use, CWR use, and survivorship results for Grande Ronde River summer steelhead under year 2017 temperatures for the Columbia River

11. Cumulative degree days summary results for Snake River Fall Chinook Salmon under year 2017 temperatures for the Columbia River

12. Energy use, CWR use, and survivorship results for Snake River Fall Chinook Salmon under year 2017 temperatures for the Columbia River

Acute temperature stress sensitivity:

13. Sensitivity testing of acute temperature stress curve

Additional simulated coldwater refuges:

14. Cumulative degree days summary results for Grande Ronde River summer steelhead under year 2017 temperatures for the Columbia River with simulated additional coldwater refuges

15. Energy use, CWR use, and survivorship results for Grande Ronde River summer steelhead under year 2017 temperatures for the Columbia River with simulated additional coldwater refuges

16. Cumulative degree days summary results for Snake River Fall Chinook Salmon under year 2017 temperatures for the Columbia River with simulated additional coldwater refuges

17. Energy use, CWR use, and survivorship results for Snake River Fall Chinook Salmon under year 2017 temperatures for the Columbia River with simulated additional coldwater refuges

1. Cumulative degree days summary results for Tucannon summer steelhead under long-term average temperatures for the Columbia River
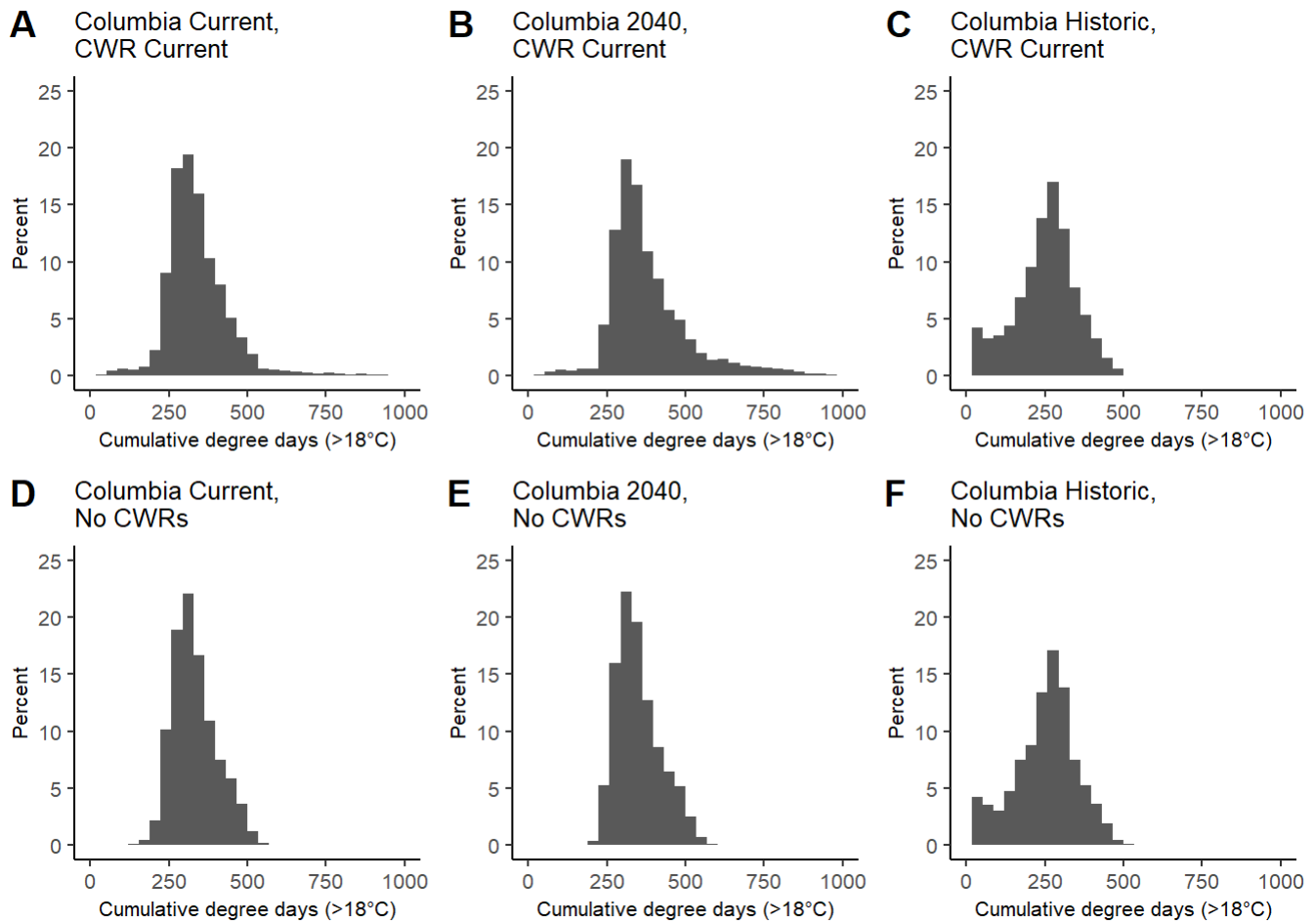

Fig. 1.1 Histograms of modeled Tucannon River summer steelhead accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.
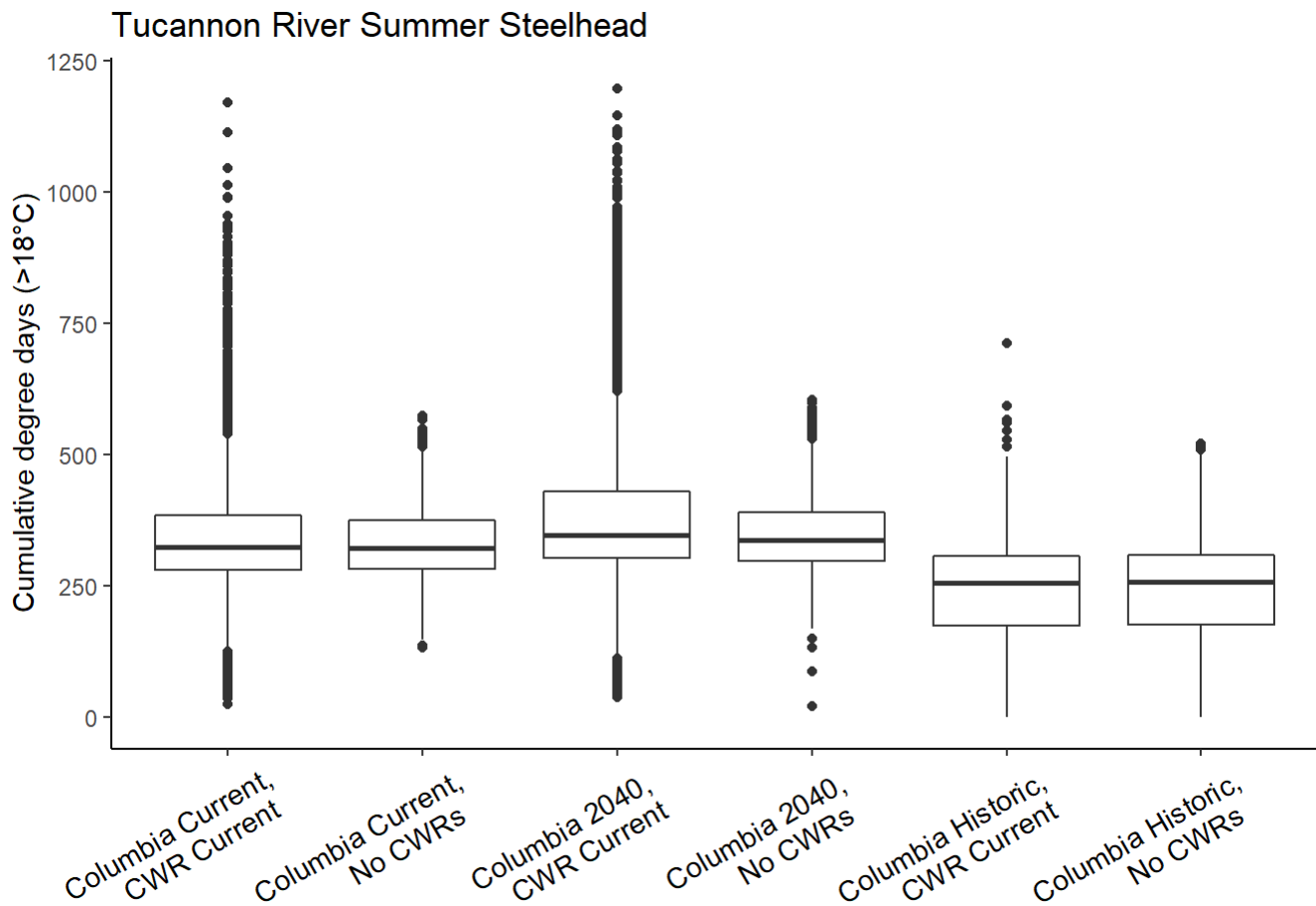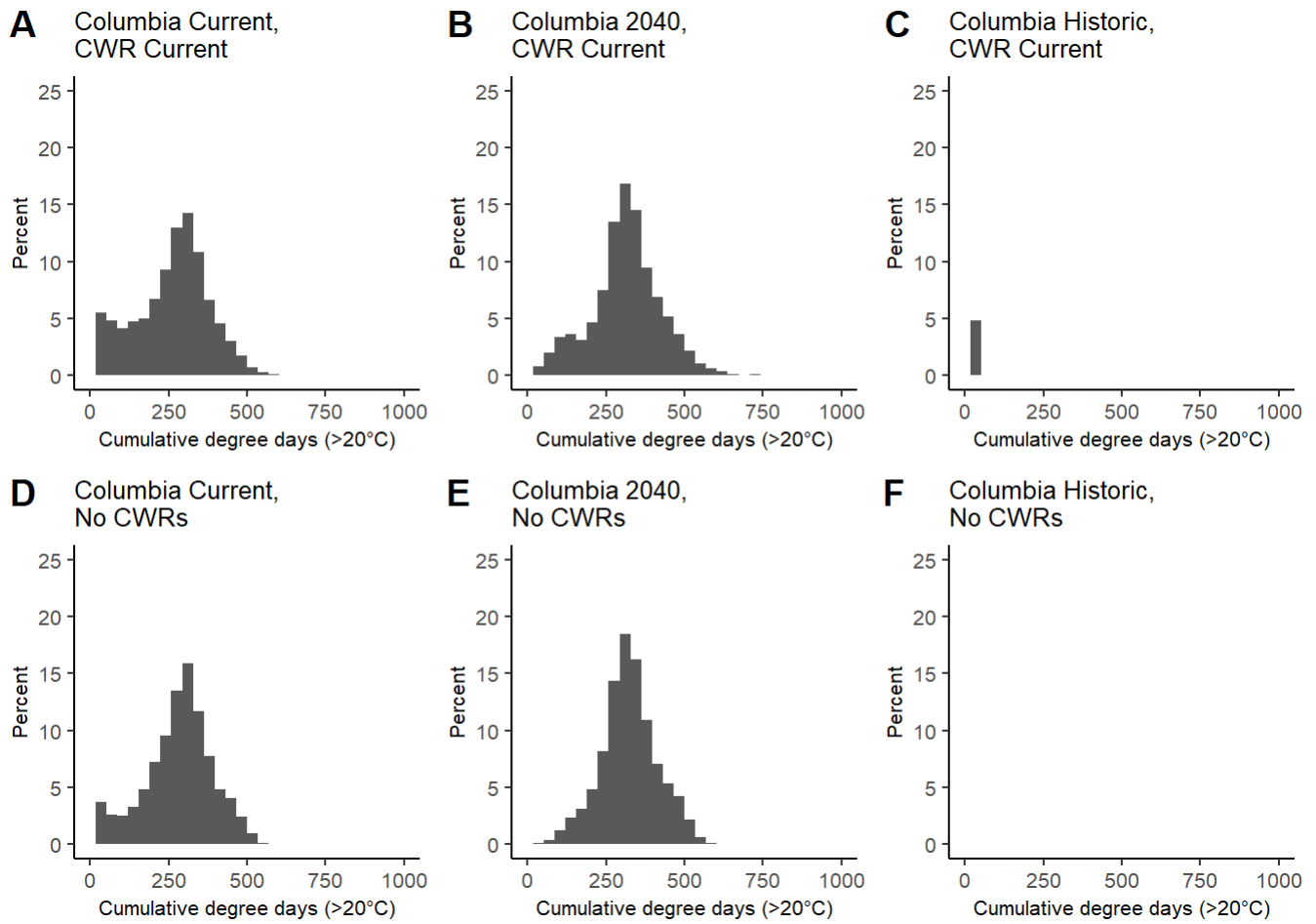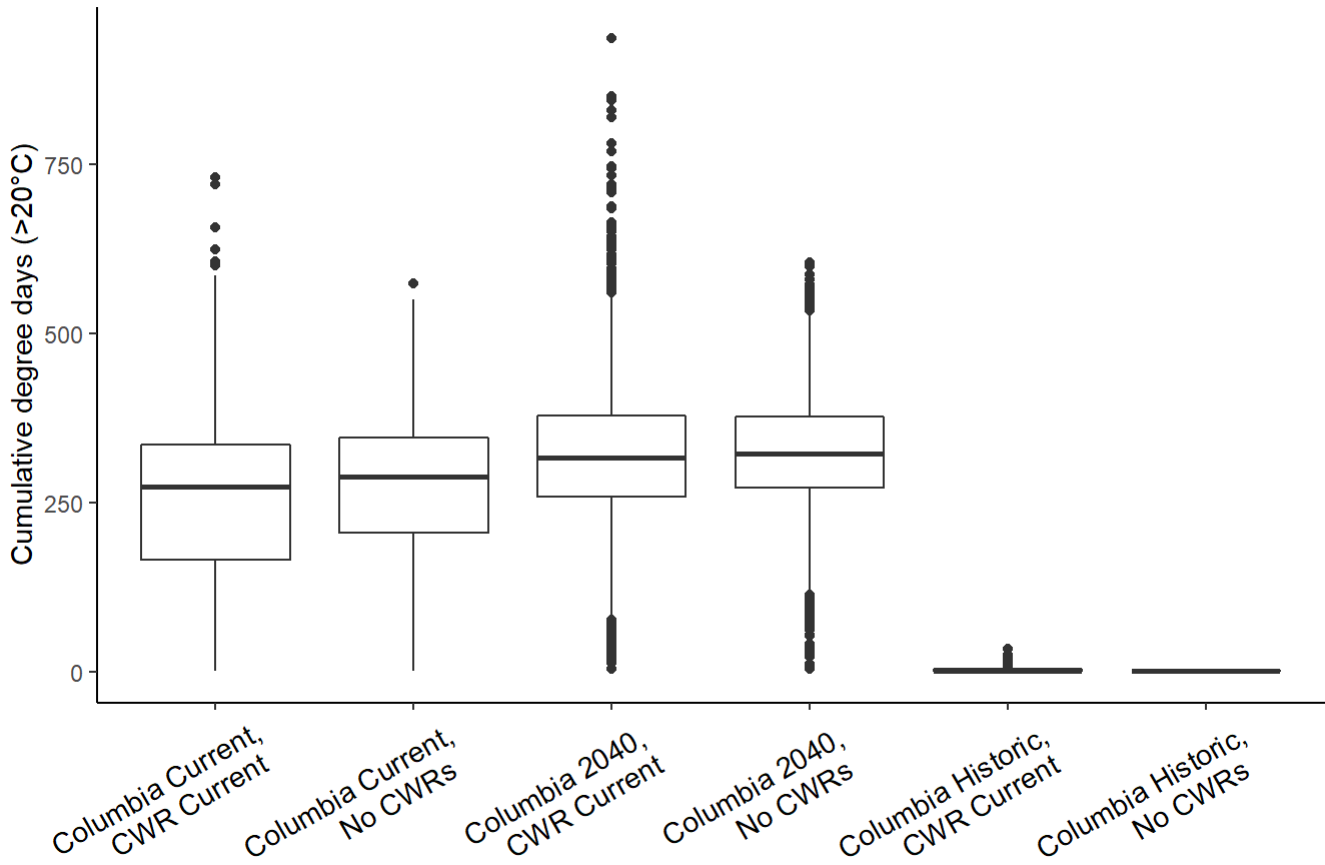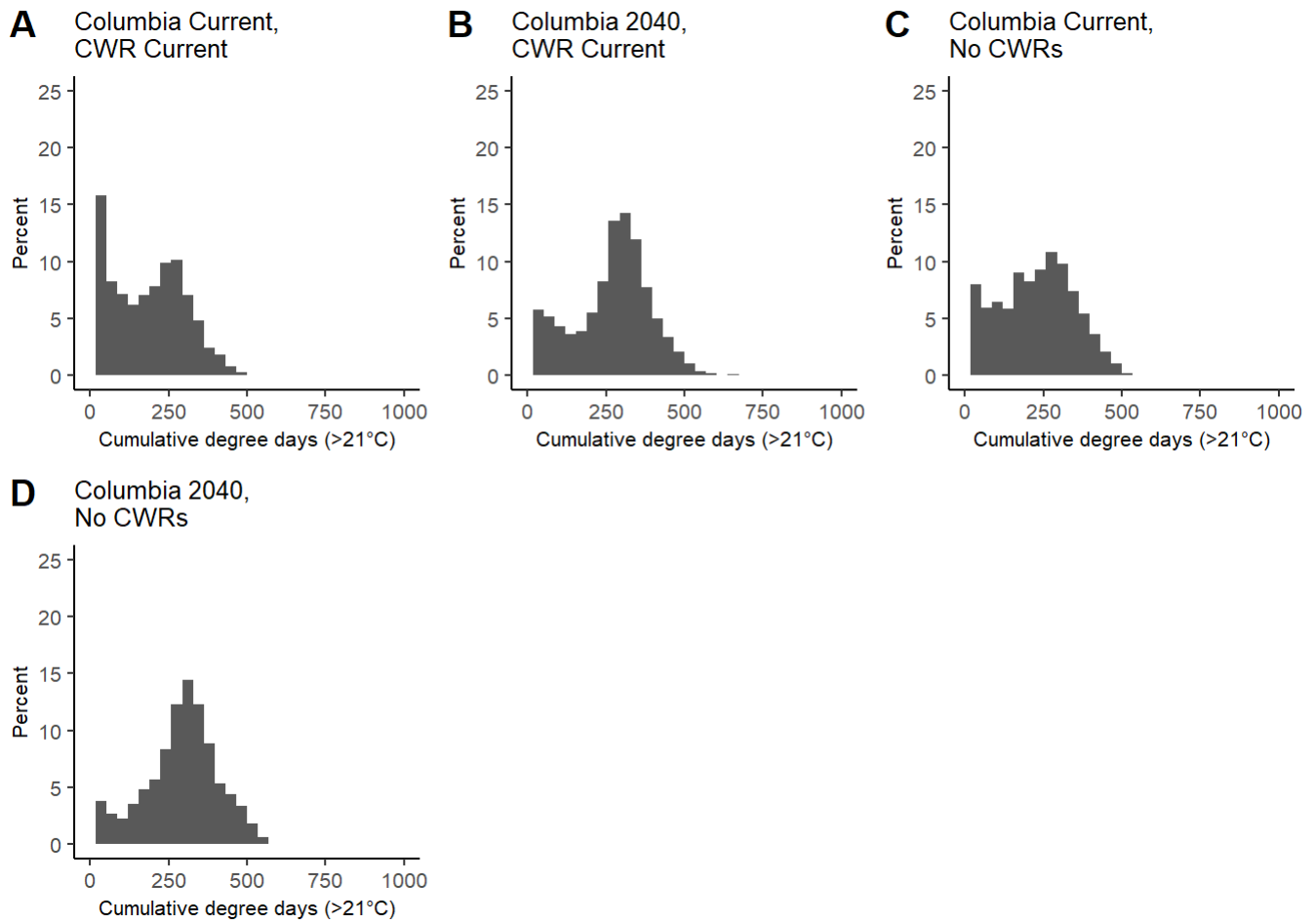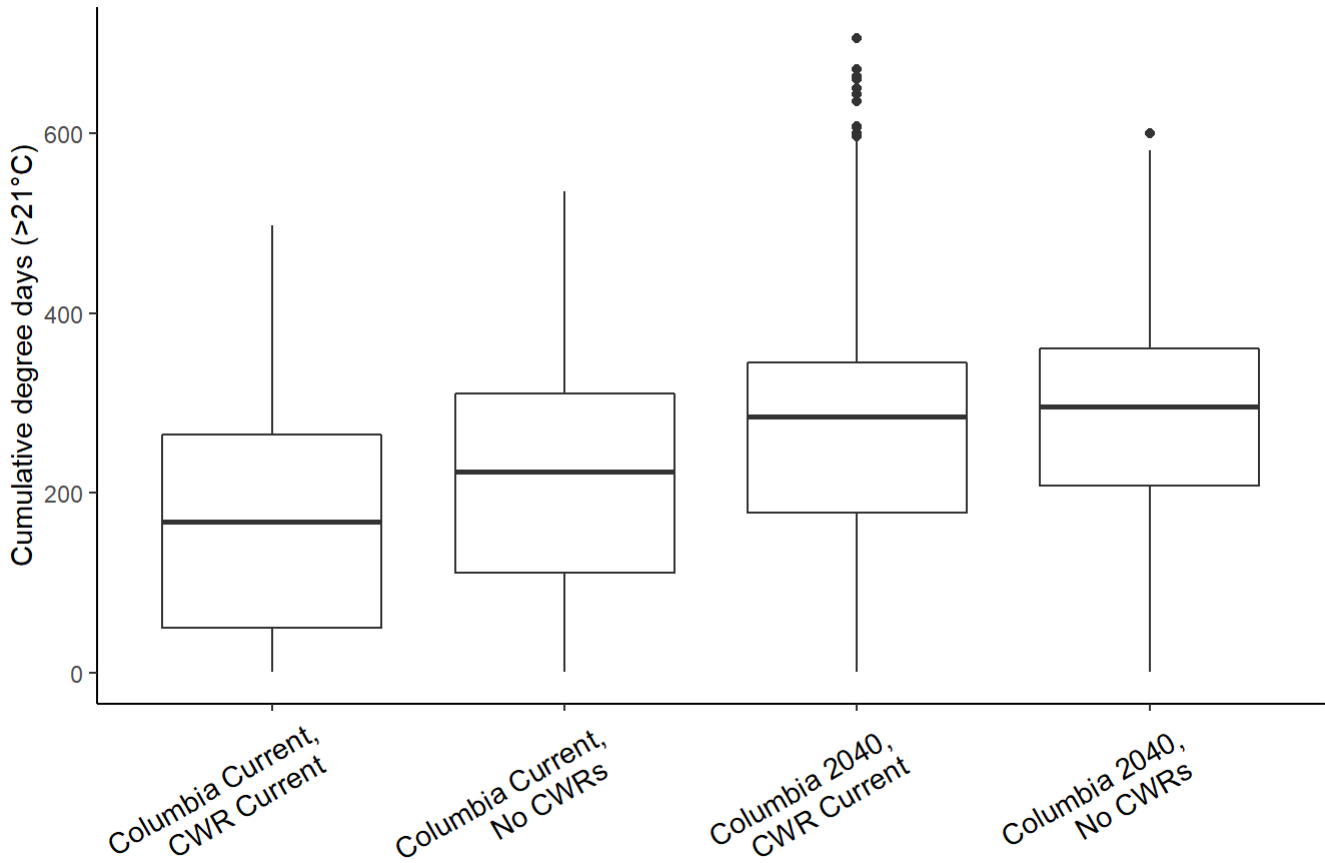
Fig. 1.2 Boxplots of modeled Tucannon River summer steelhead accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.

Table 1.1 Cumulative degree days (>18°C) used across different HexSim thermalscapes summarized for Tucannon River Summer Steelhead.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2040, CWR Current	38	303	348	431	1197
Columbia Historic, CWR Current	1	175	256	308	712
Columbia Current, CWR Current	25	281	325	385	1170
Columbia 2040, No CWRs	21	298	337	391	605
Columbia Historic, No CWRs	1	177	258	310	521
Columbia Current, No CWRs	134	282	322	375	574

Fig. 1.3 Histograms of modeled Tucannon River summer steelhead accumulated degrees day over 20°C from Bonneville to the Snake River confluence in the Columbia River.

Tucannon River Summer Steelhead

Fig. 1.4 Boxplots of modeled Tucannon River summer steelhead accumulated degrees day over 20°C from Bonneville to the Snake River confluence in the Columbia River.

Table 1.2 Cumulative degree days (>20°C) used across different HexSim thermalscapes summarized for Tucannon River Summer Steelhead.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2040, CWR Current	3	258	316	379	937
Columbia Historic, CWR Current	1	1	1	3	33
Columbia Current, CWR Current	1	165	273	336	732
Columbia 2040, No CWRs	3	272	322	377	605
Columbia Historic, No CWRs	1	1	1	1	1
Columbia Current, No CWRs	1	205	288	347	574

A Columbia Current,
CWR Current

B Columbia 2040,
CWR Current
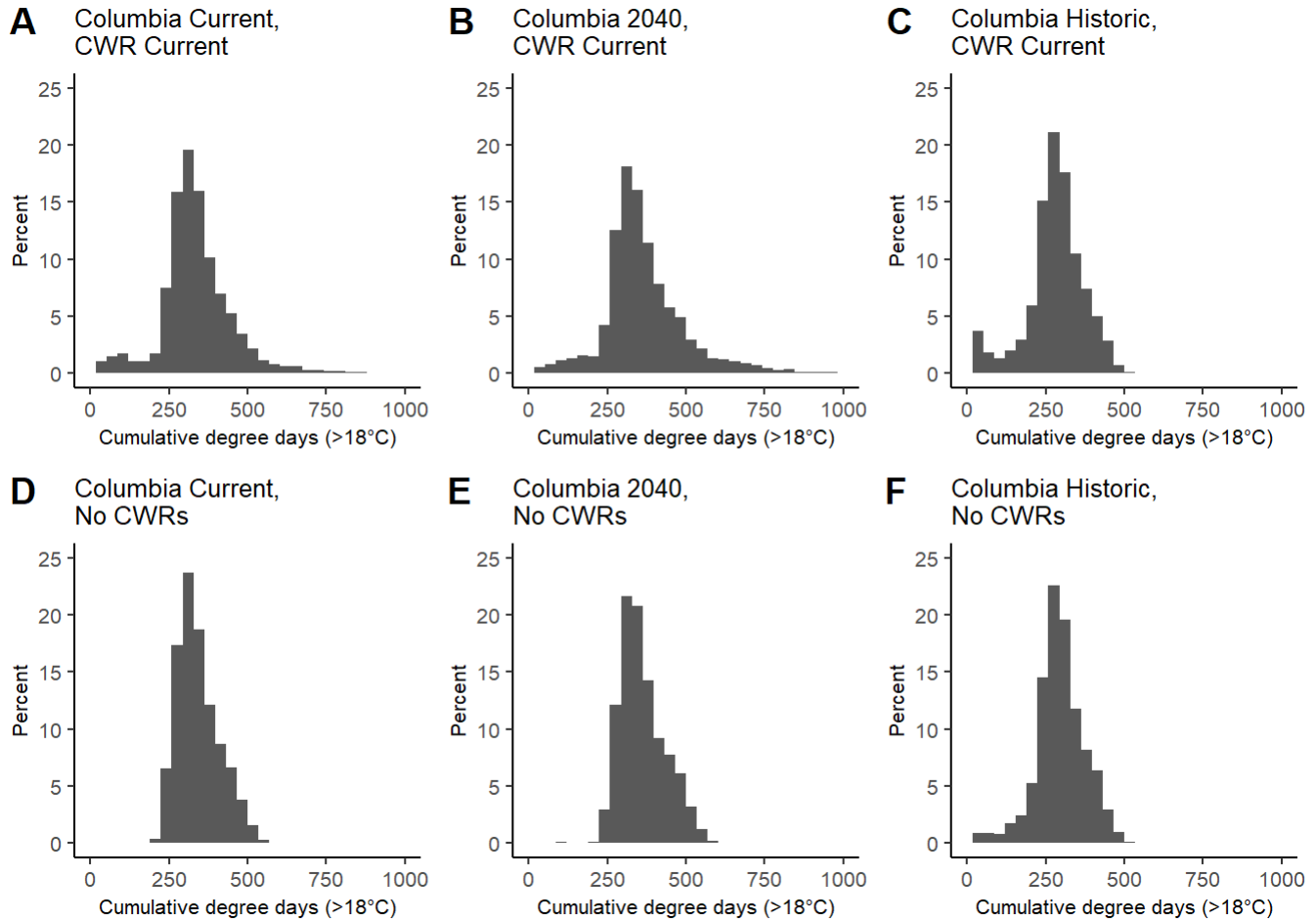
C Columbia Current,
No CWRs

D Columbia 2040,
No CWRs

Fig. 1.5 Histograms of modeled Tucannon River summer steelhead accumulated degrees day over 21°C from Bonneville to the Snake River confluence in the Columbia River.
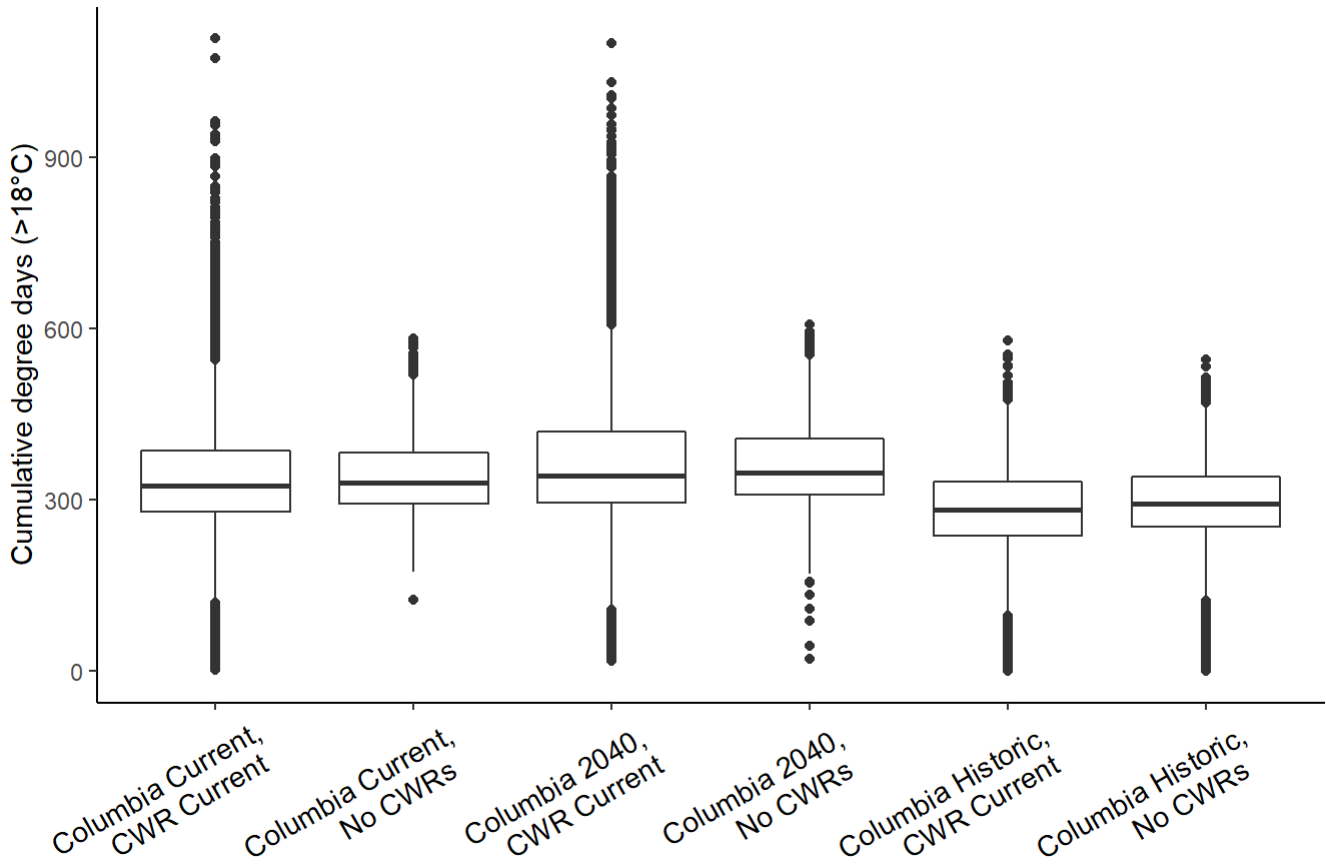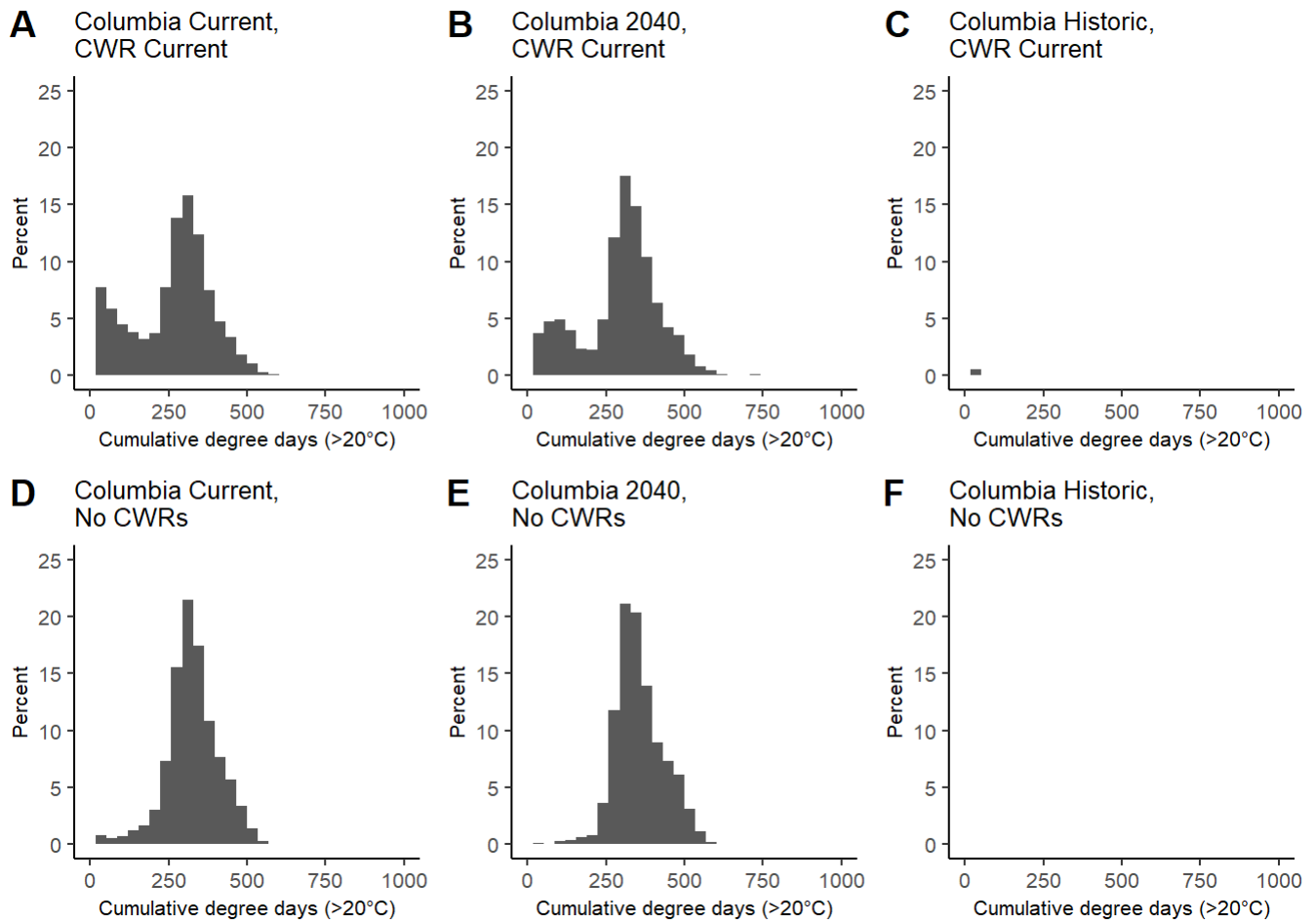
Tucannon River Summer Steelhead

Fig. 1.6 Boxplots of modeled Tucannon River summer steelhead accumulated degrees day over 21°C from Bonneville to the Snake River confluence in the Columbia River.

Table 1.3 Cumulative degree days (>21°C) used across different HexSim thermalscapes summarized for Tucannon River Summer Steelhead.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2040, CWR Current	1	177	285	345	705
Columbia Current, CWR Current	1	50	168	265	497
Columbia 2040, No CWRs	1	208	296	361	600
Columbia Current, No CWRs	1	111	223	310	535

2. Energy use, CWR use, and survivorship results for Tucannon River summer steelhead under long-term average temperatures for the Columbia River

A Columbia Current, CWR Current

B Columbia 2040, CWR Current

C Columbia Historic, CWR Current

D Columbia Current, No CWRs

E Columbia 2040, No CWRs

F Columbia Historic, No CWRs
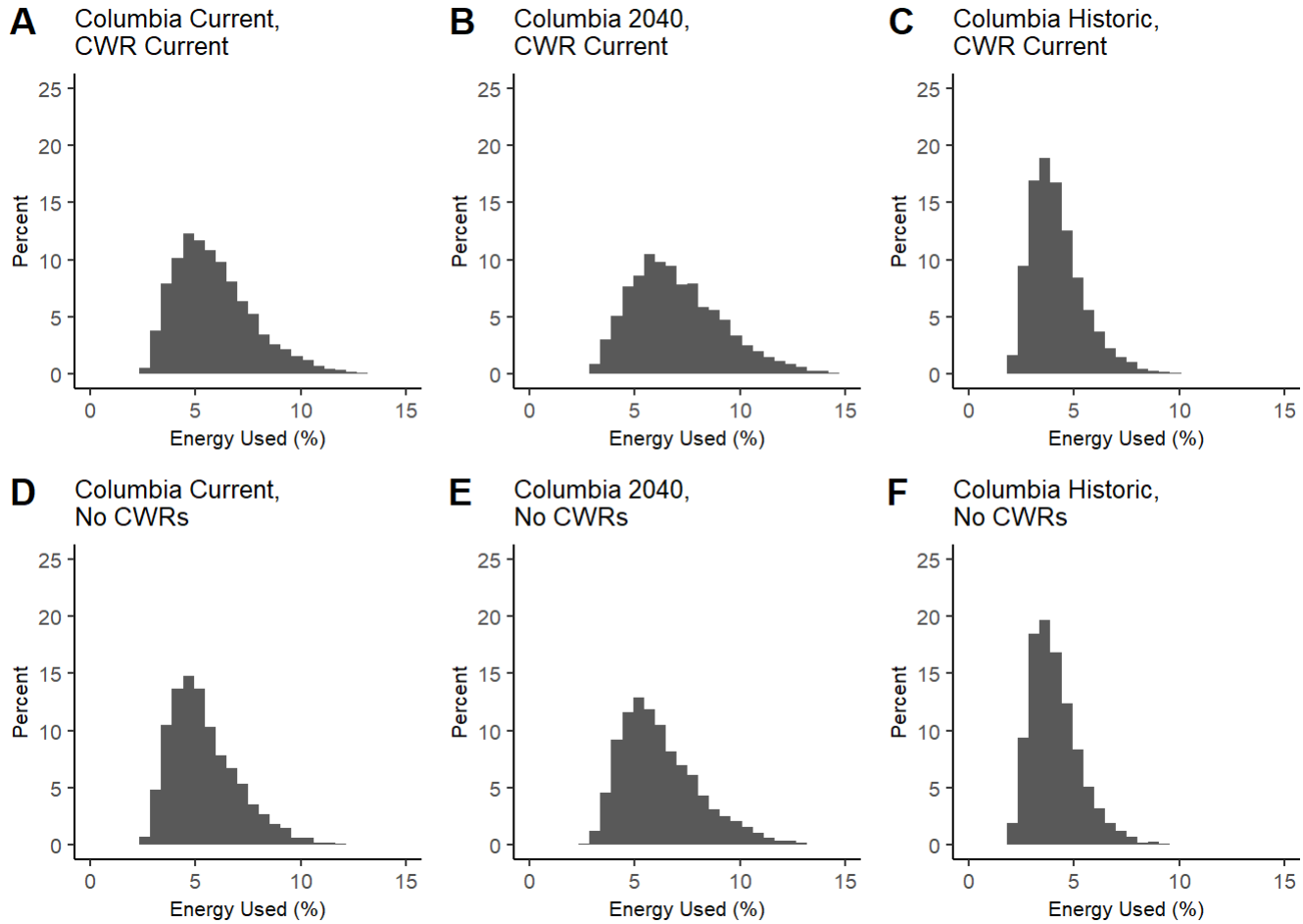
Fig. 2.1 Histogram of percent energy lost for modeled Grande Ronde summer steelhead migrating through different modeled thermalscapes.

Tucannon River Summer Steelhead
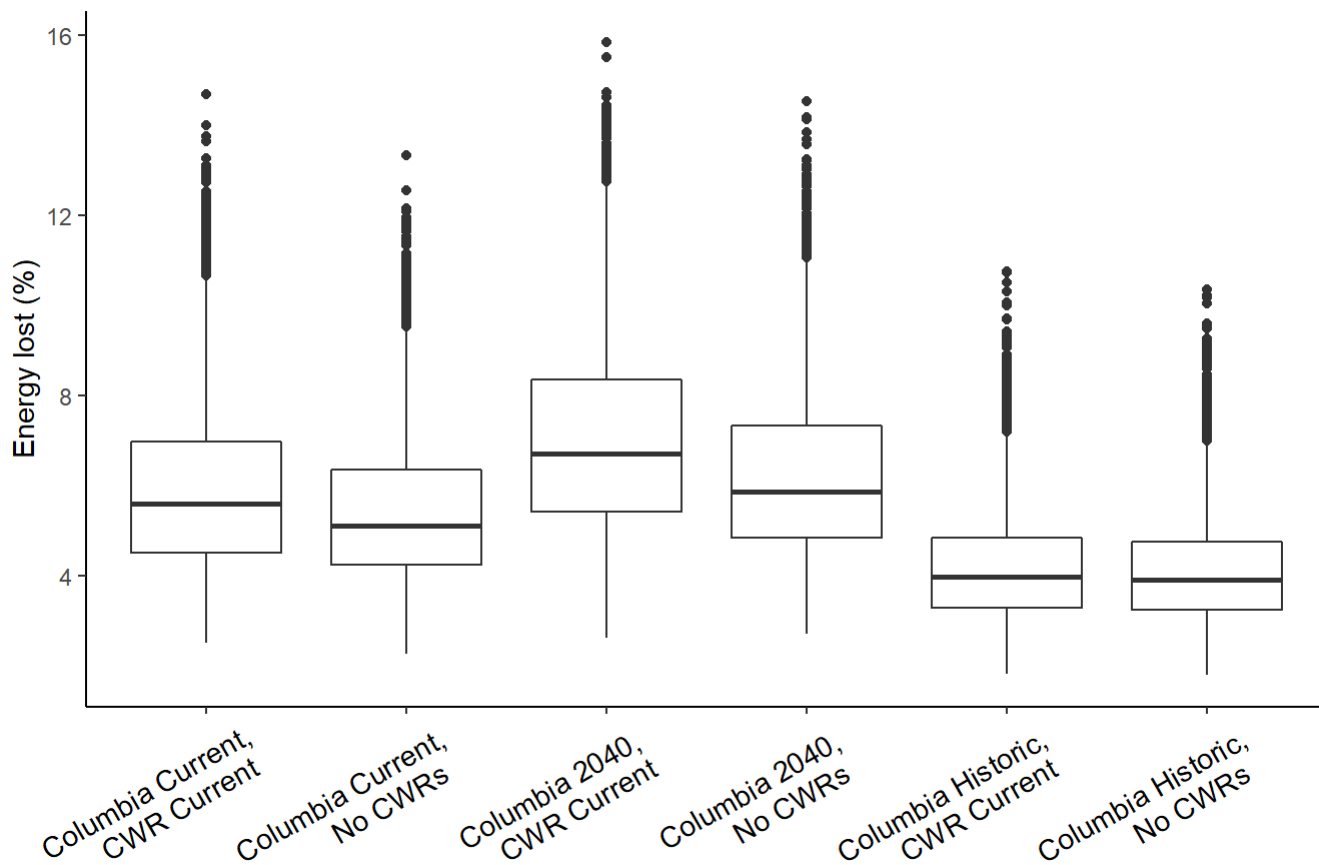
Fig. 2.2 Boxplot of percent energy lost for modeled Grande Ronde summer steelhead migrating through different modeled thermalscapes.

Table 2.1 Percent energy used across different HexSim thermalscapes summarized for Tucannon River Summer Steelhead.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2040, CWR Current	2.6	5.4	6.7	8.4	15.8
Columbia Historic, CWR Current	1.8	3.3	4.0	4.8	10.8
Columbia Current, CWR Current	2.5	4.5	5.6	7.0	14.7
Columbia 2040, No CWRs	2.7	4.8	5.9	7.3	14.5
Columbia Historic, No CWRs	1.8	3.2	3.9	4.7	10.3
Columbia Current, No CWRs	2.2	4.2	5.1	6.3	13.3

Table 2.2 Model output for hours residing in cold water refuges summarized for Tucannon River Summer Steelhead.

Scenario	CWR Residence (h/individual)
Columbia Current,CWR Current	295
Columbia Current, No CWRs	0

Scenario	CWR Residence (h/individual)
Columbia 2040, Current	445
Columbia 2040, No CWRs	0
Columbia Historic, Current	73
Columbia Historic, No CWRs	0

Table 2.3 Model output for percent of individuals dying from acute temperature stress summarized for Tucannon River Summer Steelhead.

Scenario	Total mortality
Columbia Current,CWR Current	0.00
Columbia Current, No CWRs	0.00
Columbia 2040, Current	0.15
Columbia 2040, No CWRs	0.13
Columbia Historic, Current	0.00
Columbia Historic, No CWRs	0.00

3. Cumulative degree days summary results for Grande Ronde River summer steelhead under long-term average temperatures for the Columbia River
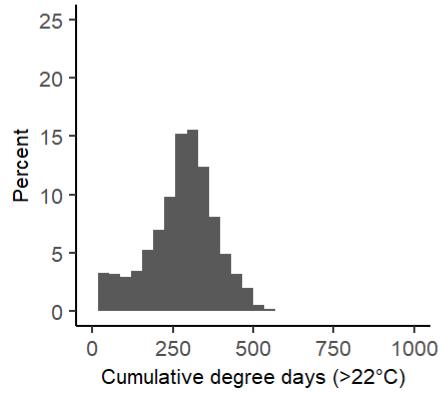

Fig. 3.1 Histograms of modeled Grande Ronde River summer steelhead accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.
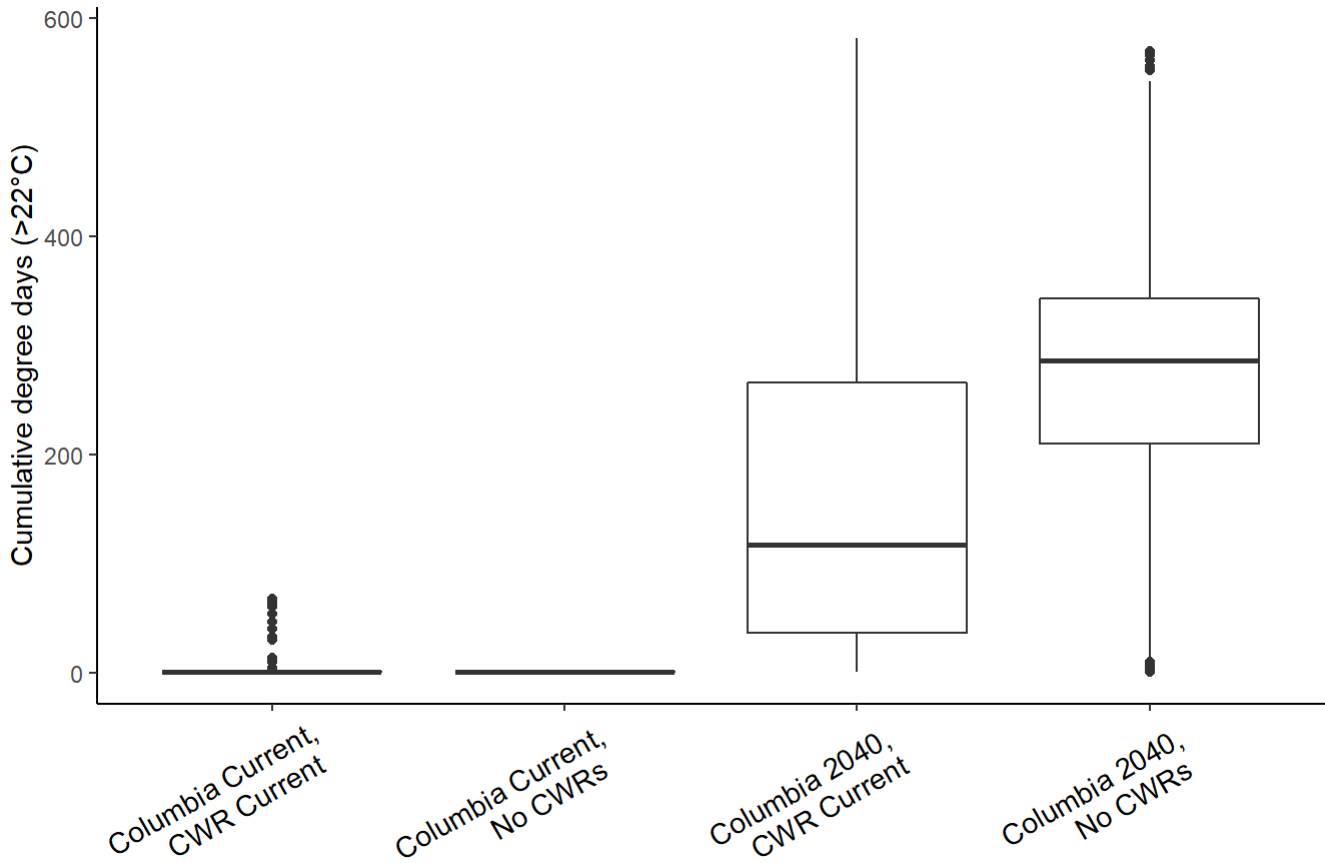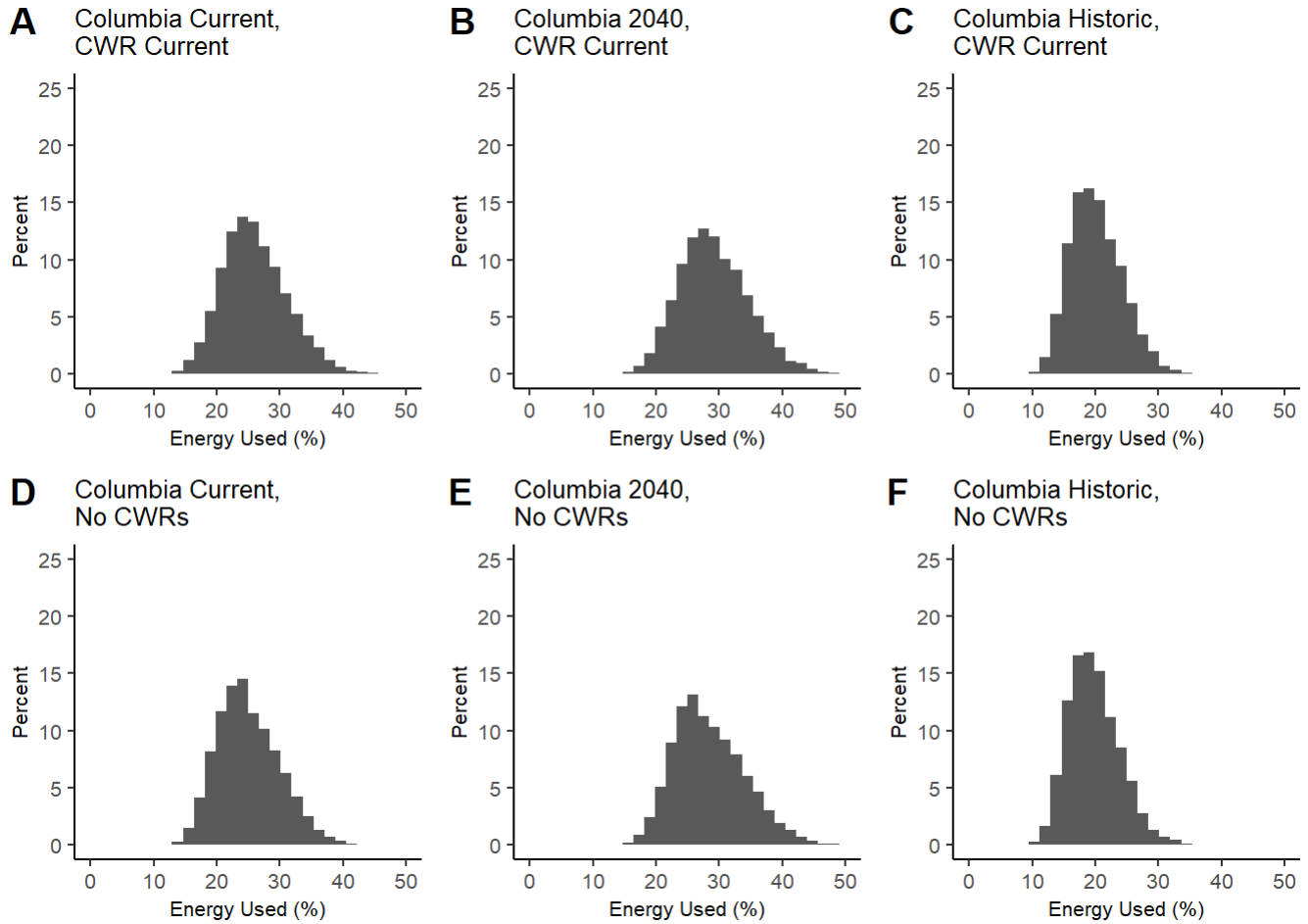
Grande Ronde River Summer Steelhead

Fig. 3.2 Boxplots of modeled Grande Ronde River summer steelhead accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.

Table 3.1 Cumulative degree days (>18°C) used across different HexSim thermalscapes summarized for Grande Ronde River Summer Steelhead.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2040, CWR Current	19	296	343	421	1101
Columbia Historic, CWR Current	1	238	284	332	580
Columbia Current, CWR Current	2	280	325	387	1109
Columbia 2040, No CWRs	21	309	347	407	607
Columbia Historic, No CWRs	1	254	293	340	546
Columbia Current, No CWRs	126	294	330	384	583

Fig. 3.3 Histograms of modeled Grande Ronde River summer steelhead accumulated degrees day over 20°C from Bonneville to the Snake River confluence in the Columbia River.
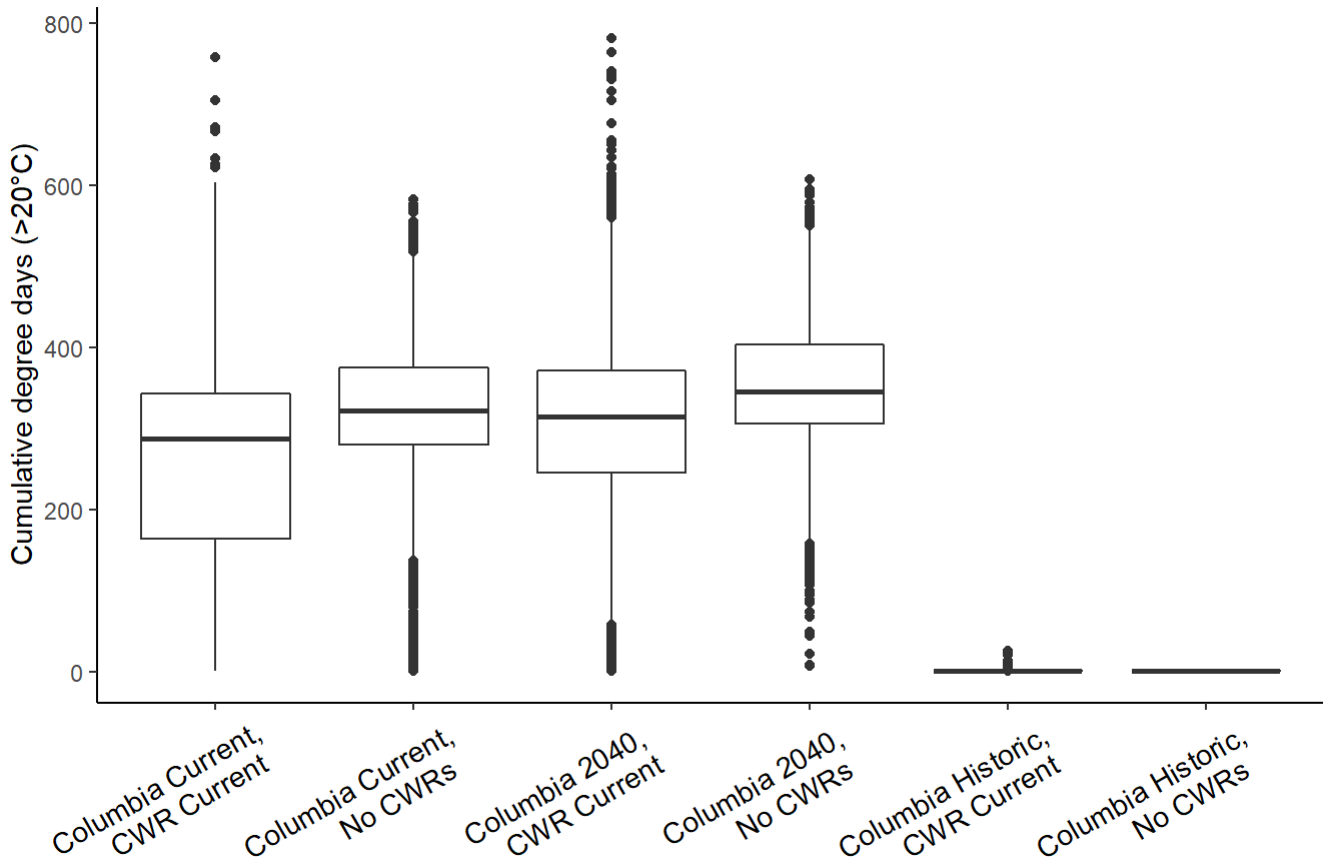
Fig. 3.4 Boxplots of modeled Grande Ronde River summer steelhead accumulated degrees day over 20°C from Bonneville to the Snake River confluence in the Columbia River.

Table 3.2 Cumulative degree days (>20°C) used across different HexSim thermalscapes summarized for Grande Ronde River Summer Steelhead.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2040, CWR Current	1	246	315	372	781
Columbia Historic, CWR Current	1	1	1	1	25
Columbia Current, CWR Current	1	164	287	343	758
Columbia 2040, No CWRs	7	305	345	404	607
Columbia Historic, No CWRs	1	1	1	1	1
Columbia Current, No CWRs	1	280	322	375	583
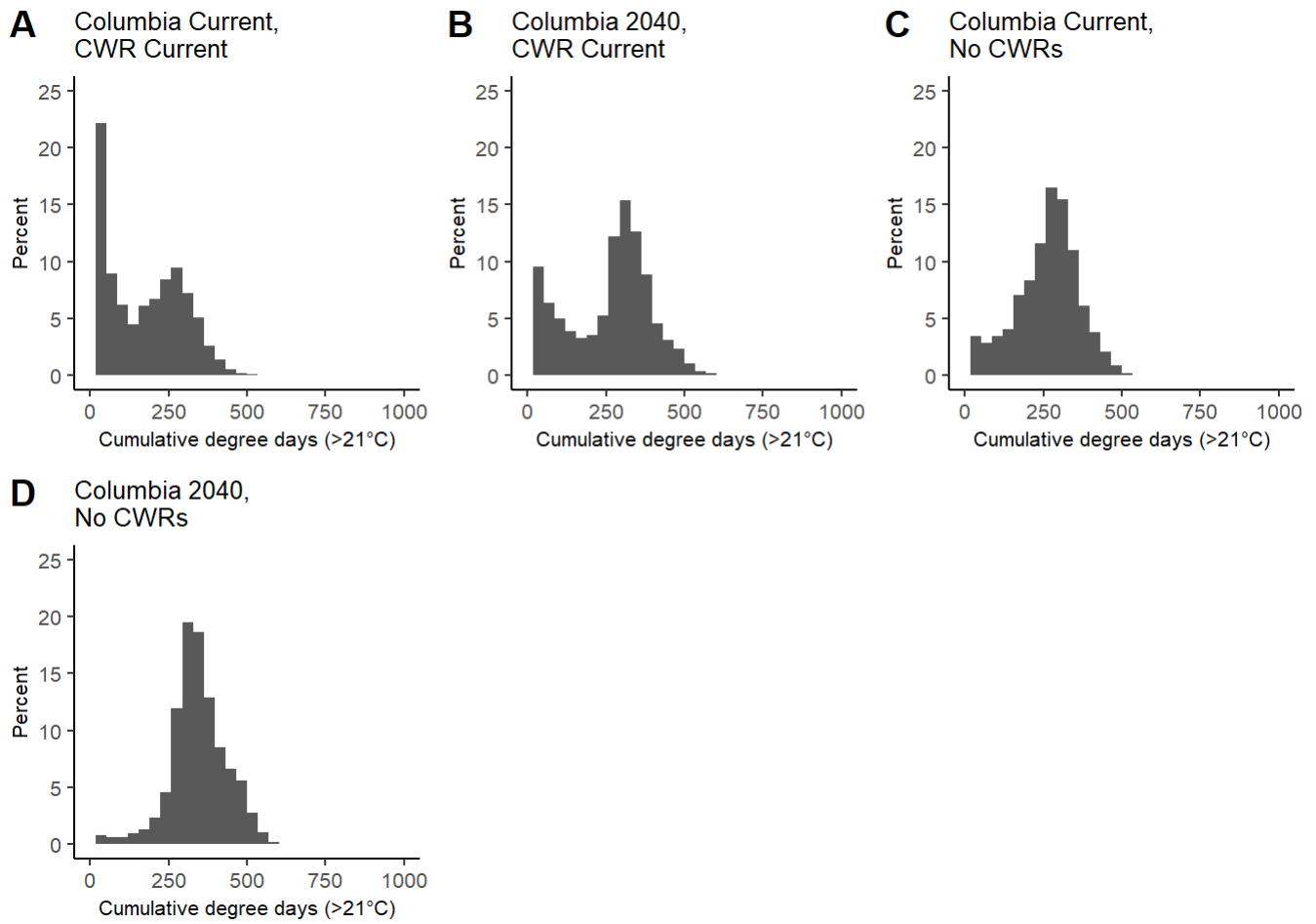
Fig. 3.5 Histograms of modeled Grande Ronde River summer steelhead accumulated degrees day over 21°C from Bonneville to the Snake River confluence in the Columbia River.

Grande Ronde River Summer Steelhead

Fig. 3.6 Boxplots of modeled Grande Ronde River summer steelhead accumulated degrees day over 21°C from Bonneville to the Snake River confluence in the Columbia River.

Table 3.3 Cumulative degree days (>21°C) used across different HexSim thermalscapes summarized for Grande Ronde River Summer Steelhead.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2040, CWR Current	1	137	290	349	652
Columbia Current, CWR Current	1	38	139	264	538
Columbia 2040, No CWRs	1	295	338	396	607
Columbia Current, No CWRs	1	194	272	326	555

A Columbia Current, CWR Current
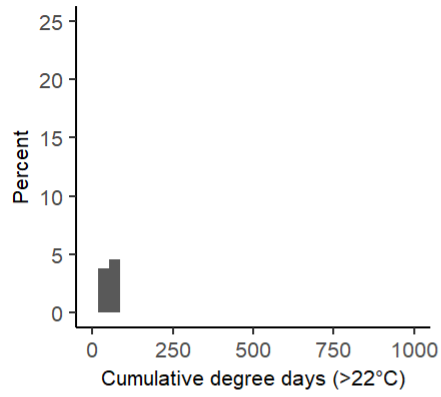
B Columbia 2040, CWR Current
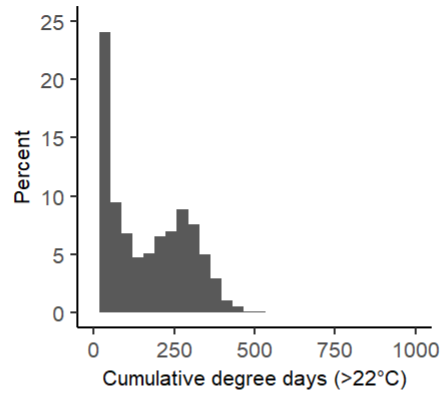
C Columbia Current, No CWRs
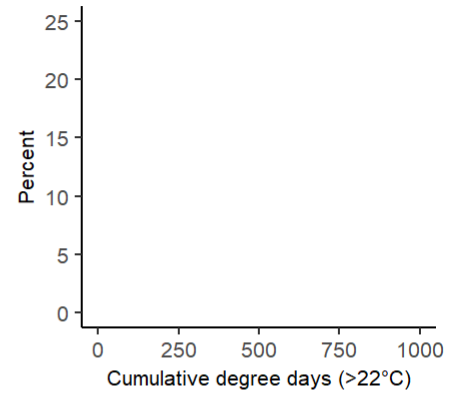
D Columbia 2040, No CWRs

Fig. 3.5 Histograms of modeled Grande Ronde River summer steelhead accumulated degrees day over 22°C from Bonneville to the Snake River confluence in the Columbia River.

Fig. 3.6 Boxplots of modeled Grande Ronde River summer steelhead accumulated degrees day over 22°C from Bonneville to the Snake River confluence in the Columbia River.

Table 3.3 Cumulative degree days (>22°C) used across different HexSim thermalscapes summarized for Grande Ronde River Summer Steelhead.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2040, CWR Current	1	37	118	266	582
Columbia Current, CWR Current	1	1	1	1	68
Columbia 2040, No CWRs	1	210	286	344	570
Columbia Current, No CWRs	1	1	1	1	1

4. Energy use, CWR use, and survivorship results for Grande Ronde River summer steelhead under long-term average temperatures for the Columbia River

Fig. 4.1 Histogram of percent energy lost for modeled Grande Ronde summer steelhead migrating through different modeled thermalscapes.

Grande Ronde River Summer Steelhead
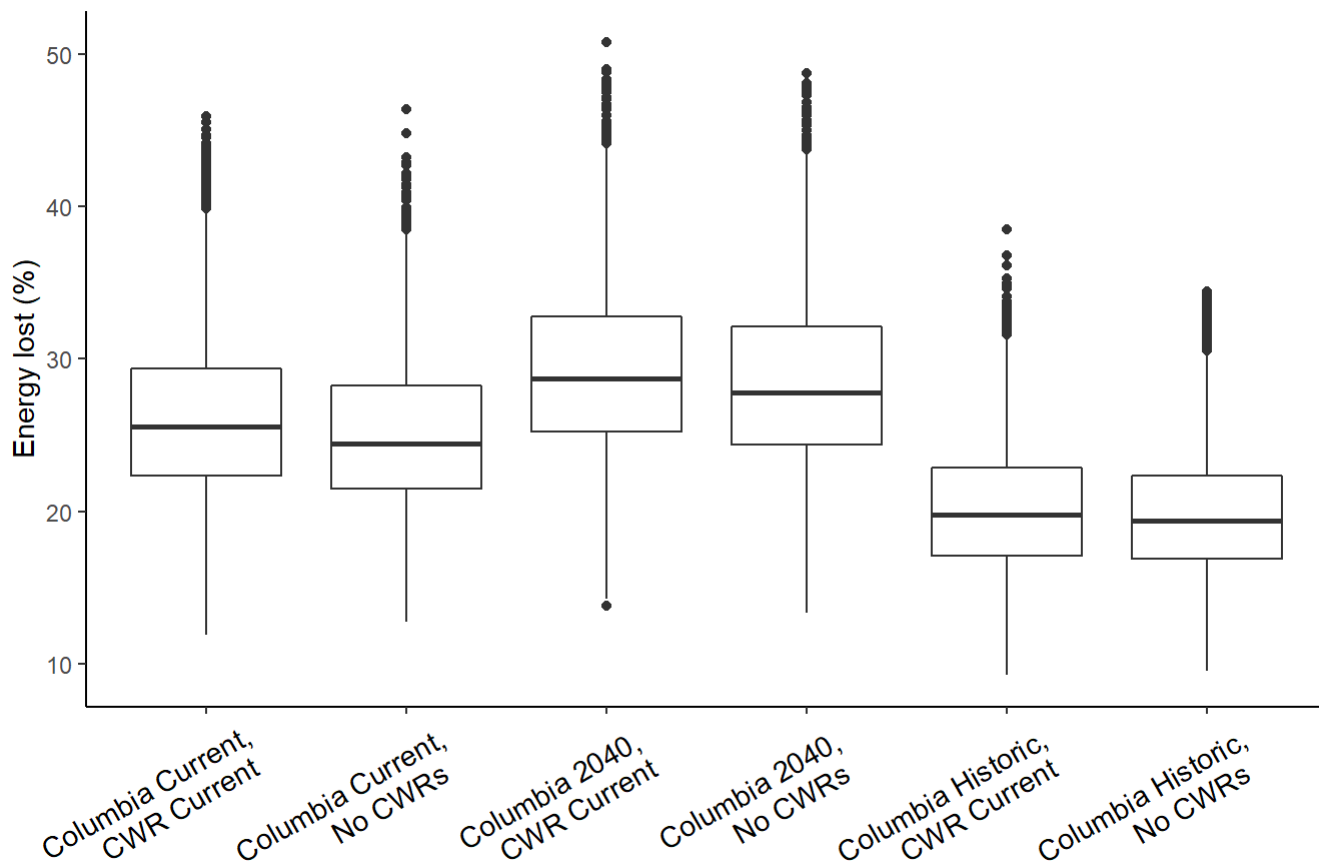
Fig. 4.2 Boxplot of percent energy lost for modeled Grande Ronde summer steelhead migrating through different modeled thermalscapes.

Table 4.1 Percent energy used across different HexSim thermalscapes summarized for Grande Ronde River Summer Steelhead.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2040, CWR Current	13.8	25.2	28.7	32.8	50.8
Columbia Historic, CWR Current	9.2	17.1	19.8	22.9	38.5
Columbia Current, CWR Current	11.8	22.3	25.5	29.3	45.9
Columbia 2040, No CWRs	13.3	24.4	27.8	32.1	48.8
Columbia Historic, No CWRs	9.5	16.9	19.4	22.4	34.4
Columbia Current, No CWRs	12.8	21.5	24.4	28.3	46.4

Table 4.2 Model output for hours residing in cold water refuges summarized for Grande Ronde River Summer Steelhead.

Scenario	CWR Residence (h/individual)
Columbia Current,CWR Current	389
Columbia Current, No CWRs	0

Scenario	CWR Residence (h/individual)
Columbia 2040, Current	497
Columbia 2040, No CWRs	0
Columbia Historic, Current	124
Columbia Historic, No CWRs	0

Table 4.3 Model output for percent of individuals dying from acute temperature stress summarized for Grande Ronde River Summer Steelhead.

Scenario	Total mortality
Columbia Current,CWR Current	0.02
Columbia Current, No CWRs	0.02
Columbia 2040, Current	0.32
Columbia 2040, No CWRs	0.53
Columbia Historic, Current	0.00
Columbia Historic, No CWRs	0.00
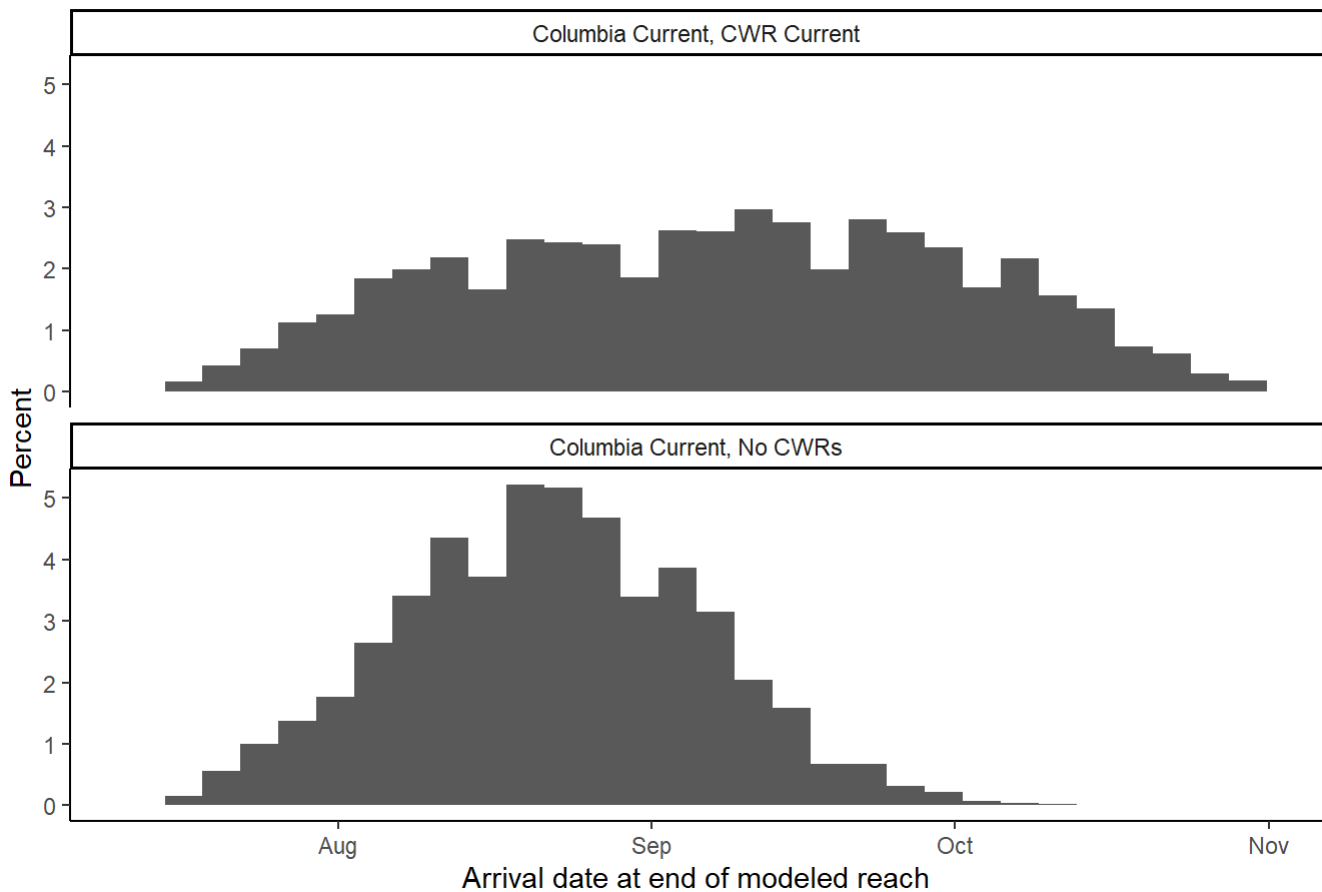
5. Cumulative degree days summary results for Snake River Fall Chinook Salmon under long-term average temperatures for the Columbia River
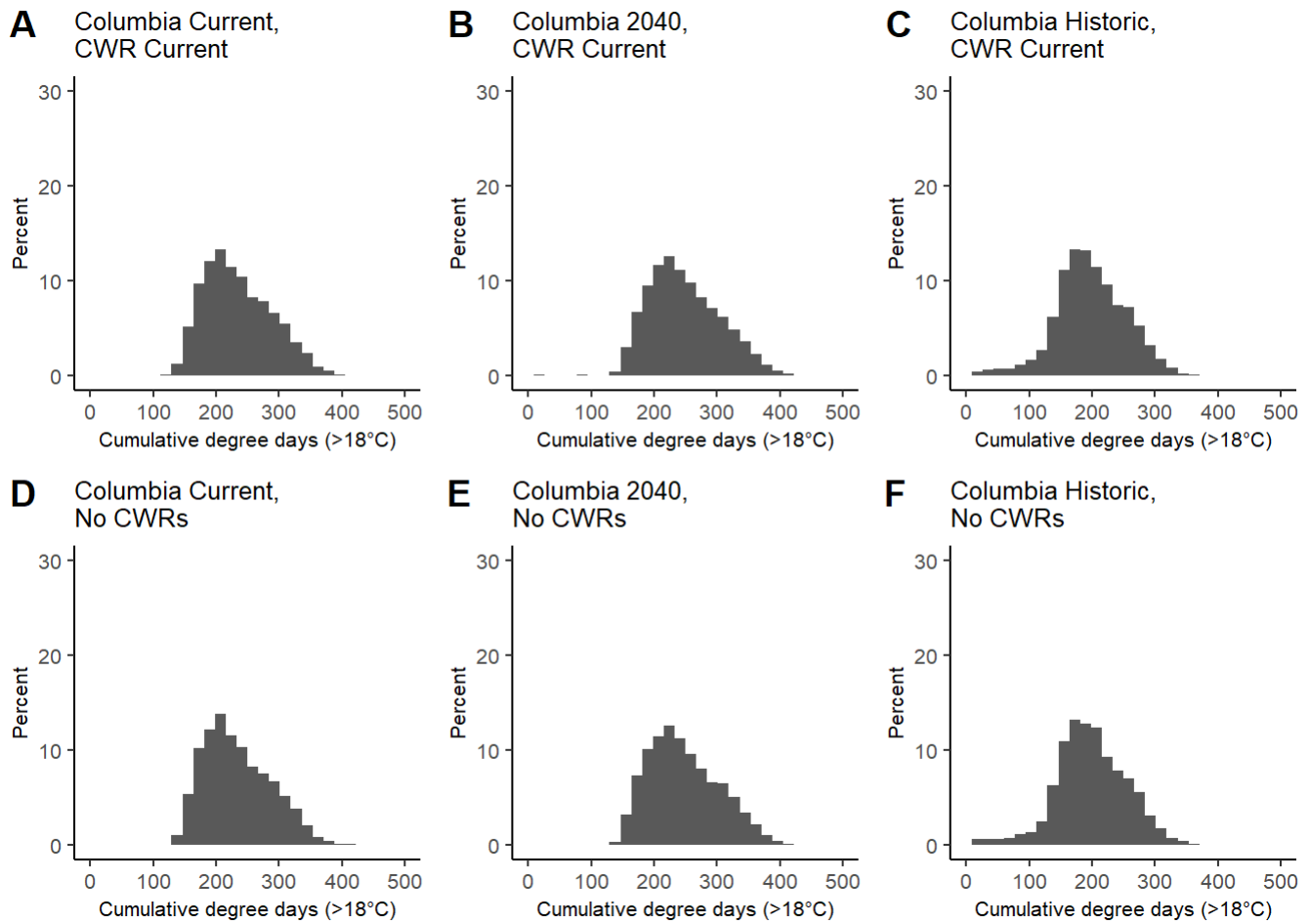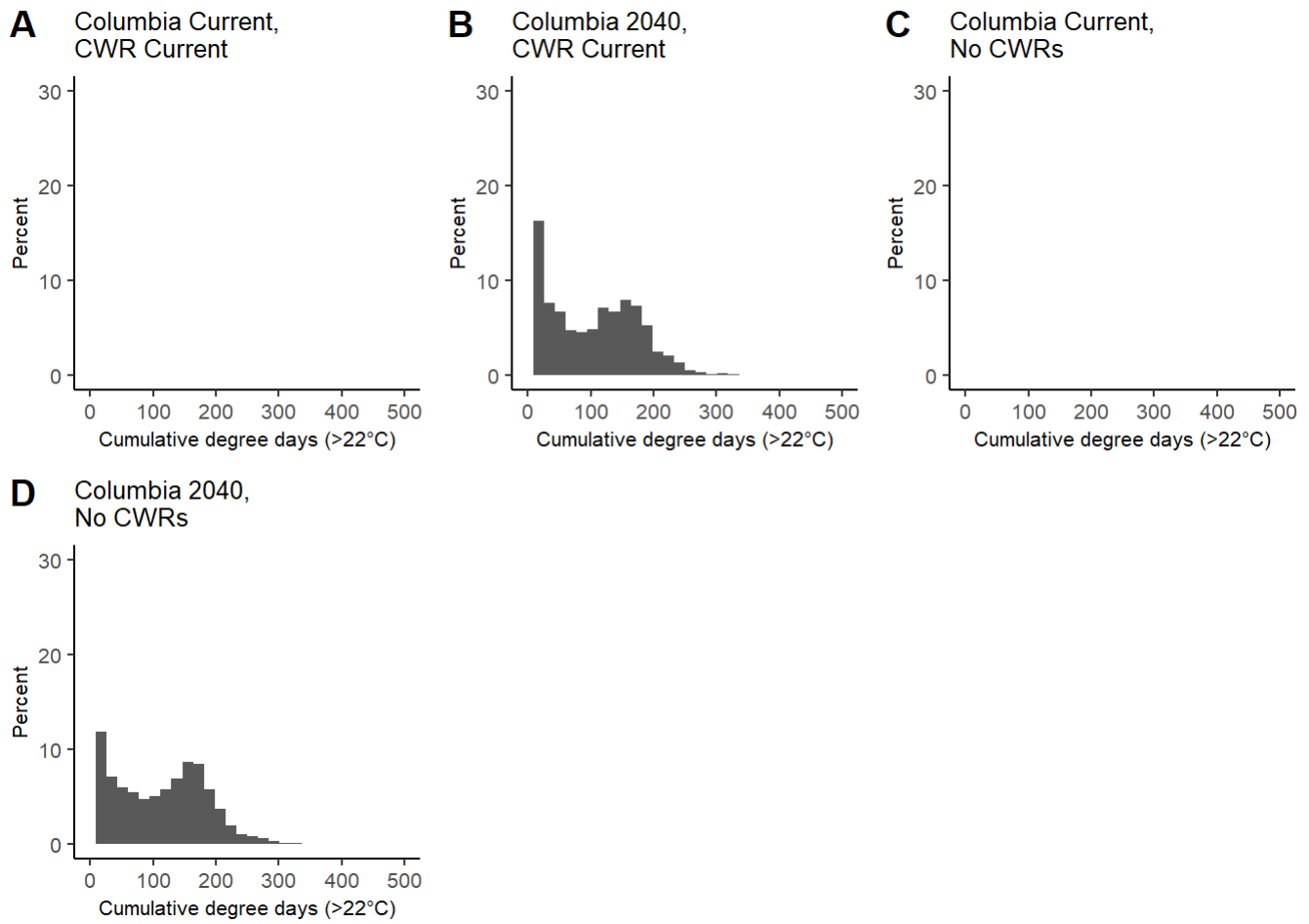

Fig. 5.1 Histograms of modeled Snake River fall Chinook accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.
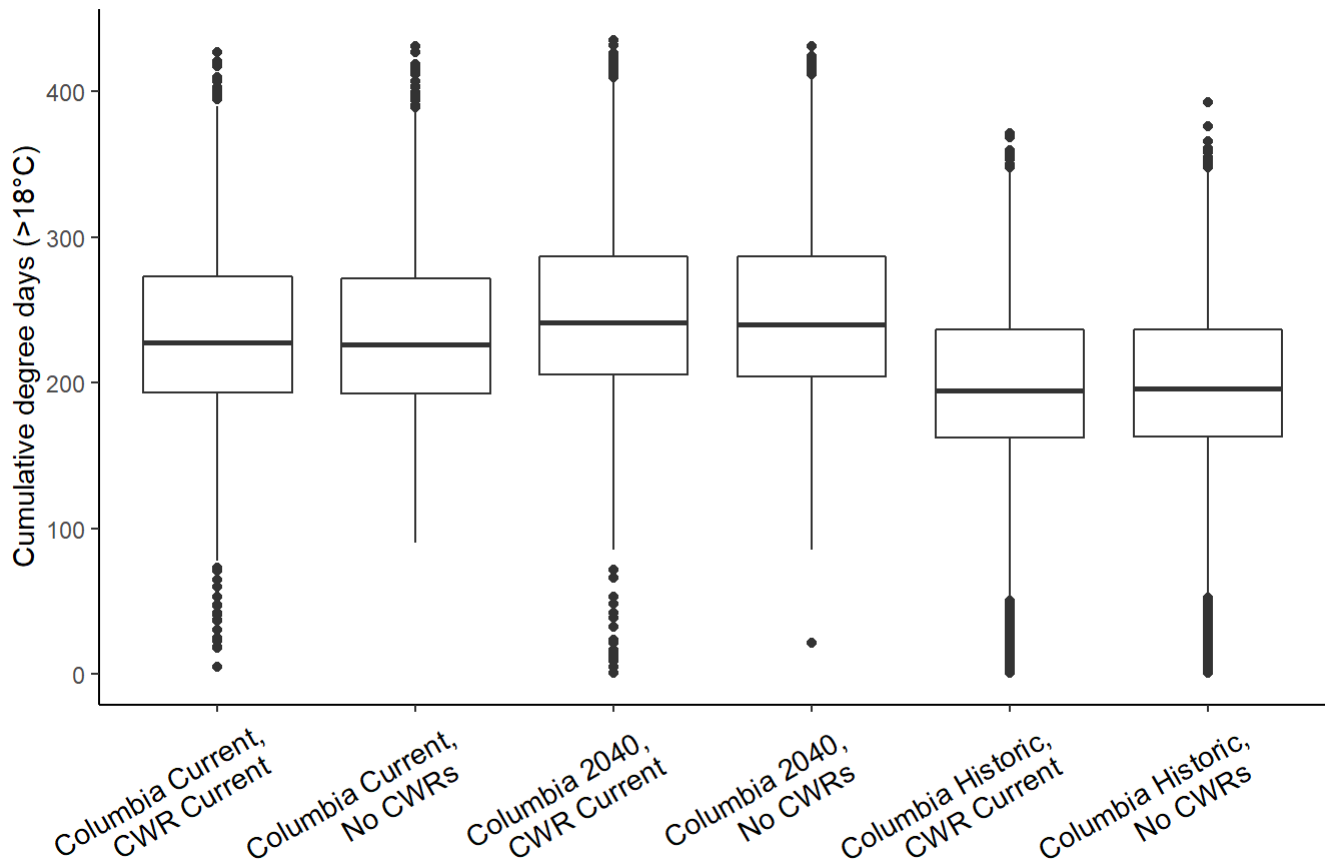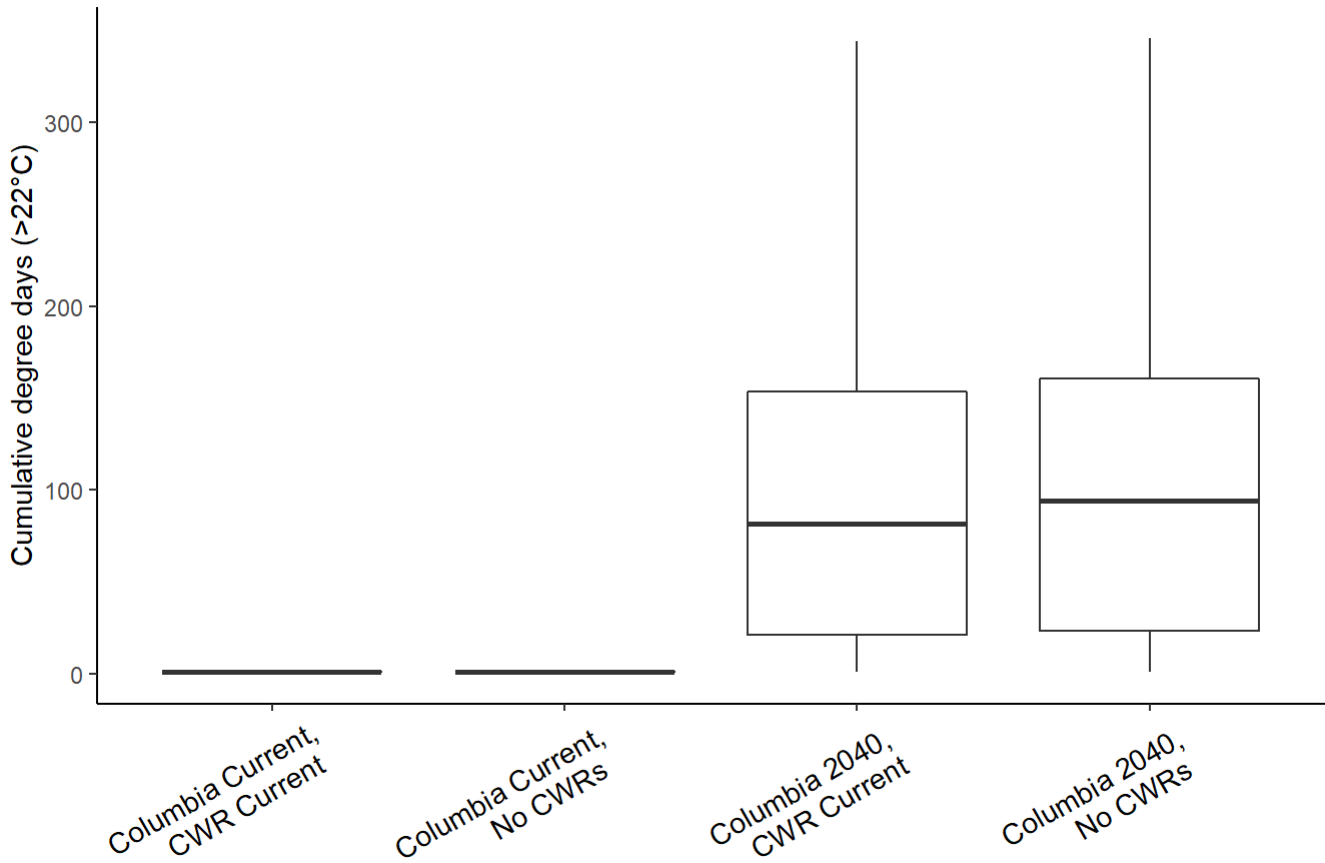
Fig. 5.2 Boxplots of modeled Snake River fall Chinook accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.

Table 5.1 Cumulative degree days (>18°C) used across different HexSim thermalscapes summarized for Snake River fall Chinook.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2040, CWR Current	1	205	241	287	435
Columbia Historic, CWR Current	1	162	194	236	371
Columbia Current, CWR Current	5	193	227	273	427
Columbia 2040, No CWRs	21	204	240	287	431
Columbia Historic, No CWRs	1	163	196	236	393
Columbia Current, No CWRs	90	193	226	271	431

Fig. 5.3 Histograms of modeled Snake River fall Chinook accumulated degrees day over 20°C from Bonneville to the Snake River confluence in the Columbia River.
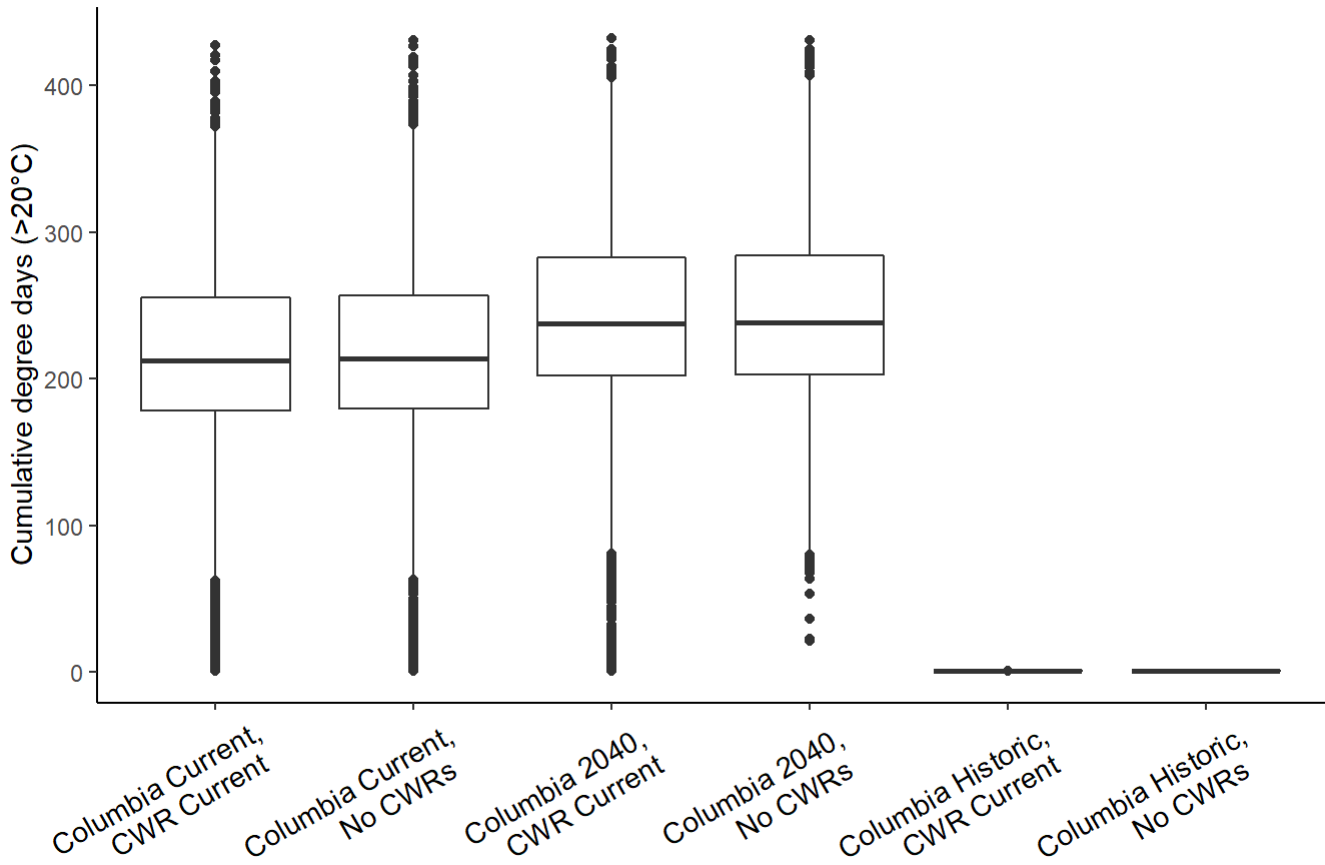
Fig. 5.4 Boxplots of modeled Snake River fall Chinook accumulated degrees day over 20°C from Bonneville to the Snake River confluence in the Columbia River.

Table 5.2 Cumulative degree days (>20°C) used across different HexSim thermalscapes summarized for Snake River fall Chinook.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2040, CWR Current	1	202	238	283	432
Columbia Historic, CWR Current	1	1	1	1	1
Columbia Current, CWR Current	1	178	212	256	427
Columbia 2040, No CWRs	21	203	238	284	431
Columbia Historic, No CWRs	1	1	1	1	1
Columbia Current, No CWRs	1	179	214	257	431

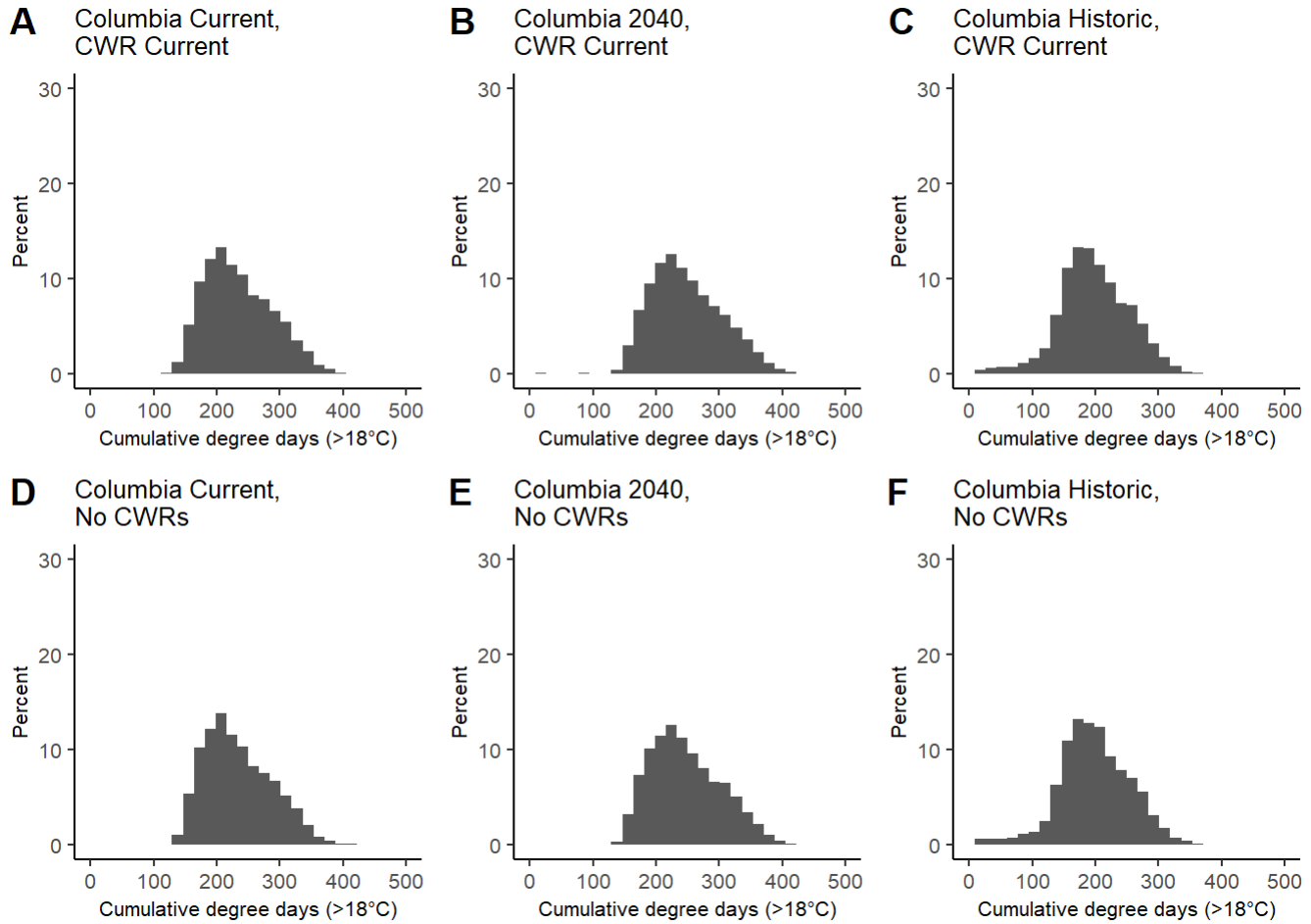Fig. 5.5 Histograms of modeled Snake River fall Chinook accumulated degrees day over 21°C from Bonneville to the Snake River confluence in the Columbia River.
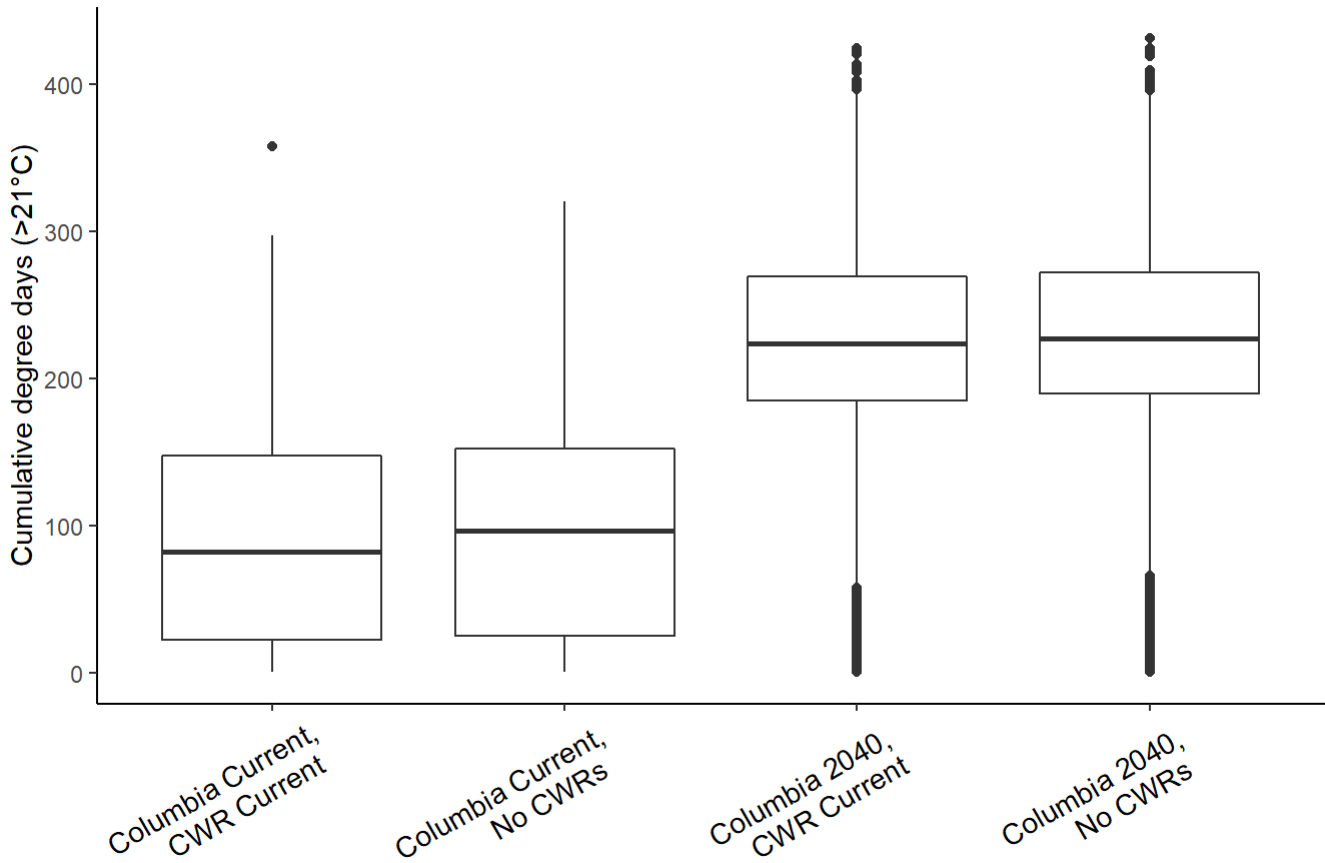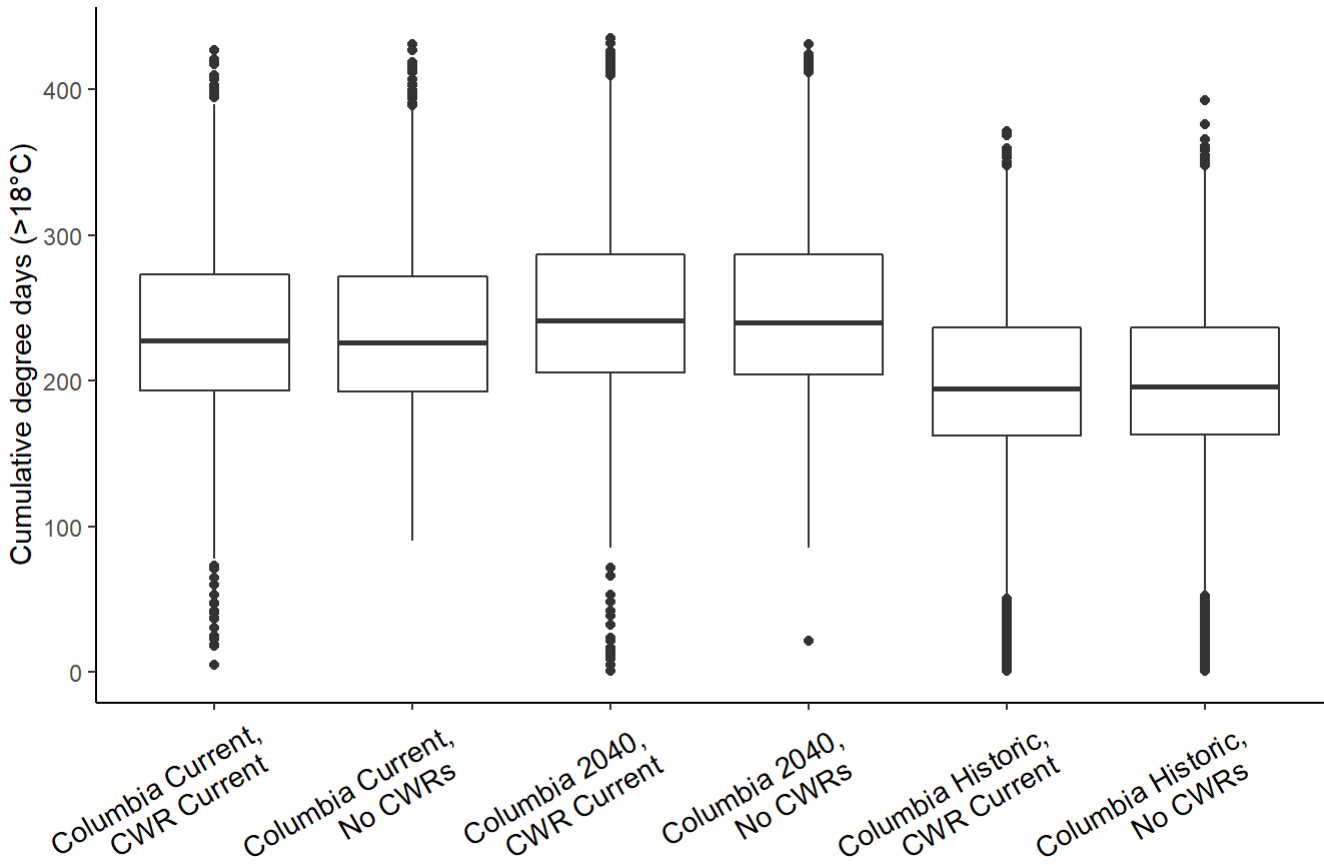
Fig. 5.6 Boxplots of modeled Snake River fall Chinook accumulated degrees day over 21°C from Bonneville to the Snake River confluence in the Columbia River.

Table 5.3 Cumulative degree days (>21°C) used across different HexSim thermalscapes summarized for Snake River fall Chinook.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2040, CWR Current	1	185	224	269	425
Columbia Current, CWR Current	1	23	83	148	358
Columbia 2040, No CWRs	1	190	227	272	431
Columbia Current, No CWRs	1	25	97	153	320

A Columbia Current,
CWR Current

B Columbia 2040,
CWR Current

C Columbia Current,
No CWRs

D Columbia 2040,
No CWRs

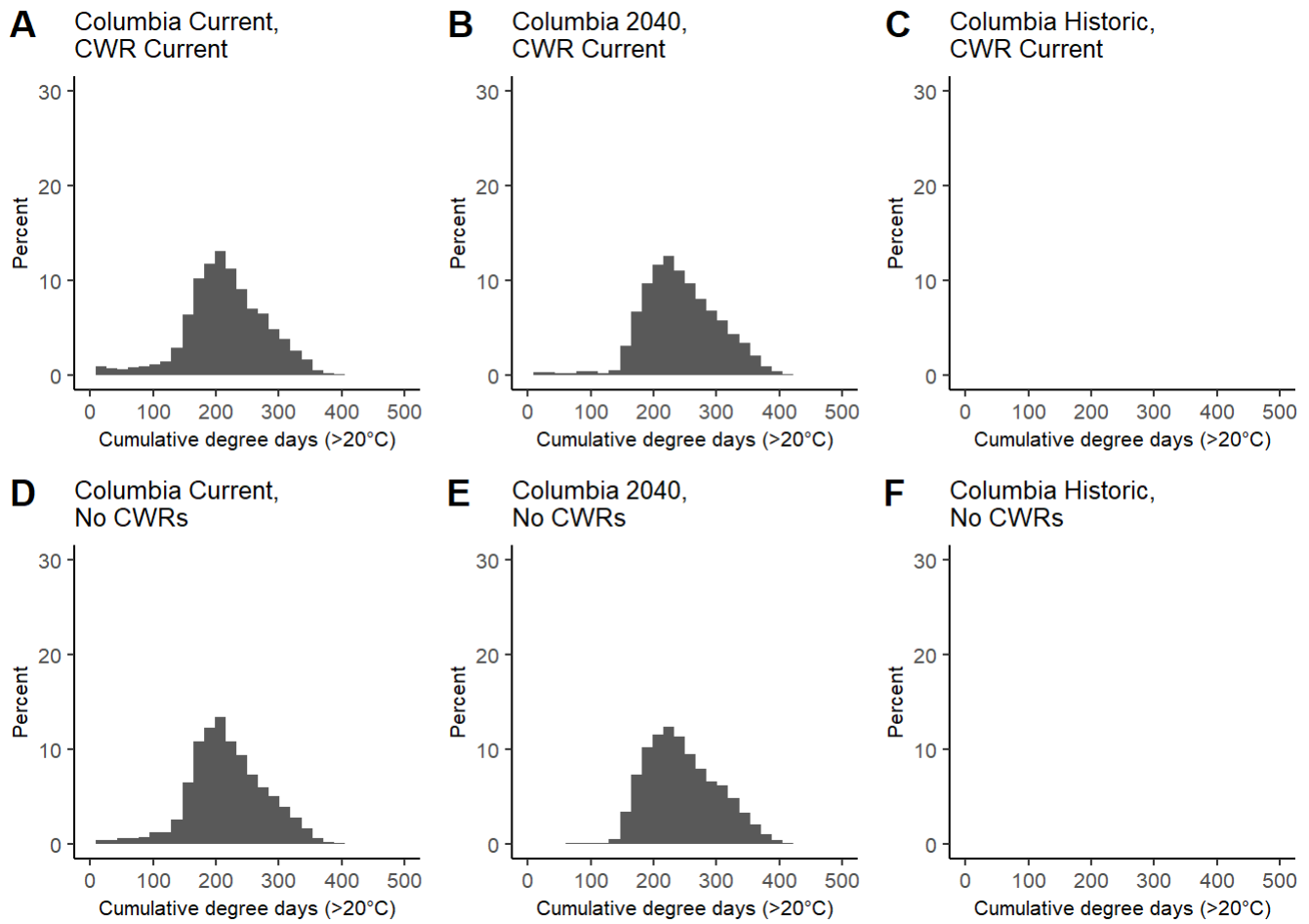Fig. 5.7 Histograms of modeled Snake River fall Chinook accumulated degrees day over 22°C from Bonneville to the Snake River confluence in the Columbia River.
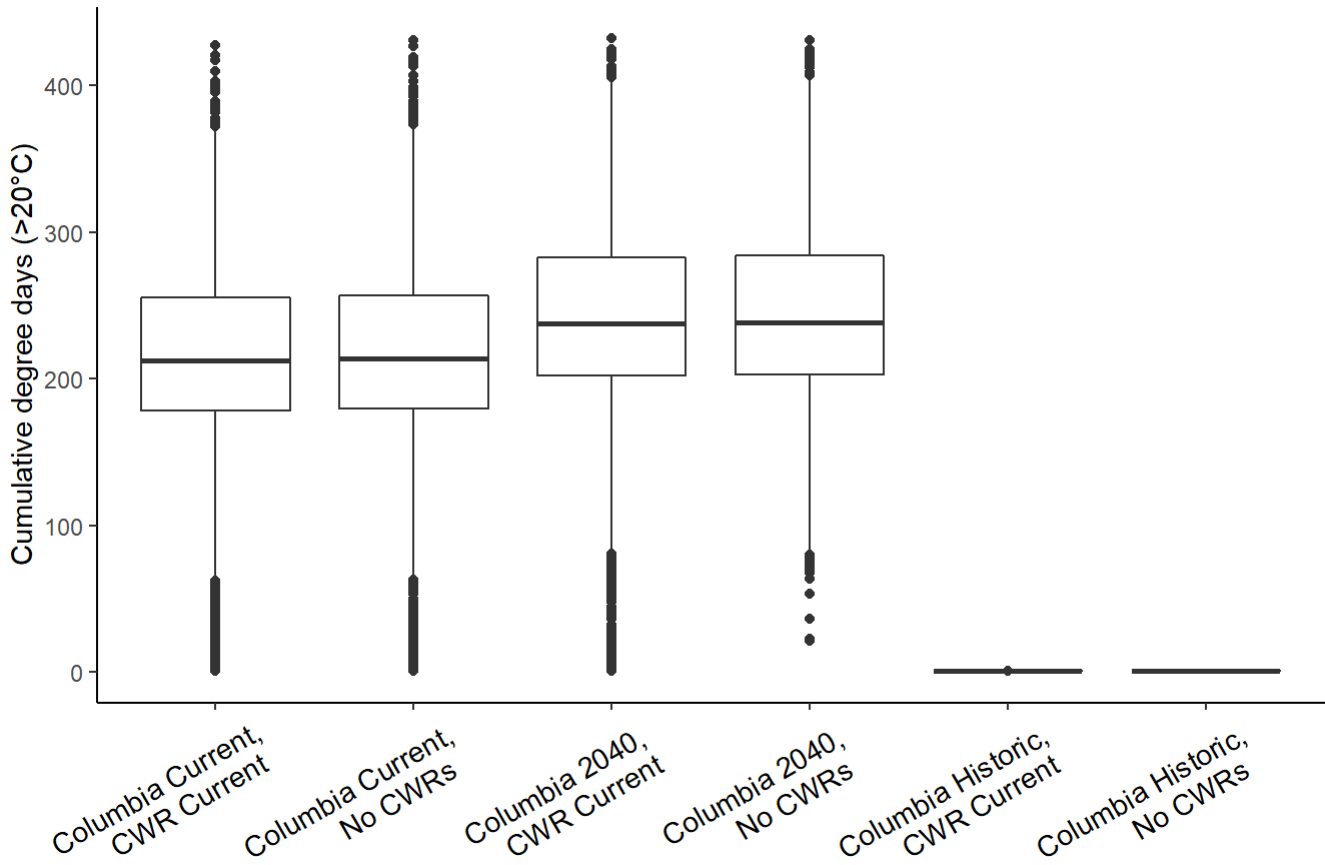
Fig. 5.8 Boxplots of modeled Snake River fall Chinook accumulated degrees day over 22°C from Bonneville to the Snake River confluence in the Columbia River.

Table 5.4 Cumulative degree days (>22°C) used across different HexSim thermalscapes summarized for Snake River fall Chinook.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2040, CWR Current	1	21	81	153	344
Columbia Current, CWR Current	1	1	1	1	1
Columbia 2040, No CWRs	1	23	94	161	346
Columbia Current, No CWRs	1	1	1	1	1

6. Energy use, CWR use, and survivorship results for Snake River Fall Chinook Salmon under long-term average temperatures for the Columbia River
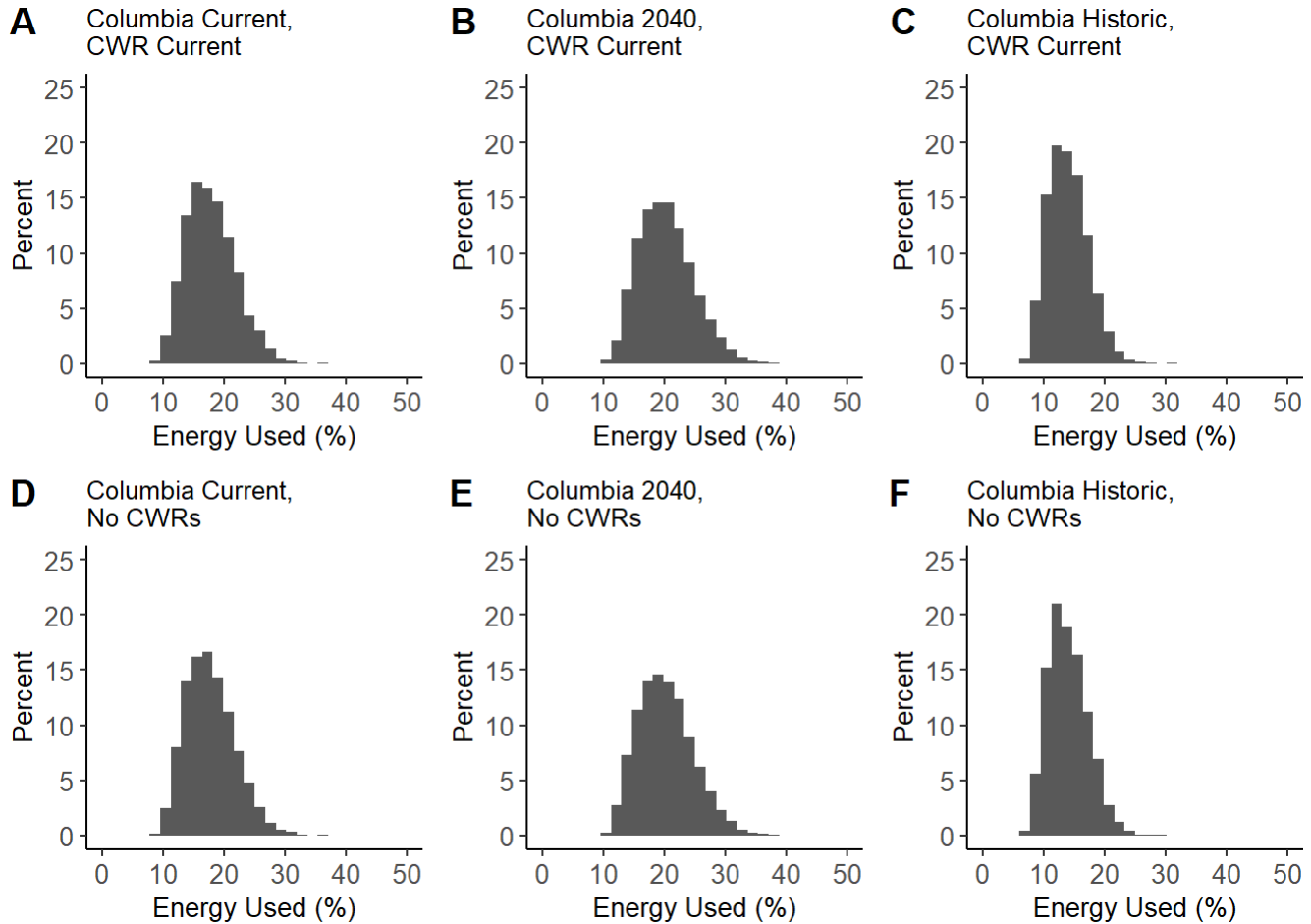
Fig. 6.1 Histogram of percent energy lost for modeled Snake River Fall Chinook salmon migrating through different modeled thermalscapes.
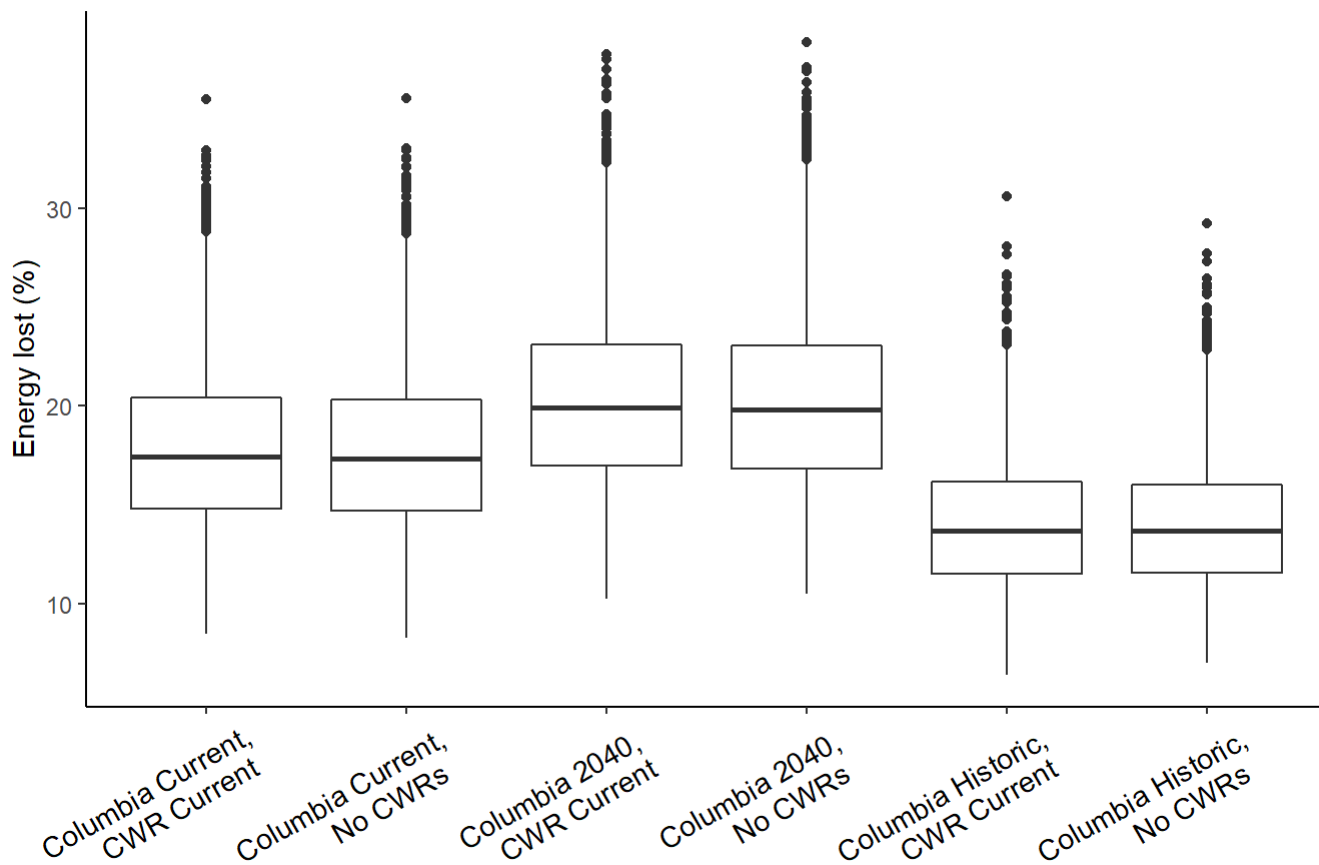
Fig. 6.2 Boxplot of percent energy lost for modeled Snake River Fall Chinook migrating through different modeled thermalscapes.

Table 6.1 Percent energy used across different HexSim thermalscapes summarized for Snake River Fall Chinook.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2040, CWR Current	10.2	17.0	19.9	23.1	37.8
Columbia Historic, CWR Current	6.4	11.5	13.7	16.2	30.6
Columbia Current, CWR Current	8.5	14.8	17.4	20.4	35.5
Columbia 2040, No CWRs	10.5	16.8	19.8	23.1	38.4
Columbia Historic, No CWRs	7.0	11.5	13.7	16.0	29.2
Columbia Current, No CWRs	8.3	14.7	17.3	20.3	35.6

Table 6.2 Model output for total hours residing in cold water refuges summarized for Snake River Fall Chinook.

Scenario	CWR Residence (h/individual)
Columbia Current,CWR Current	11
Columbia Current, No CWRs	0
Columbia 2040, Current	21

Scenario	CWR Residence (h/individual)
Columbia 2040, No CWRs	0
Columbia Historic, Current	2
Columbia Historic, No CWRs	0

Table 6.3 Model output for percent of individuals dying from acute temperature stress summarized for Snake River Fall Chinook.

Scenario	Total mortality
Columbia Current,CWR Current	0.00
Columbia Current, No CWRs	0.00
Columbia 2040, Current	0.07
Columbia 2040, No CWRs	0.10
Columbia Historic, Current	0.00
Columbia Historic, No CWRs	0.00
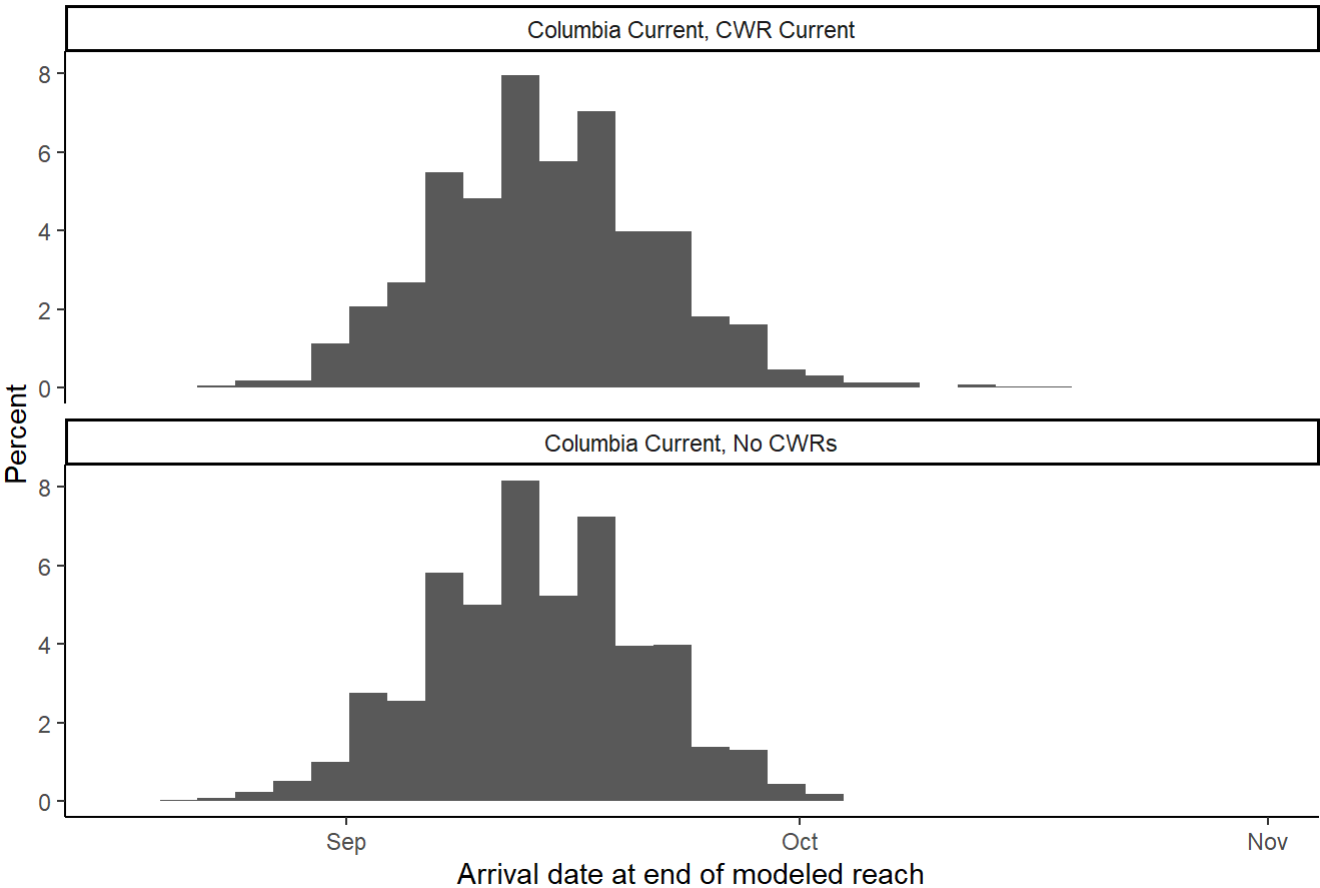
7. Cumulative degree days summary results for Hanford Reach Fall Chinook Salmon under long-term average temperatures for the Columbia River

Fig. 7.1 Histograms of modeled Hanford Reach fall Chinook accumulated degrees day over 18°C from Bonneville to the Hanford Reach confluence in the Columbia River.

Hanford Reach fall Chinook

Fig. 7.2 Boxplots of modeled Hanford Reach fall Chinook accumulated degrees day over 18°C from Bonneville to the Hanford Reach confluence in the Columbia River.

Table 7.1 Cumulative degree days (>18°C) used across different HexSim thermalscapes summarized for Hanford Reach fall Chinook.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2040, CWR Current	1	205	241	287	435
Columbia Historic, CWR Current	1	162	194	236	371
Columbia Current, CWR Current	5	193	227	273	427
Columbia 2040, No CWRs	21	204	240	287	431
Columbia Historic, No CWRs	1	163	196	236	393
Columbia Current, No CWRs	90	193	226	271	431

Fig. 7.3 Histograms of modeled Hanford Reach fall Chinook accumulated degrees day over 20°C from Bonneville to the Hanford Reach confluence in the Columbia River.

Fig. 7.4 Boxplots of modeled Hanford Reach fall Chinook accumulated degrees day over 20°C from Bonneville to the Hanford Reach confluence in the Columbia River.

Table 7.2 Cumulative degree days (>20°C) used across different HexSim thermalscapes summarized for Hanford Reach fall Chinook.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2040, CWR Current	1	202	238	283	432
Columbia Historic, CWR Current	1	1	1	1	1
Columbia Current, CWR Current	1	178	212	256	427
Columbia 2040, No CWRs	21	203	238	284	431
Columbia Historic, No CWRs	1	1	1	1	1
Columbia Current, No CWRs	1	179	214	257	431

Fig. 7.5 Histograms of modeled Hanford Reach fall Chinook accumulated degrees day over 21°C from Bonneville to the Hanford Reach confluence in the Columbia River.

Fig. 7.6 Boxplots of modeled Hanford Reach fall Chinook accumulated degrees day over 21°C from Bonneville to the Hanford Reach confluence in the Columbia River.

Table 7.3 Cumulative degree days (>21°C) used across different HexSim thermalscapes summarized for Hanford Reach fall Chinook.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2040, CWR Current	1	185	224	269	425
Columbia Current, CWR Current	1	23	83	148	358
Columbia 2040, No CWRs	1	190	227	272	431
Columbia Current, No CWRs	1	25	97	153	320

8. Energy use, CWR use, and survivorship results for Hanford Reach Fall Chinook Salmon under long-term average temperatures for the Columbia River
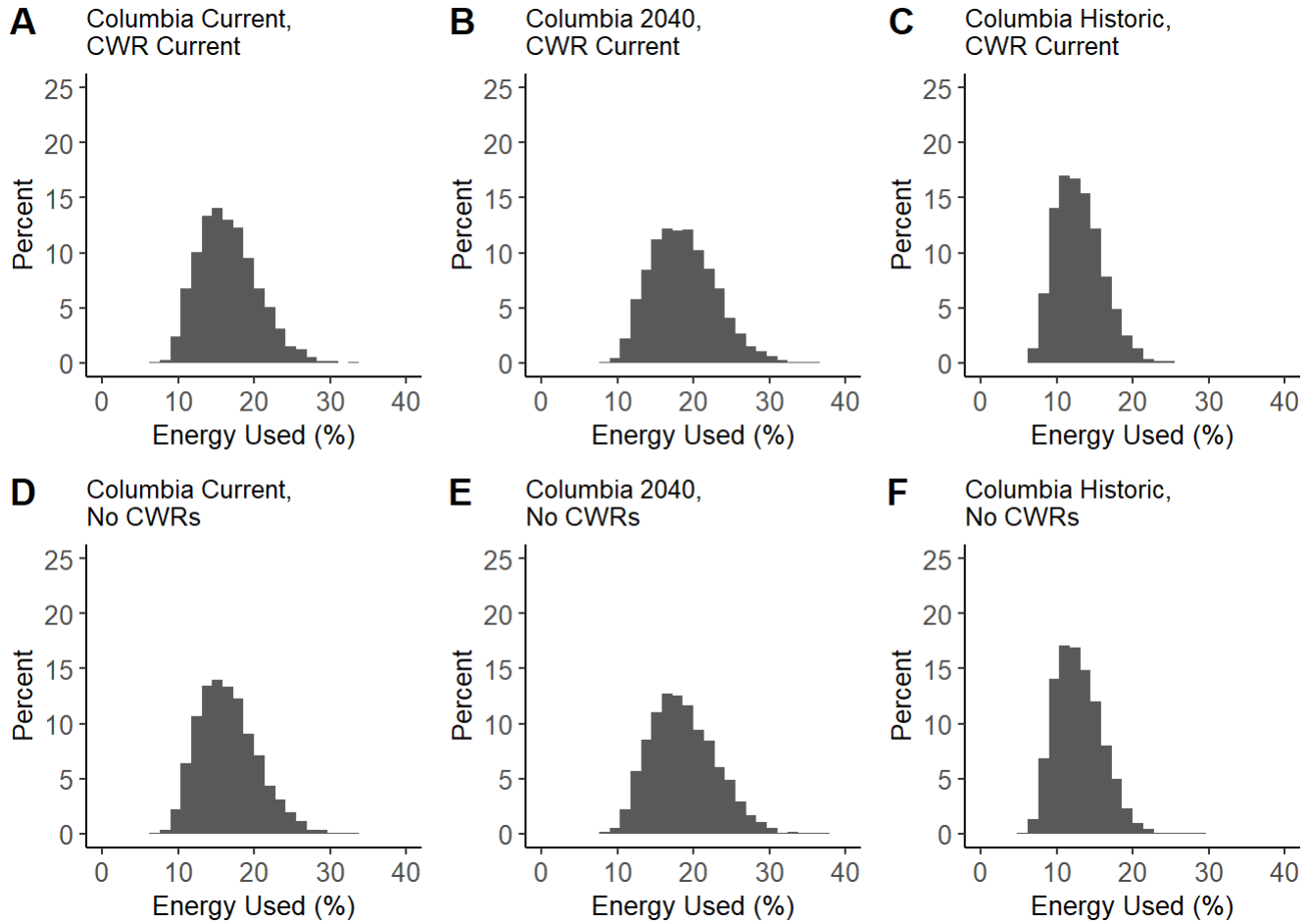
Fig. 8.1 Histogram of percent energy lost for modeled Hanford Reach Fall Chinook salmon migrating through six different modeled thermalscapes.
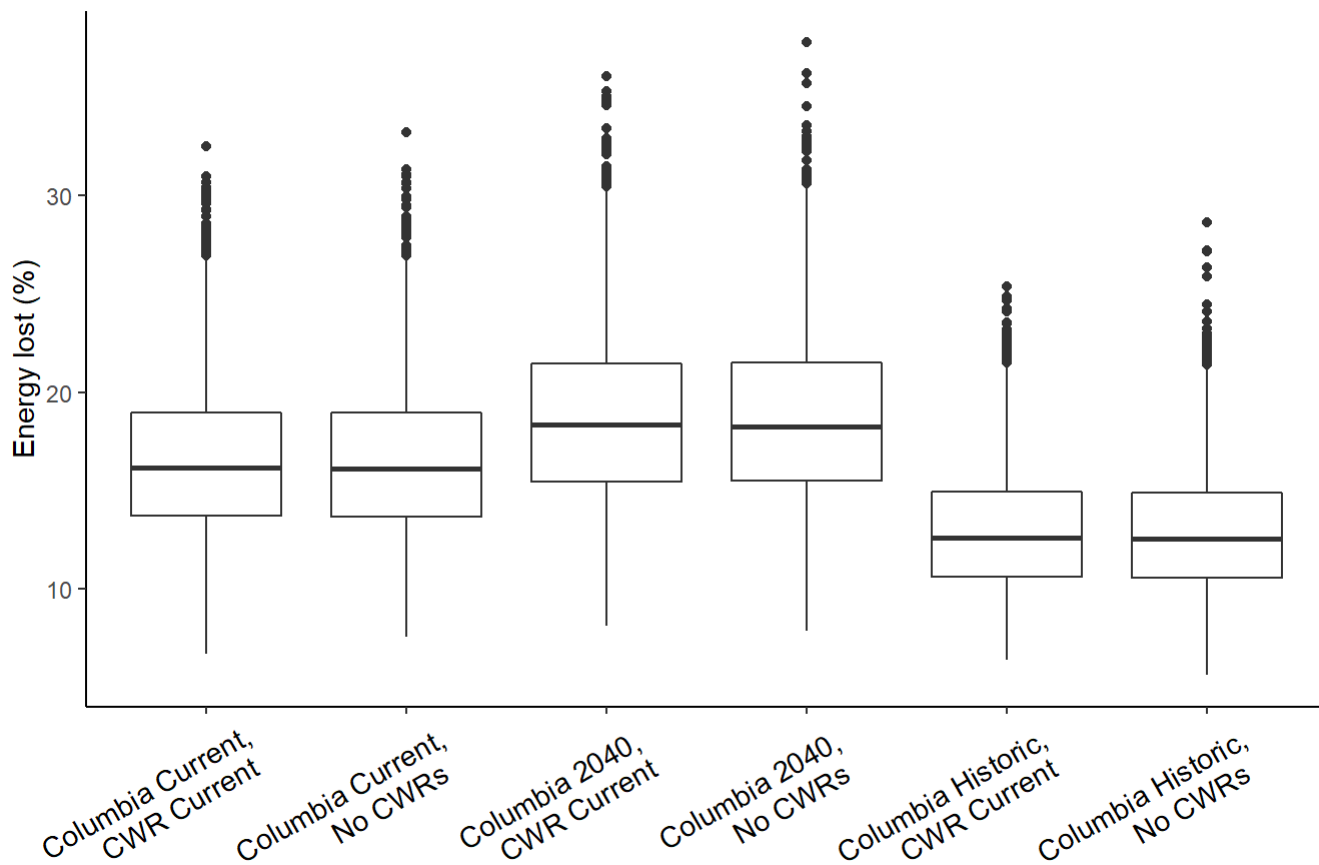
Fig. 8.2 Boxplot of percent energy lost for modeled Hanford Reach Fall Chinook migrating through six different modeled thermalscapes.

Table 8.1 Percent energy used across different HexSim thermalscapes summarized for Hanford Reach Fall Chinook.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2040, CWR Current	8.1	15.4	18.4	21.5	36.1
Columbia Historic, CWR Current	6.4	10.6	12.6	15.0	25.4
Columbia Current, CWR Current	6.7	13.7	16.2	19.0	32.5
Columbia 2040, No CWRs	7.9	15.5	18.2	21.5	37.8
Columbia Historic, No CWRs	5.6	10.6	12.6	14.9	28.7
Columbia Current, No CWRs	7.6	13.7	16.1	19.0	33.3

Table 8.2 Model output for hours residing in cold water refuges summarized for Hanford Reach Fall Chinook.

Scenario	CWR Residence (h/individual)
Columbia Current,CWR Current	8
Columbia Current, No CWRs	0

Scenario	CWR Residence (h/individual)
Columbia 2040, Current	16
Columbia 2040, No CWRs	0
Columbia Historic, Current	1
Columbia Historic, No CWRs	0

Table 8.3 Model output for percent of individuals dying from acute temperature stress summarized for Hanford Reach Fall Chinook.

Scenario	Total mortality
Columbia Current,CWR Current	0.00
Columbia Current, No CWRs	0.00
Columbia 2040, Current	0.00
Columbia 2040, No CWRs	0.03
Columbia Historic, Current	0.00
Columbia Historic, No CWRs	0.00

9. Cumulative degree days summary results for Grande Ronde River summer steelhead under year 2017 temperatures for the Columbia River
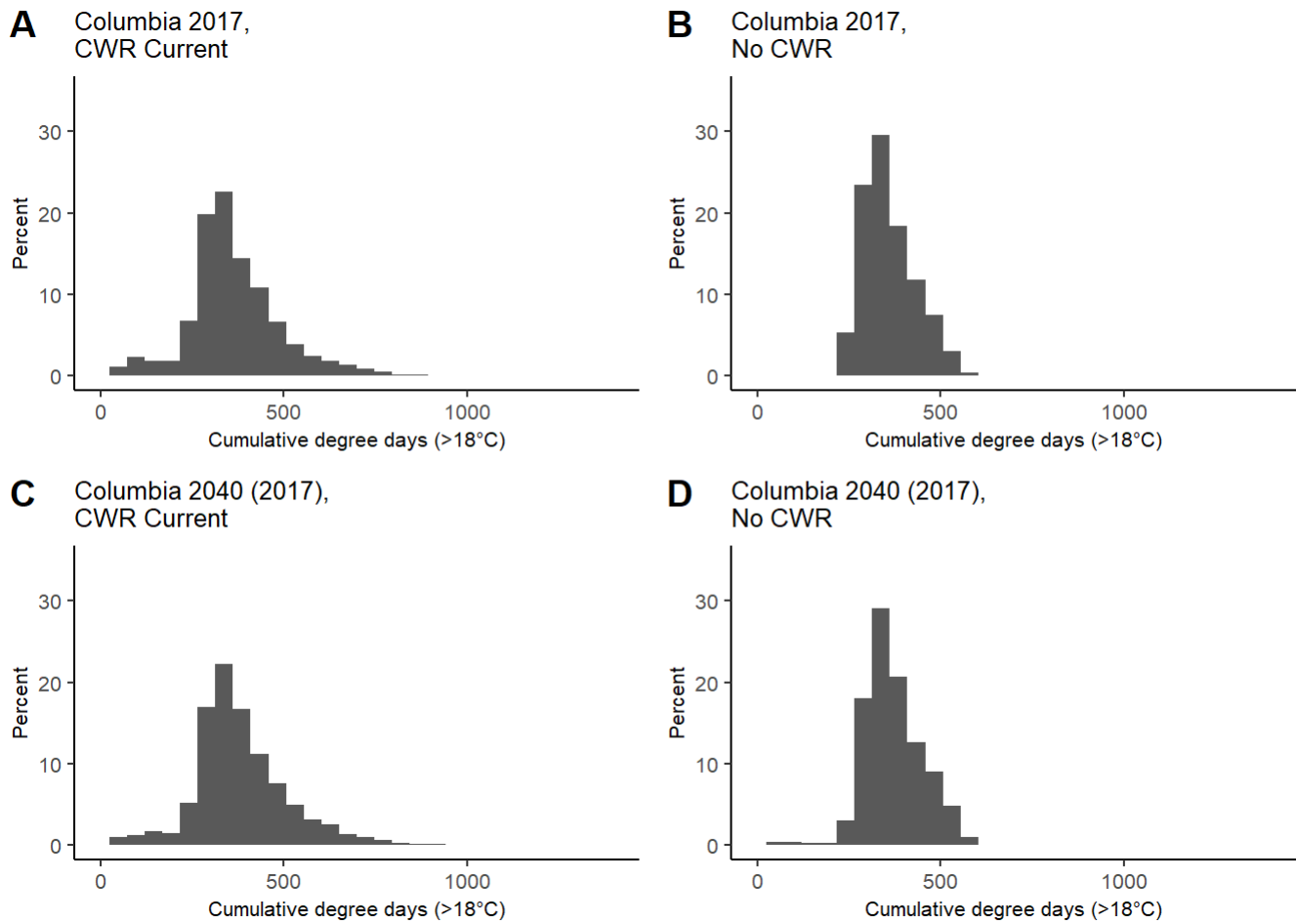
Fig. 9.1 Histograms of modeled Grande Ronde River summer steelhead accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.
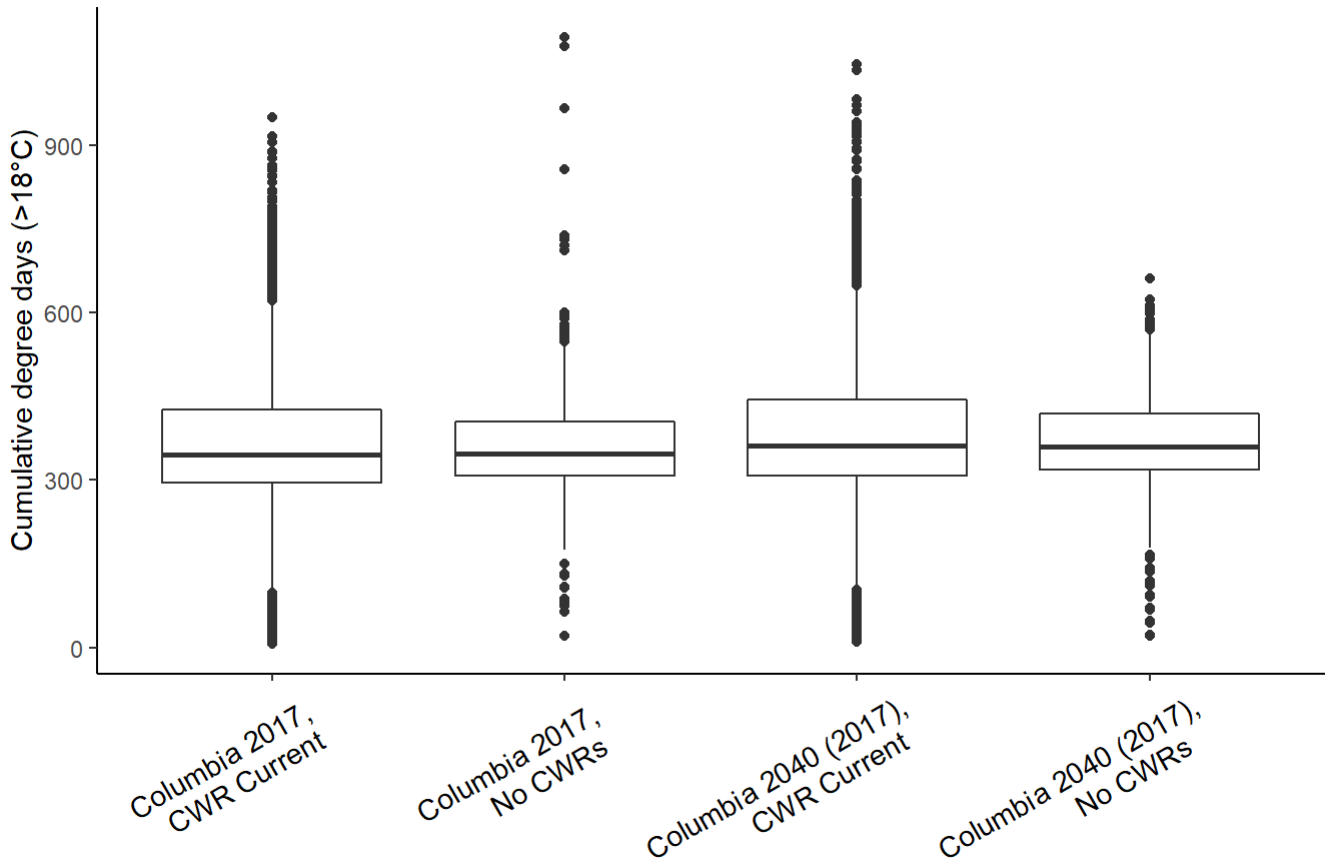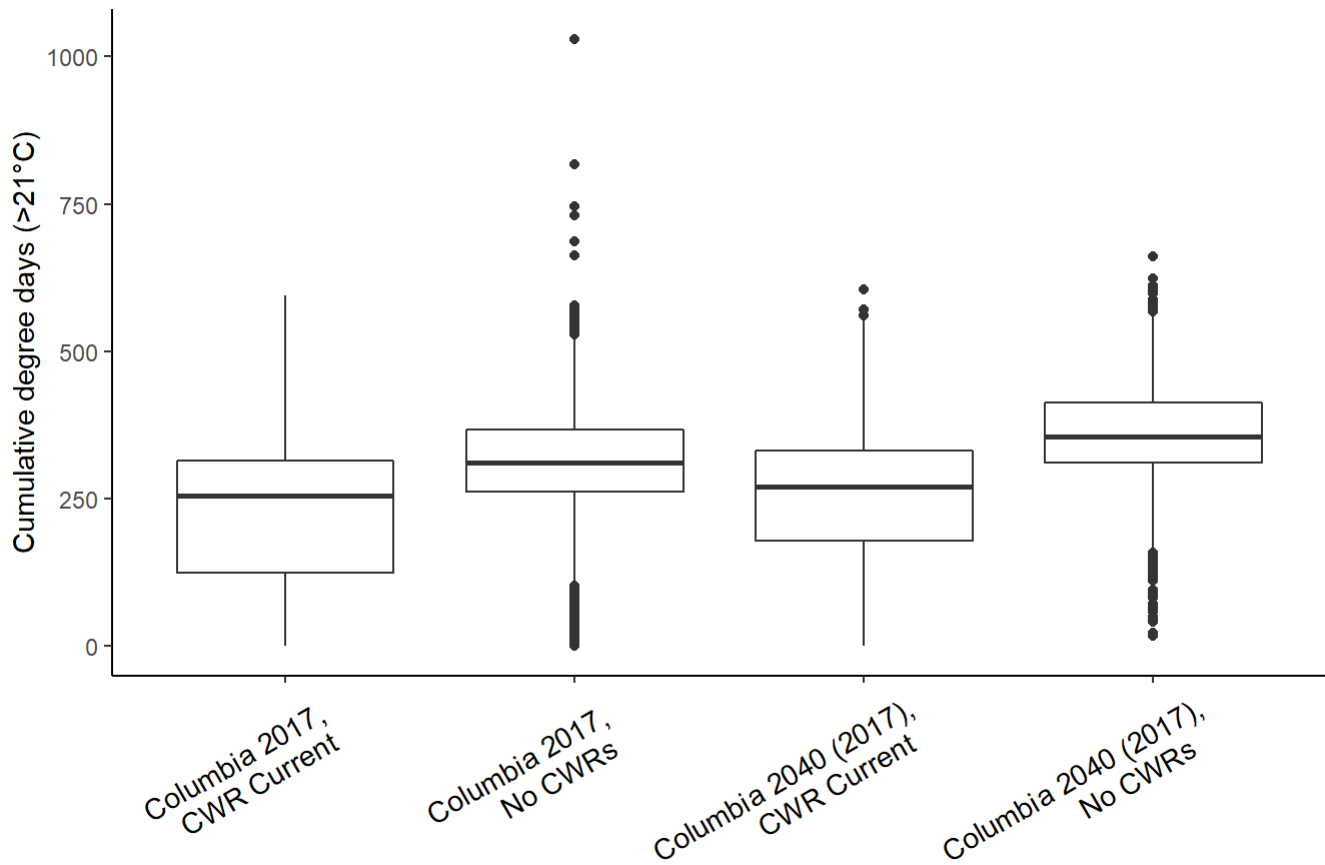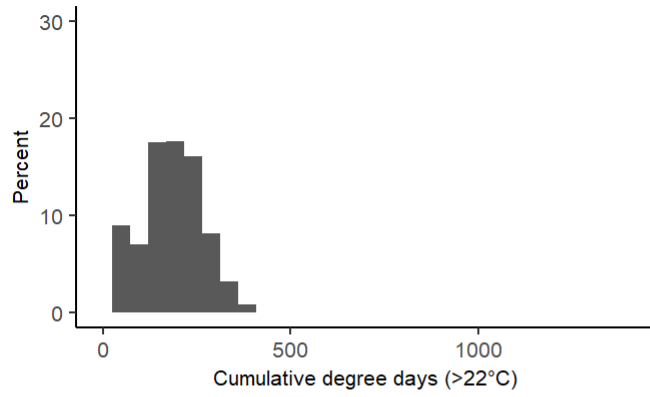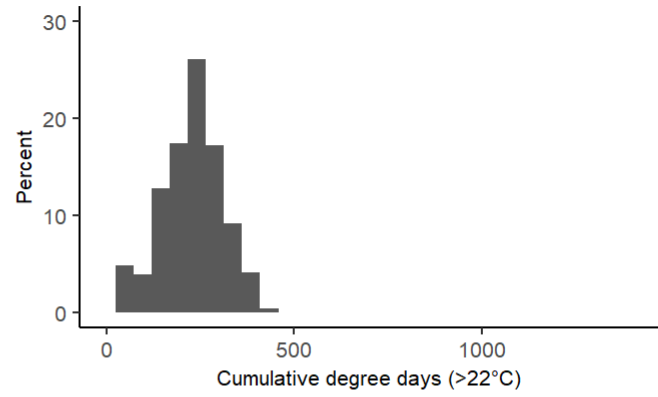
Fig. 9.2 Boxplots of modeled Grande Ronde River summer steelhead accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.

Table 9.1 Cumulative degree days (>18°C) used across different HexSim thermalscapes summarized for Grande Ronde River Summer Steelhead.

| Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2017, CWR Current	7	295	346	426	950
Columbia 2017, No CWR	21	308	347	404	1093
Columbia 2040 (2017), CWR Current	11	308	362	444	1044
Columbia 2040 (2017), No CWR	22	318	359	418	661
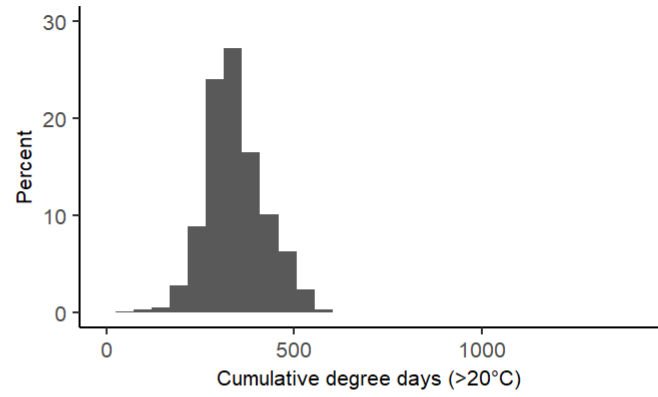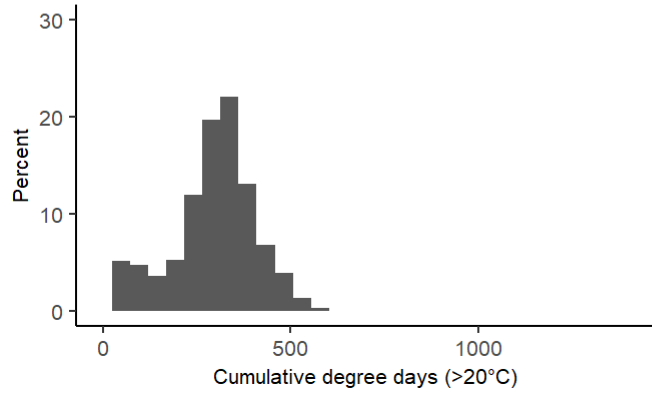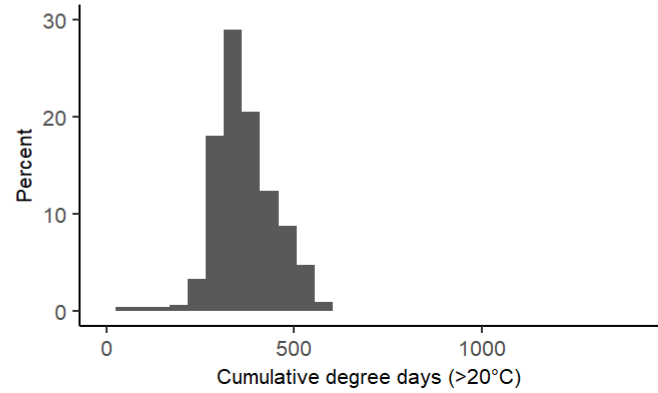
Fig. 9.3 Histograms of modeled Grande Ronde River summer steelhead accumulated degrees day over 20°C from Bonneville to the Snake River confluence in the Columbia River.
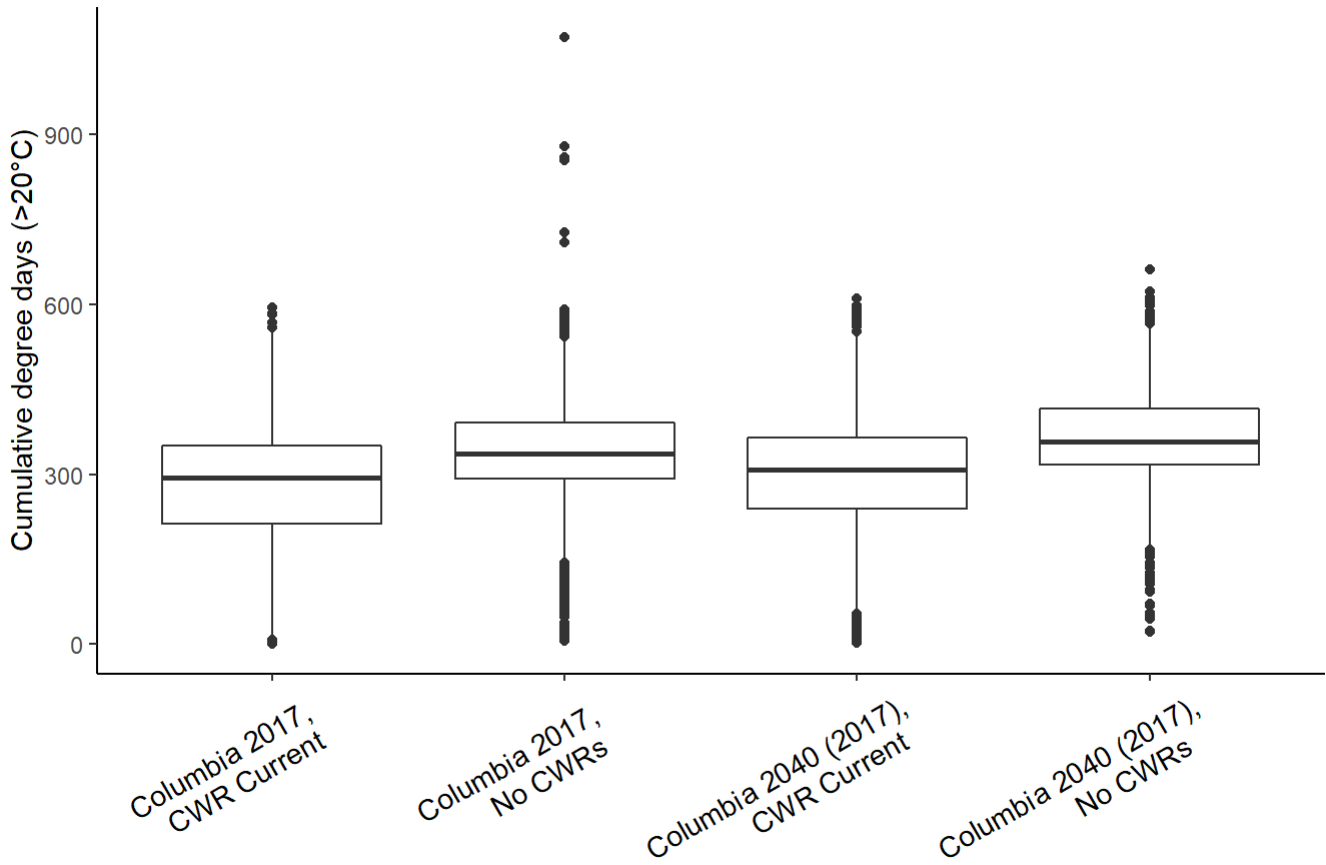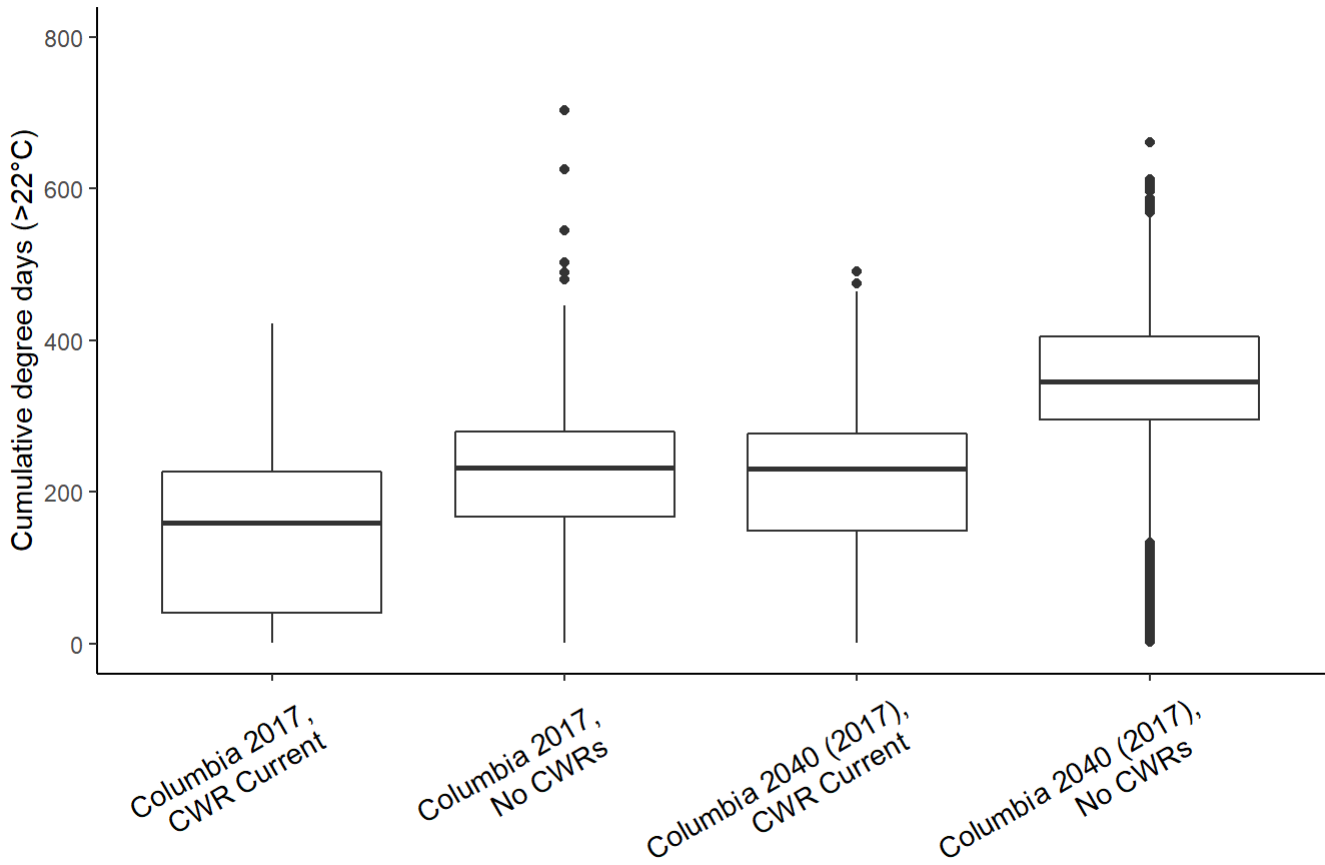
Fig. 9.4 Boxplots of modeled Grande Ronde River summer steelhead accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.

Table 9.2 Cumulative degree days (>20°C) used across different HexSim thermalscapes summarized for Grande Ronde River Summer Steelhead.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2017, CWR Current	1	213	294	351	596
Columbia 2017, No CWR	5	293	336	392	1072
Columbia 2040 (2017), CWR Current	2	240	308	364	610
Columbia 2040 (2017), No CWR	22	316	358	416	661
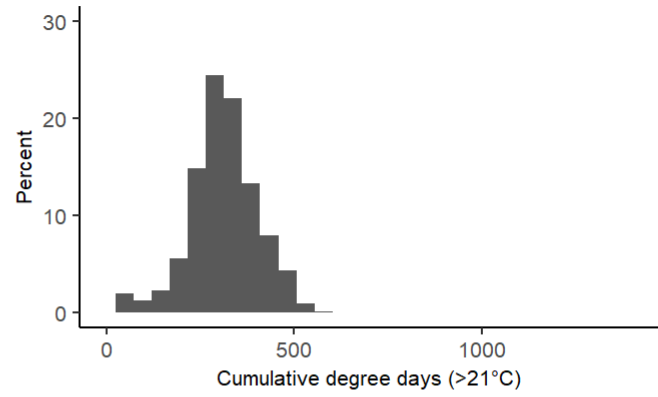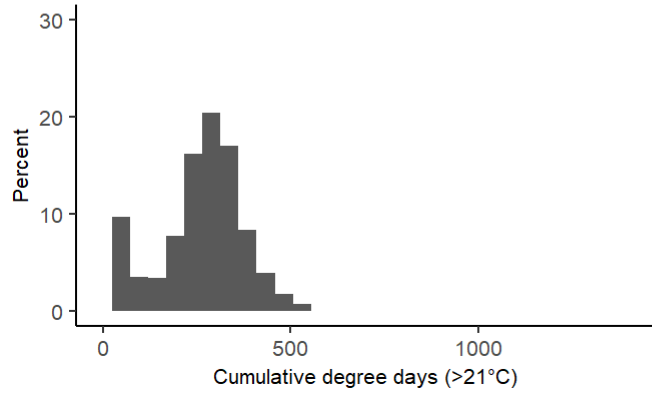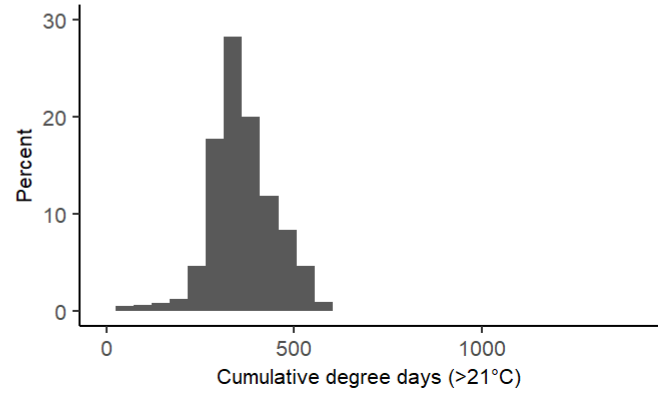
Fig. 9.5 Histograms of modeled Grande Ronde River summer steelhead accumulated degrees day over 21°C from Bonneville to the Snake River confluence in the Columbia River.

Fig. 9.6 Boxplots of modeled Grande Ronde River summer steelhead accumulated degrees day over 21°C from Bonneville to the Snake River confluence in the Columbia River.

Table 9.3 Cumulative degree days (>21°C) used across different HexSim thermalscapes summarized for Grande Ronde River Summer Steelhead.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2017, CWR Current	1	124	255	315	596
Columbia 2017, No CWR	1	262	312	368	1030
Columbia 2040 (2017), CWR Current	1	179	271	332	606
Columbia 2040 (2017), No CWR	17	312	355	414	661
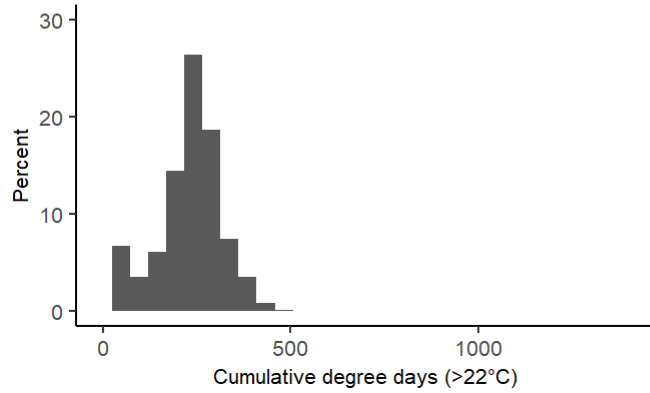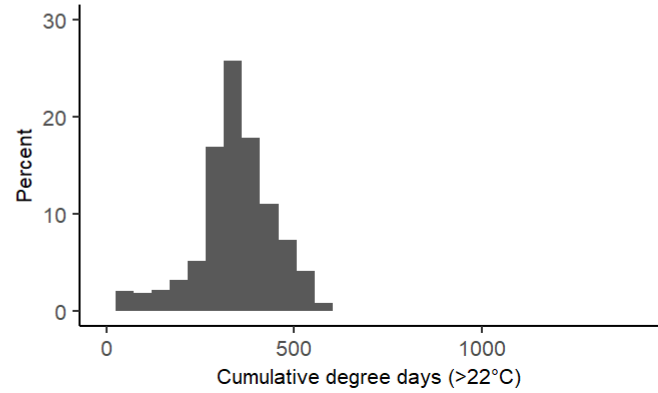
Fig. 9.7 Histograms of modeled Grande Ronde River summer steelhead accumulated degrees day over 22°C from Bonneville to the Snake River confluence in the Columbia River.

Fig. 9.8 Boxplots of modeled Grande Ronde River summer steelhead accumulated degrees day over 22°C from Bonneville to the Snake River confluence in the Columbia River.

Table 9.4 Cumulative degree days (>22°C) used across different HexSim thermalscapes summarized for Grande Ronde River Summer Steelhead.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2017, CWR Current	1	41	160	227	422
Columbia 2017, No CWR	1	168	232	280	703
Columbia 2040 (2017), CWR Current	1	149	231	277	491
Columbia 2040 (2017), No CWR	2	296	346	405	661

10. Energy use, CWR use, and survivorship results for Grande Ronde River summer steelhead under year 2017 temperatures for the Columbia River
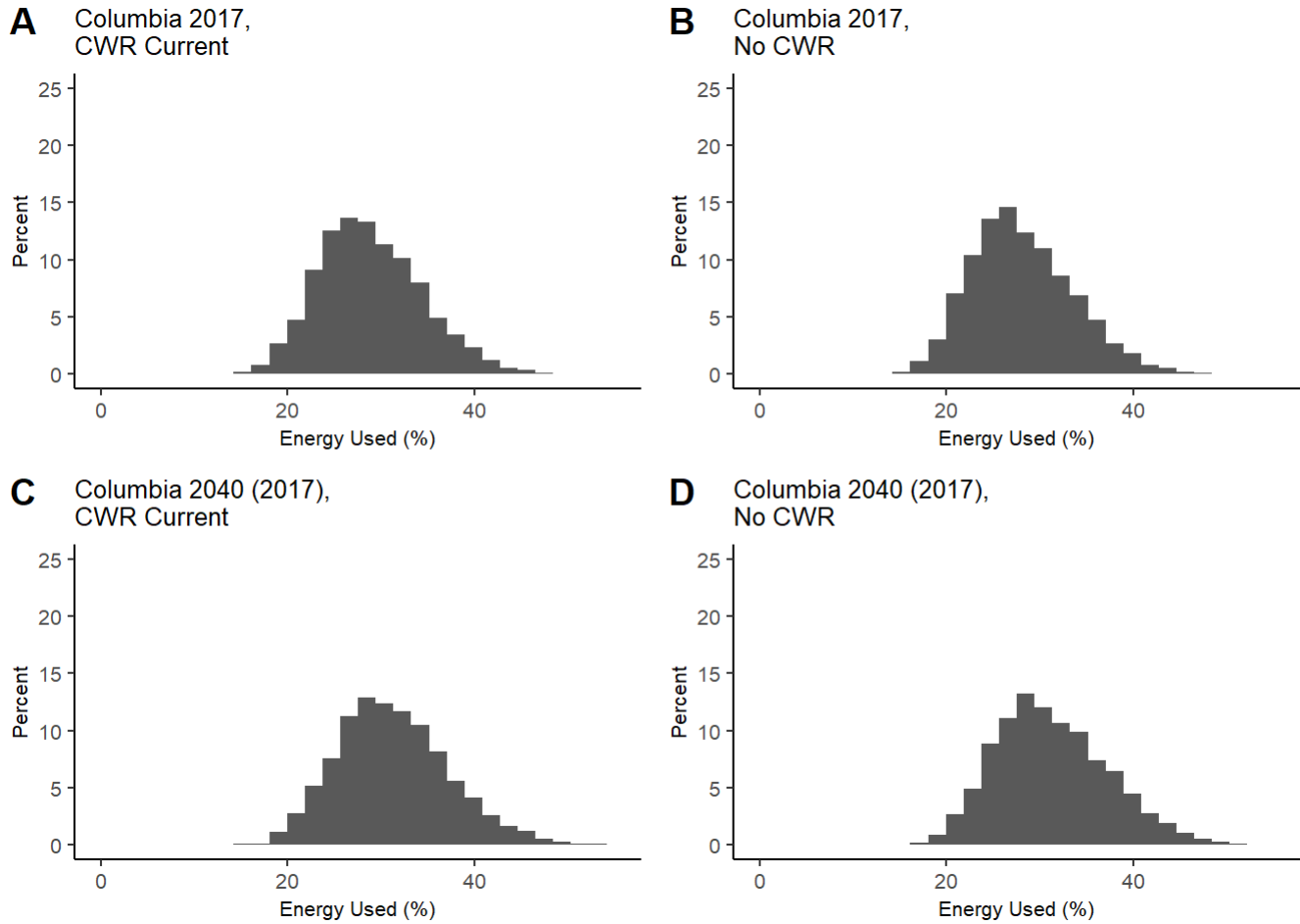
Fig. 10.1 Histogram of percent energy lost for modeled Grande Ronde summer steelhead migrating through different modeled thermalscapes.
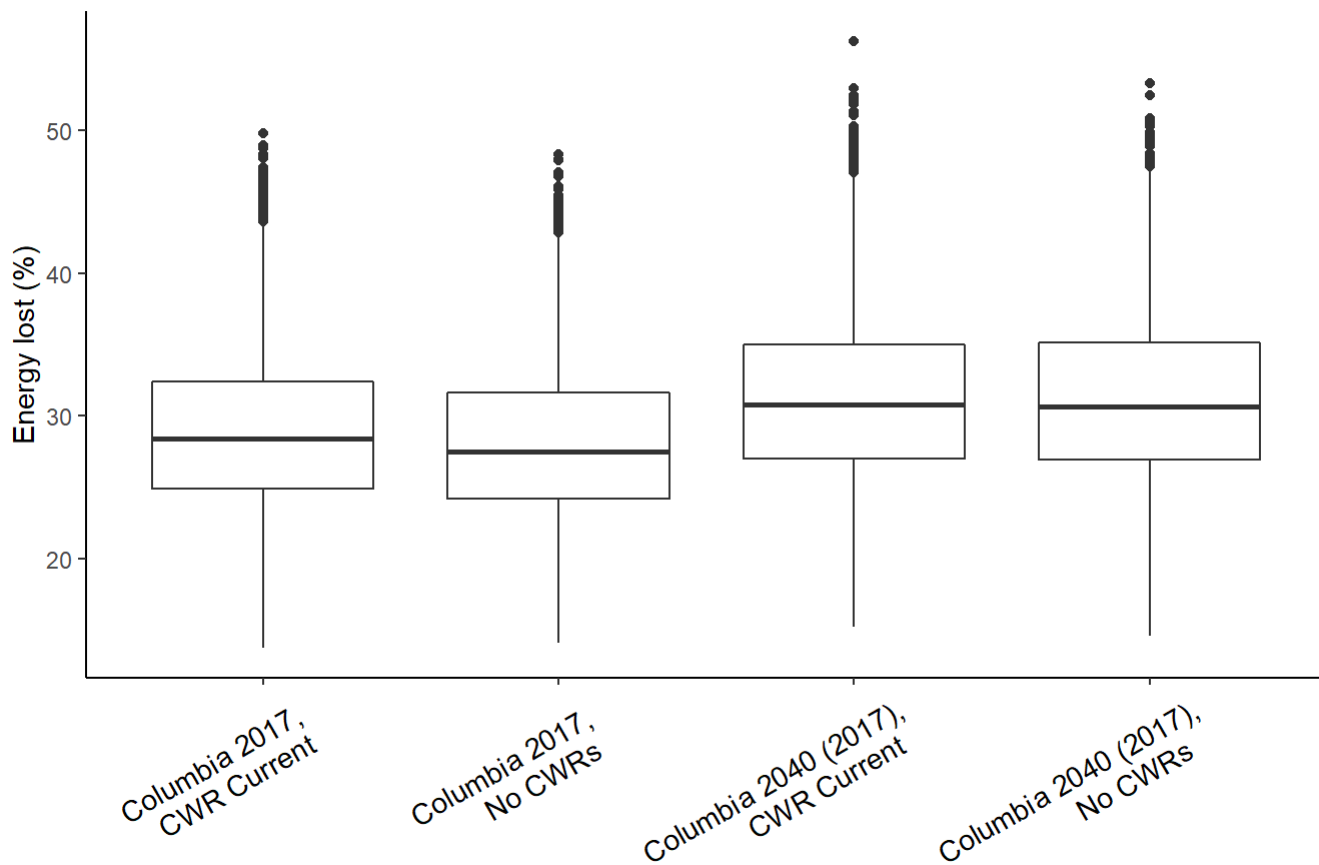
Fig. 10.2 Boxplot of percent energy lost for modeled Grande Ronde summer steelhead migrating through different modeled thermalscapes.

Table 10.1 Percent energy used across different HexSim thermalscapes summarized for Grande Ronde River Summer Steelhead.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2017, CWR Current	14	25	28	32	50
Columbia 2017, No CWR	14	24	27	32	48
Columbia 2017, CWR Current	15	27	31	35	56
Columbia 2017, No CWR	15	27	31	35	53

Table 10.2 Model output for hours residing in cold water refuges summarized for Grande Ronde River Summer Steelhead.

Scenario	CWR Residence (h/individual)
Columbia 2017,CWR Current	474
Columbia 2017, No CWRs	4
Columbia 2040 (2017), Current	500
Columbia 2040 (2017), No CWRs	0

Table 10.3 Model output for percent of individuals dying from acute temperature stress summarized for Grande Ronde River Summer Steelhead.

Scenario	Total mortality
Columbia 2017,CWR Current	0.23
Columbia 2017, No CWRs	0.53
Columbia 2040 (2017), Current	1.07
Columbia 2040 (2017), No CWRs	1.90

11. Cumulative degree days summary results for Snake River Fall Chinook Salmon under year 2017 temperatures for the Columbia River
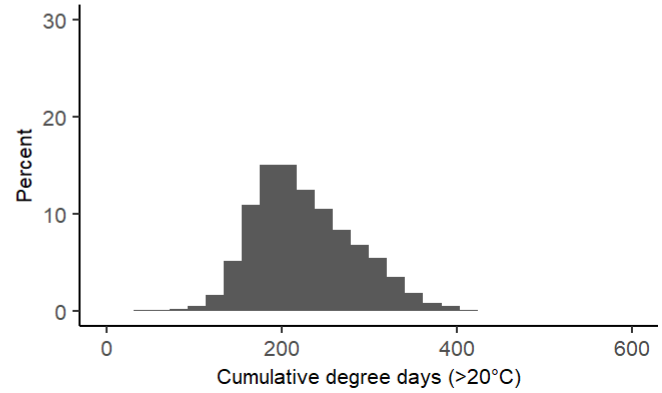

Fig. 11.1 Histograms of modeled Snake River fall chinook accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.
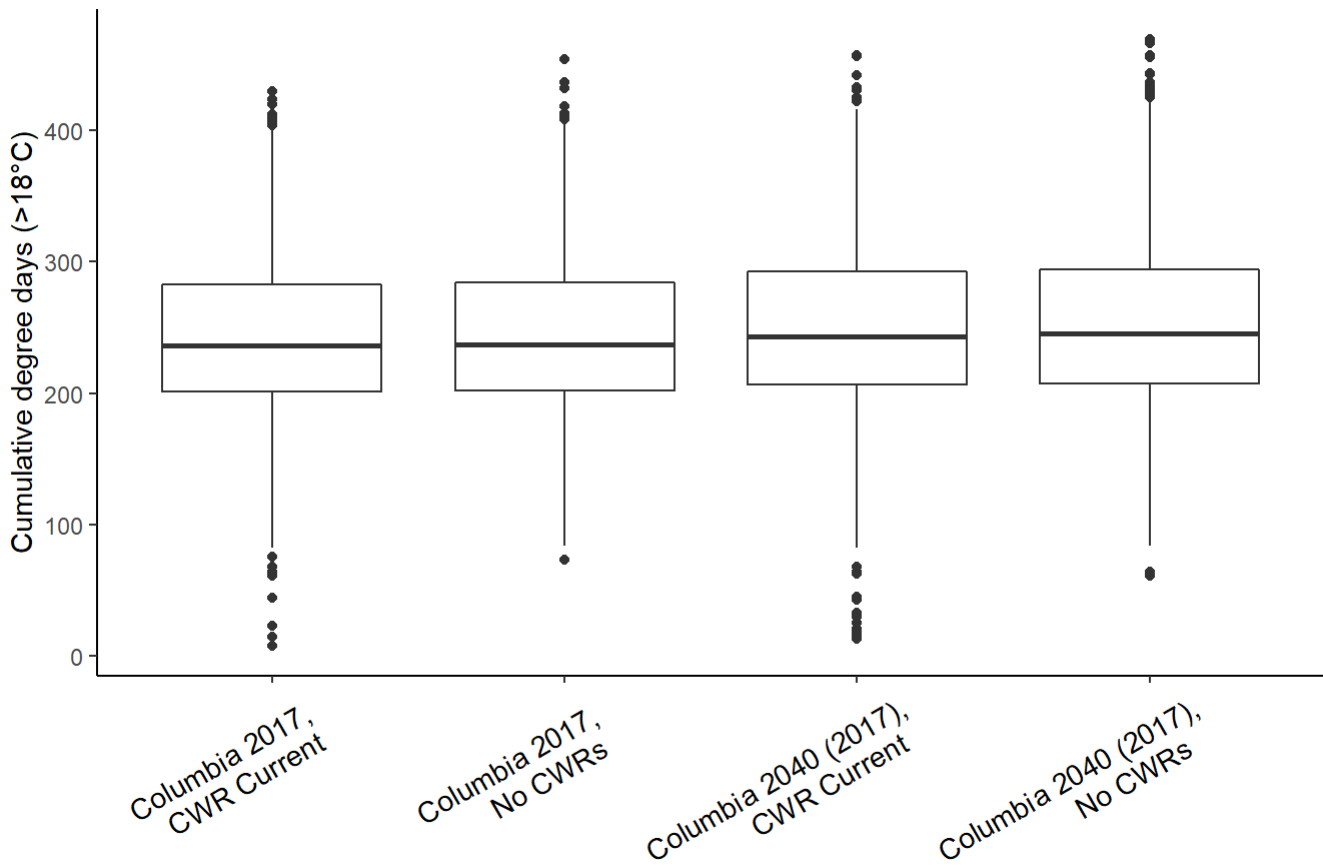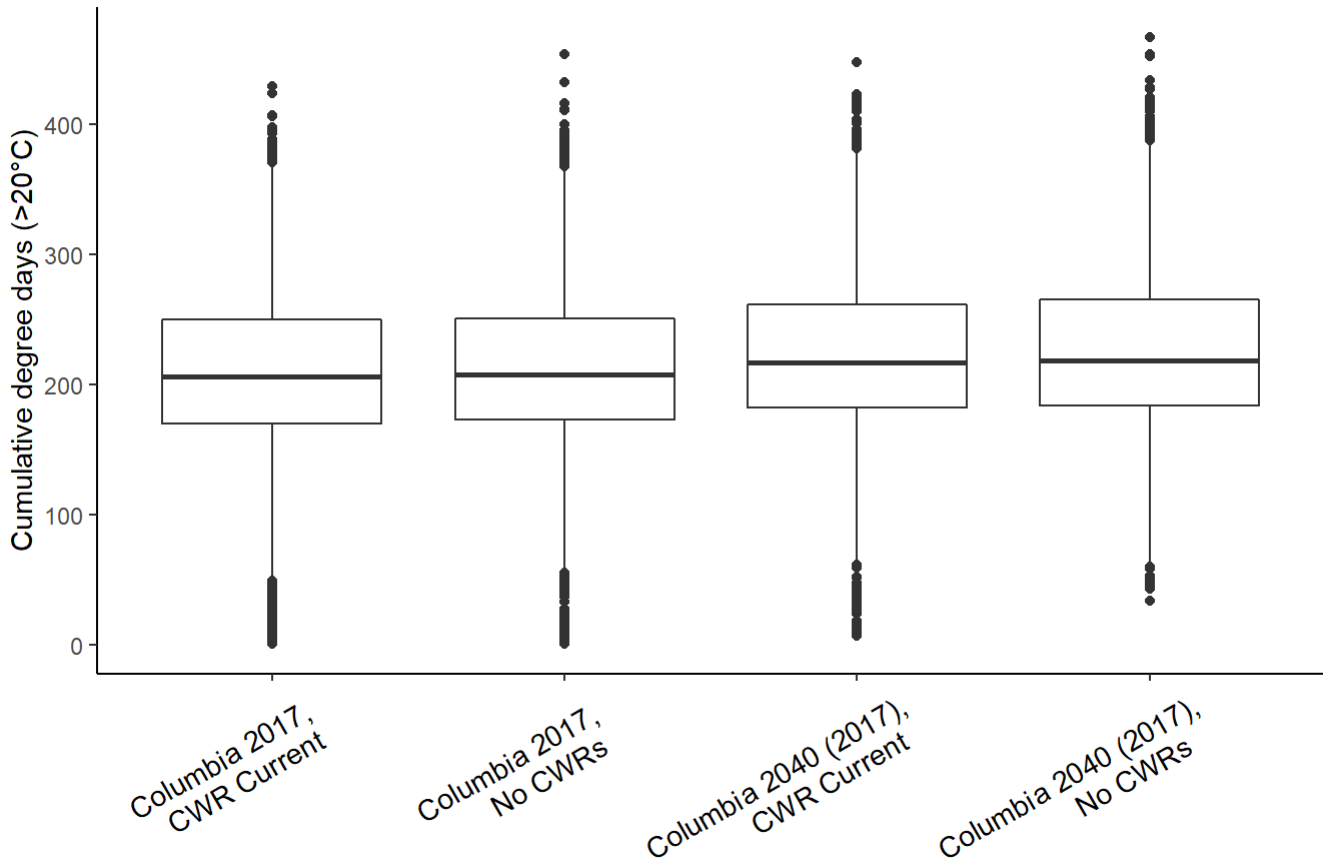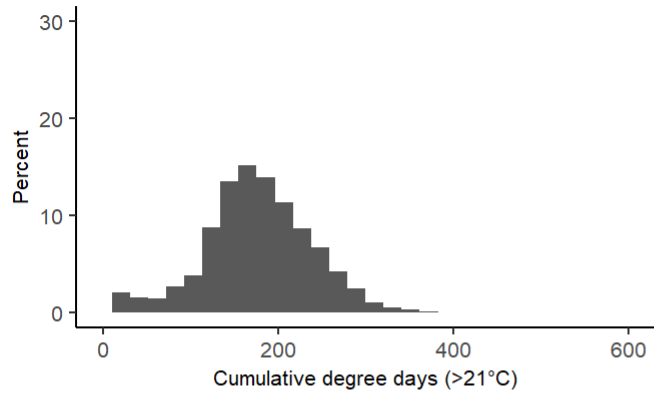
Fig. 11.2 Boxplots of modeled Snake River fall chinook accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.
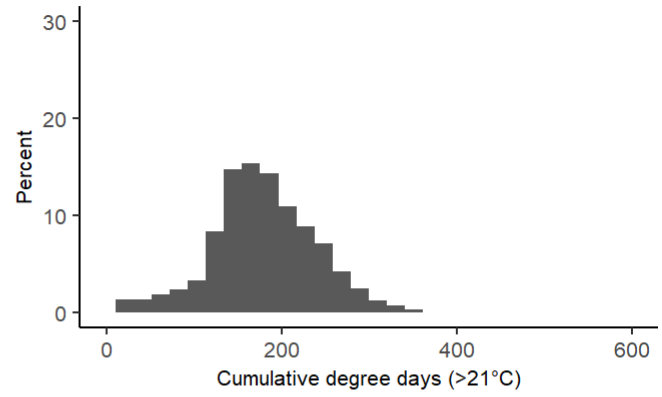
Table 11.1 Cumulative degree days (>18°C) used across different HexSim thermalscapes summarized for Snake River River fall chinook.

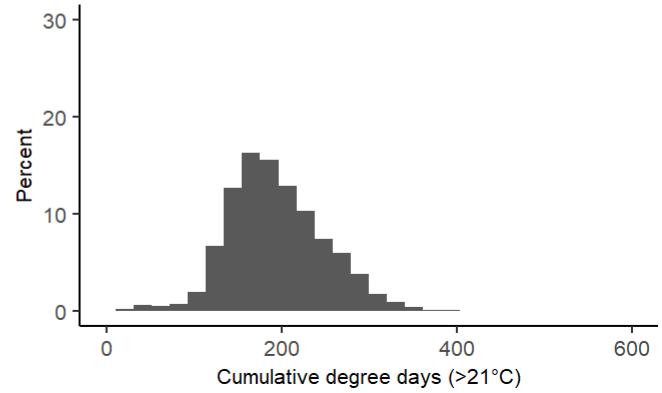| Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2017, CWR Current	8	202	237	283	430
Columbia 2017, No CWR	73	202	237	284	454
Columbia 2040 (2017), CWR Current	13	207	243	293	458
Columbia 2040 (2017), No CWR	61	207	245	295	470

Fig. 11.3 Histograms of modeled Snake River fall chinook accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.

Fig. 11.4 Boxplots of modeled Snake River fall chinook accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.

Table 11.2 Cumulative degree days (>20°C) used across different HexSim thermalscapes summarized for Snake River River fall chinook.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2017, CWR Current	1	170	206	250	429
Columbia 2017, No CWR	1	173	208	251	454
Columbia 2040 (2017), CWR Current	7	183	217	262	448
Columbia 2040 (2017), No CWR	33	184	219	265	467

Fig. 11.5 Histograms of modeled Snake River fall chinook accumulated degrees day over 21°C from Bonneville to the Snake River confluence in the Columbia River.
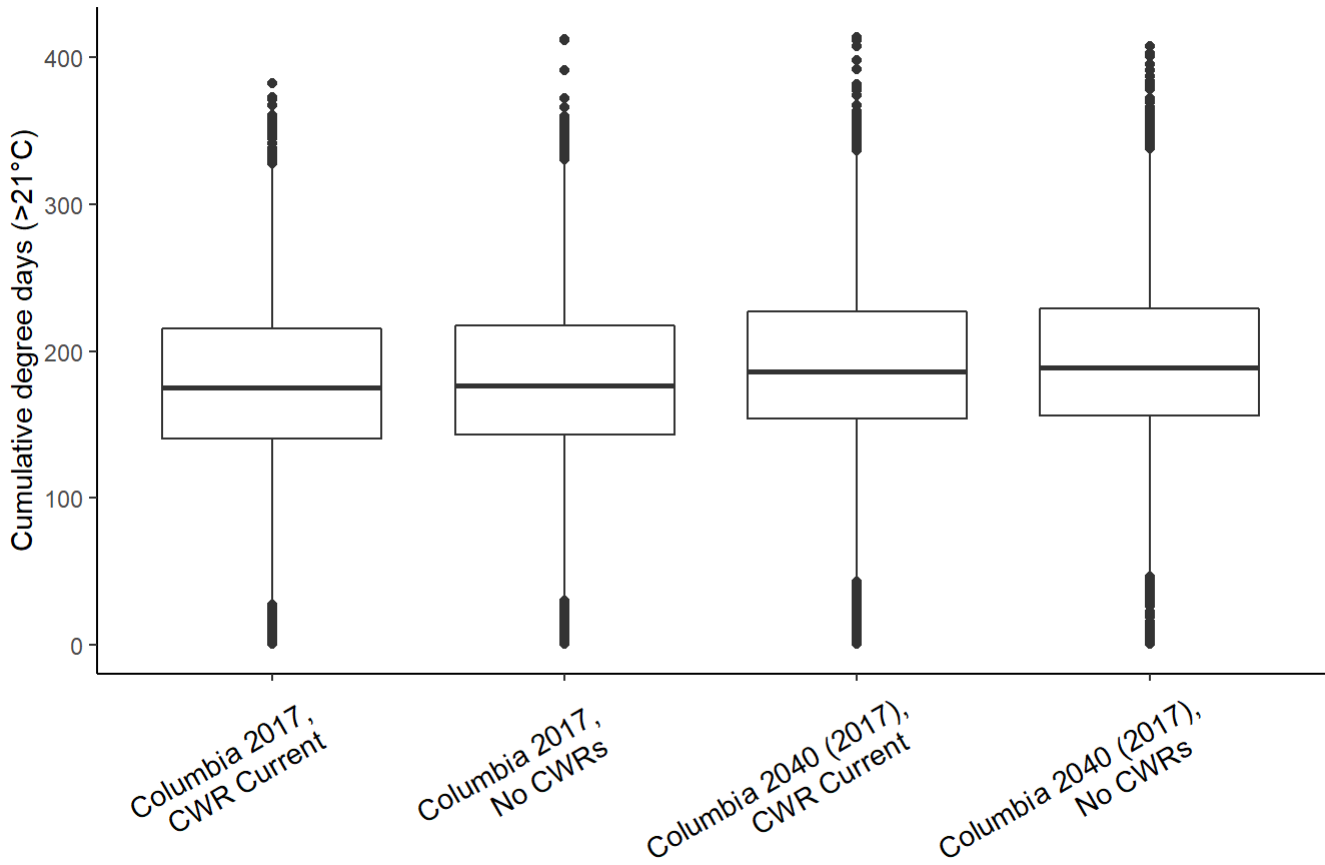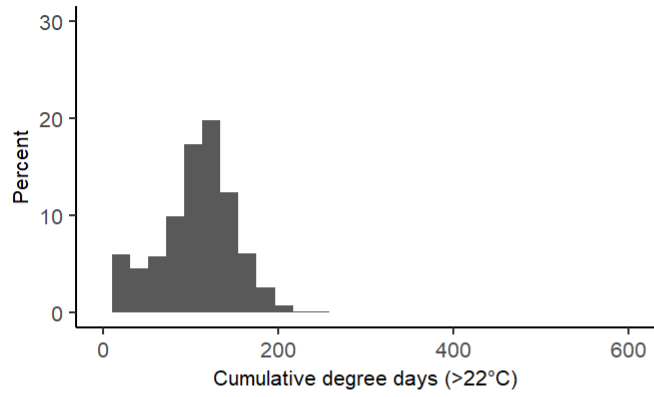
Fig. 11.6 Boxplots of modeled Snake River fall chinook accumulated degrees day over 21°C from Bonneville to the Snake River confluence in the Columbia River.
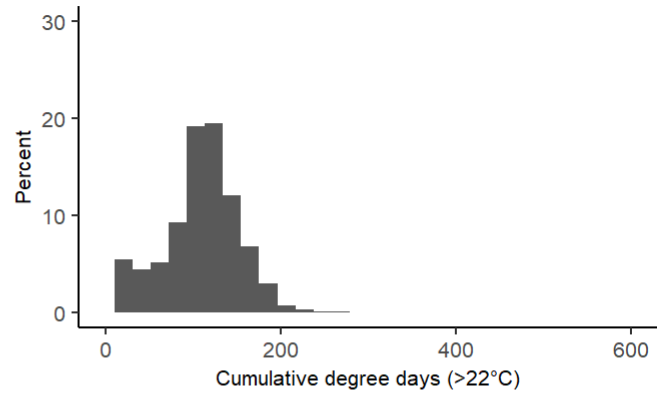
Table 11.3 Cumulative degree days (>21°C) used across different HexSim thermalscapes summarized for Snake River River fall chinook.

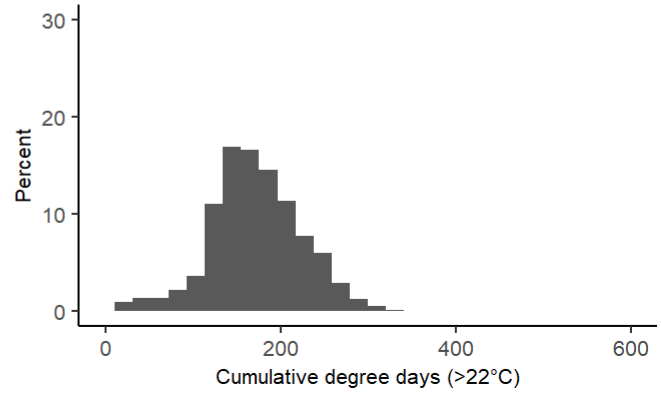| Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2017, CWR Current	1	140	175	215	383
Columbia 2017, No CWR	1	143	177	218	412
Columbia 2040 (2017), CWR Current	1	154	186	227	414
Columbia 2040 (2017), No CWR	1	156	188	229	408

Fig. 11.7 Histograms of modeled Snake River fall chinook accumulated degrees day over 22°C from Bonneville to the Snake River confluence in the Columbia River.
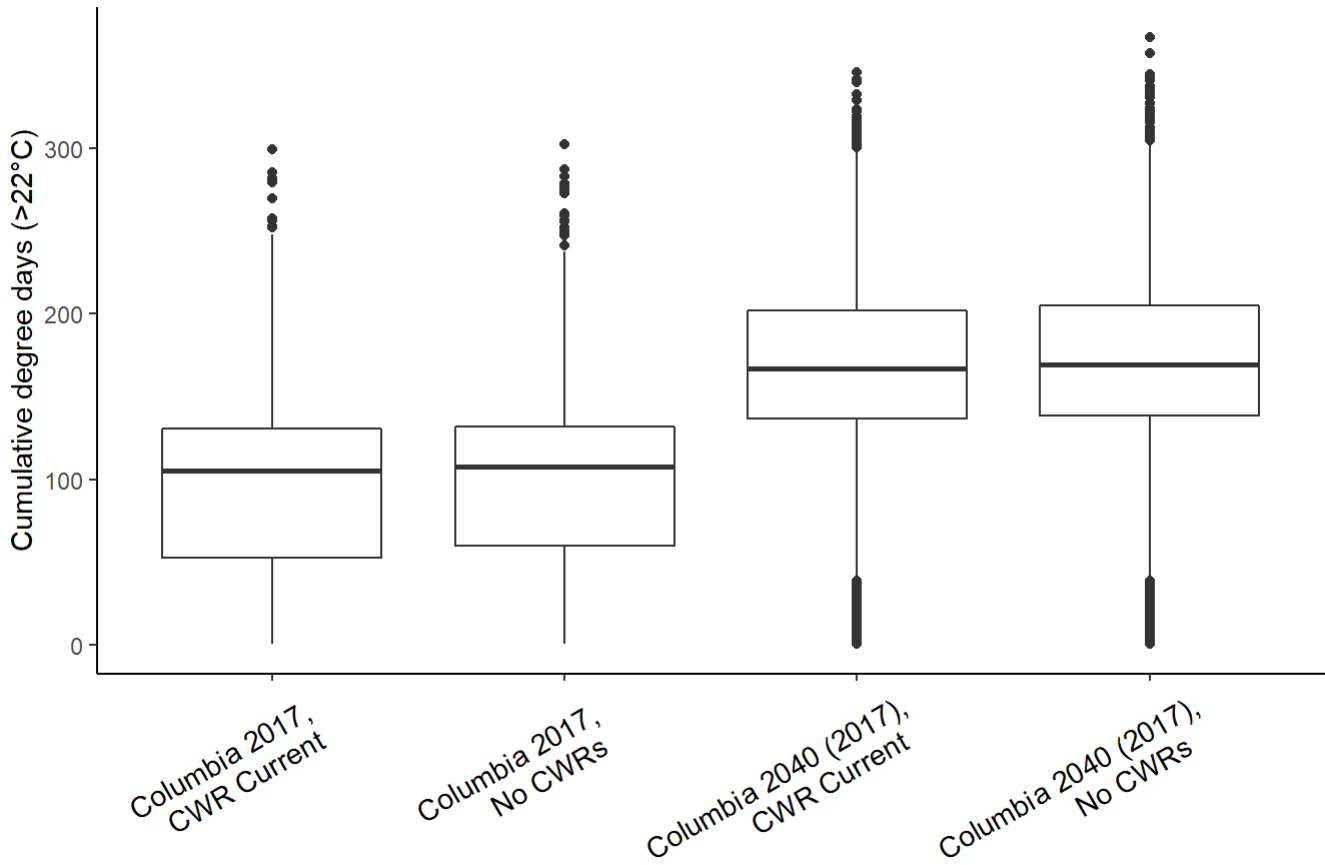
Snake River River fall chinook

Fig. 11.8 Boxplots of modeled Snake River fall chinook accumulated degrees day over 22°C from Bonneville to the Snake River confluence in the Columbia River.

Table 11.4 Cumulative degree days (>22°C) used across different HexSim thermalscapes summarized for Snake River River fall chinook.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2017, CWR Current	1	52	106	131	299
Columbia 2017, No CWR	1	60	108	132	302
Columbia 2040 (2017), CWR Current	1	137	167	202	346
Columbia 2040 (2017), No CWR	1	139	169	205	367

12. Energy use, CWR use, and survivorship results for Snake River Fall Chinook Salmon under year 2017 temperatures for the Columbia River
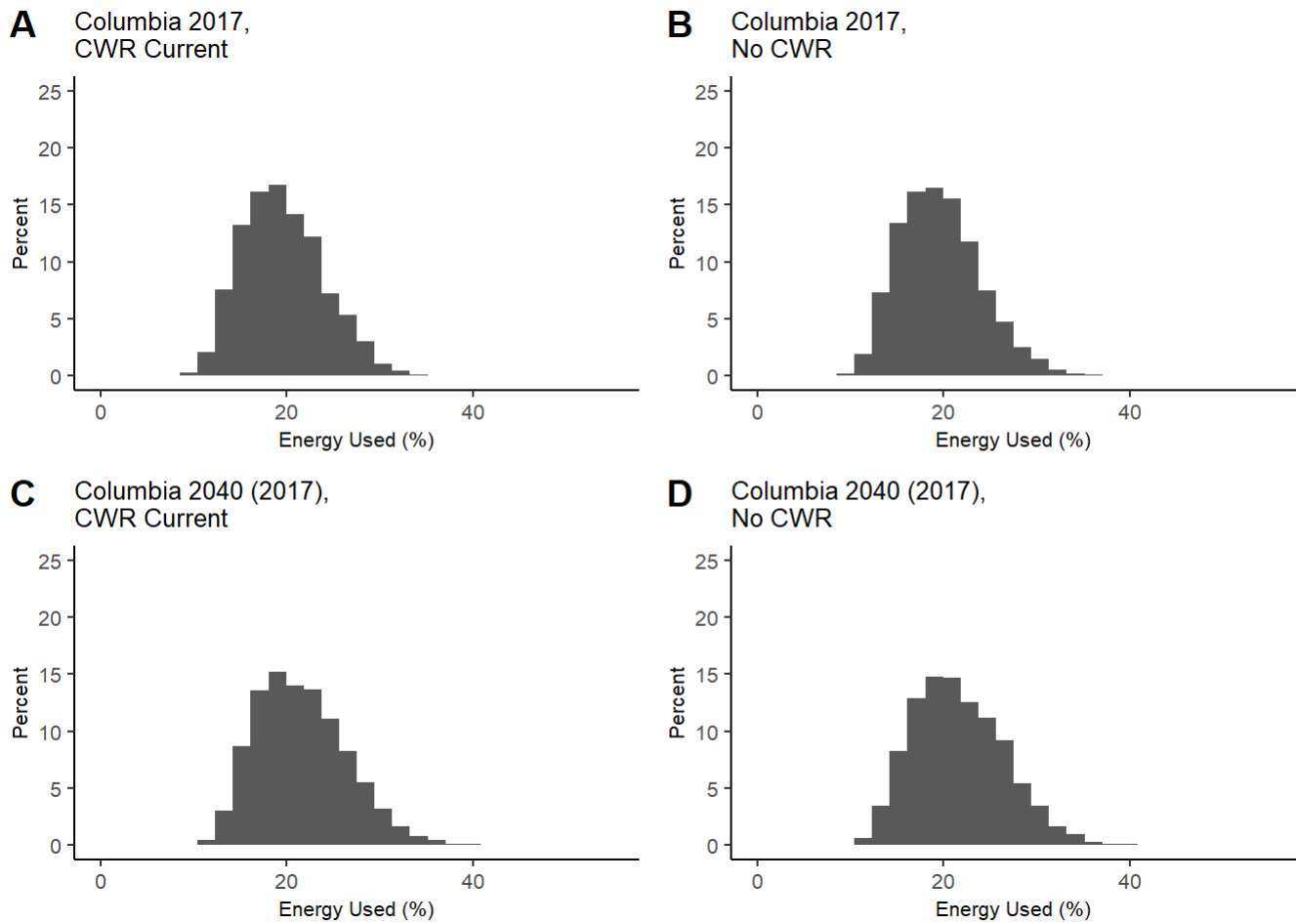
A Columbia 2017,
CWR Current

B Columbia 2017,
No CWR

C Columbia 2040 (2017),
CWR Current

D Columbia 2040 (2017),
No CWR

Fig. 12.1 Histogram of percent energy lost for modeled Snake River fall Chinook migrating through four different modeled thermalscapes.
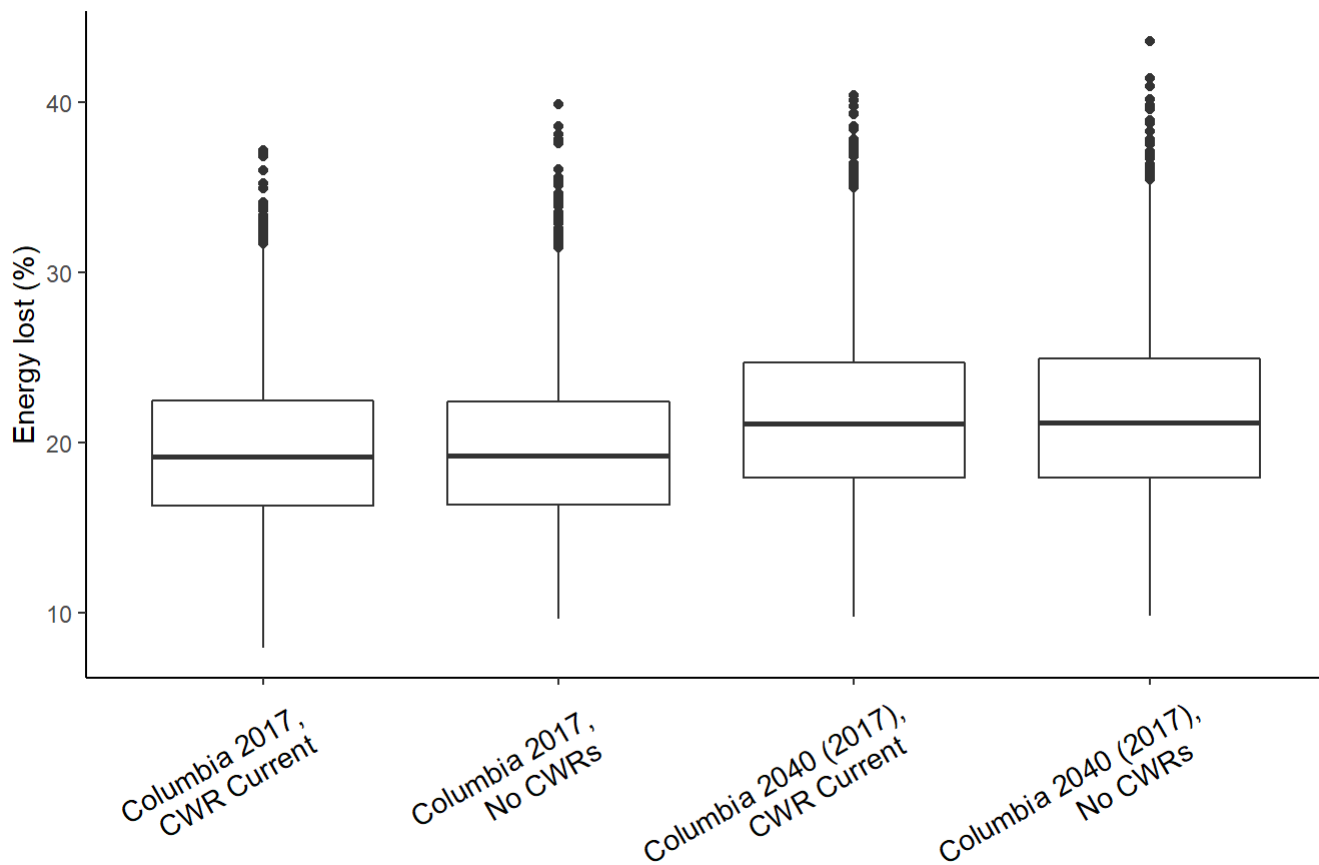
Fig. 12.2 Boxplot of percent energy lost for modeled Snake River fall Chinook migrating through four different modeled thermalscapes.

Table 12.1 Percent energy used across different HexSim thermalscapes summarized for Snake River fall Chinook.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2017, CWR Current	8.0	16.3	19.2	22.5	37.2
Columbia 2017, No CWR	9.7	16.4	19.2	22.4	39.9
Columbia 2017, CWR Current	9.8	17.9	21.1	24.8	40.4
Columbia 2017, No CWR	9.9	18.0	21.2	25.0	43.6

Table 12.2 Model output for hours residing in cold water refuges summarized for Snake River fall Chinook.

Scenario	CWR Residence (h/individual)
Columbia 2017,CWR Current	11
Columbia 2017, No CWRs	0
Columbia 2040 (2017), Current	14
Columbia 2040 (2017), No CWRs	0

Table 12.3 Model output for percent of individuals dying from acute temperature stress summarized for Snake

River fall Chinook.

Scenario	Total mortality
Columbia 2017,CWR Current	0.13
Columbia 2017, No CWRs	0.08
Columbia 2040 (2017), Current	0.70
Columbia 2040 (2017), No CWRs	0.68

13. Sensitivity testing of acute temperature stress curve

To evaluate uncertainty around how acute temperature stress influences fish fitness outcomes we performed a sensitivity analysis of the acute temperature stress curve. Sensitivity tests were based on a typical recent temperature year (2017) for the Columbia River. The effect of changing the shape of the temperature stress survival curve was measured on percent mortality. Two different curves were evaluated: an exponential relationship with LC10 and LC50 values from Jager et al. 2011 (exponential) and a curve defined in Sullivan et al. 2000 (logistic). The default acute temperature stress equation was based on the curve from the InStream model (Railsback et al. 2009). We compared three thermalscapes to the current thermalscape with CWRs: current year 2017 Columbia River temperatures without CWRs, warmer Columbia River (year 2017 +1°C), and warmer Columbia River (year 2017 +1°C without CWRs). We modeled the Grande Ronde Summer Steelhead population because of their large range in propensity to behaviorally thermoregulate.
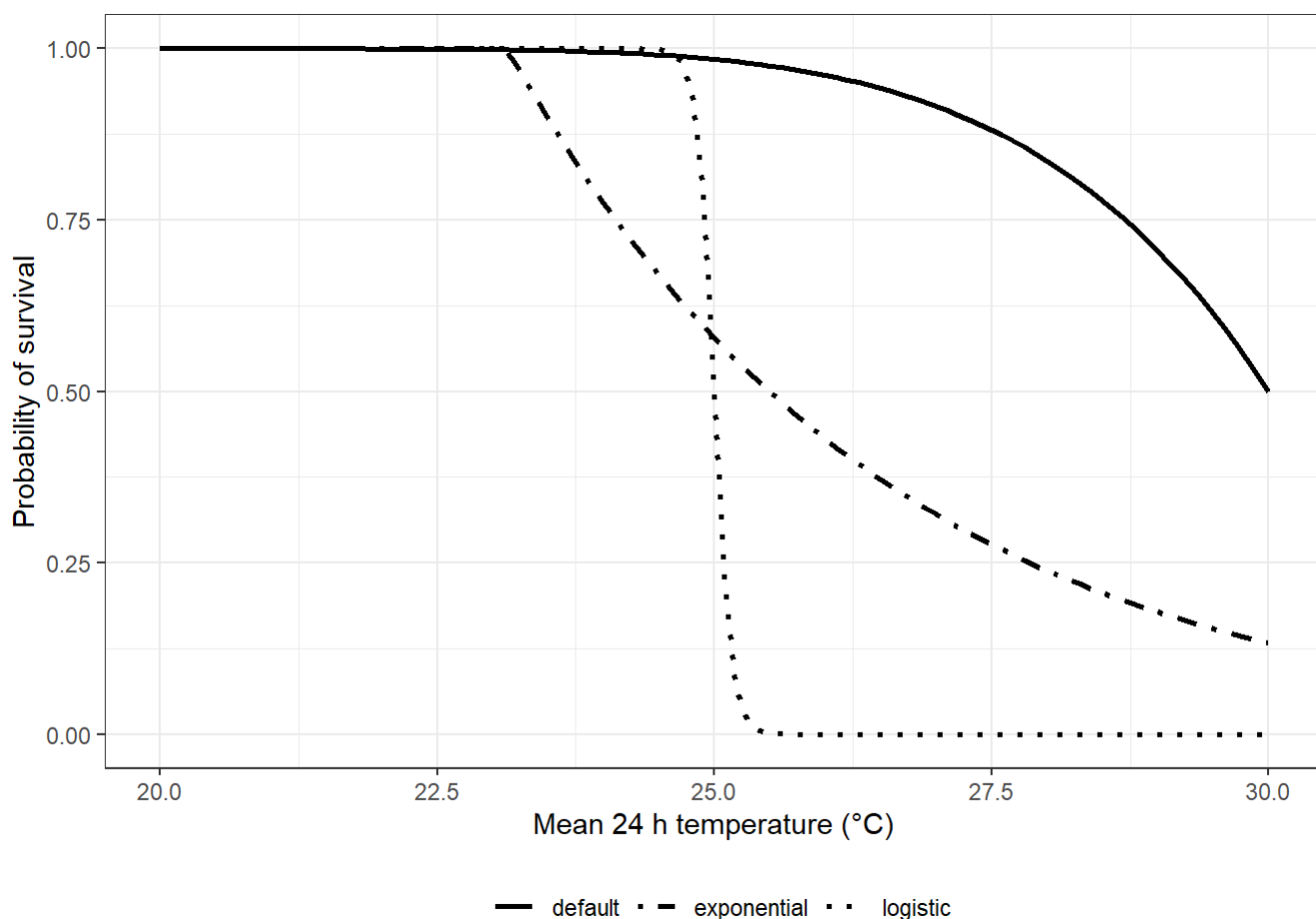

Fig. 13.1 Acute temperature stress curves tested in sensitivity experiment.

Table 13.1 Model output for percent of individuals dying from acute temperature stress summarized for Grande Ronde River Summer Steelhead.

Scenario	Total mortality
Current (2017), Default	0.2
Current (2017), Logistic	0.0
Future (2017), Logistic	0.0

Scenario	Total mortality
Future (2017) no CWR, Logistic	0.0
Current (2017), Exponential	0.0
Future (2017), Exponential	18.9
Future (2017) no CWR, Exponential	28.0
Future (2017) no CWR, Default	1.9
Future (2017), Default	1.1
Current (2017) no CWR, Exponential	0.1
Current (2017) no CWR, Logistic	0.0
Current (2017) no CWR, Default	0.5

14. Cumulative degree days summary results for Grande Ronde River summer steelhead under year 2017 temperatures for the Columbia River with simulated additional coldwater refuges
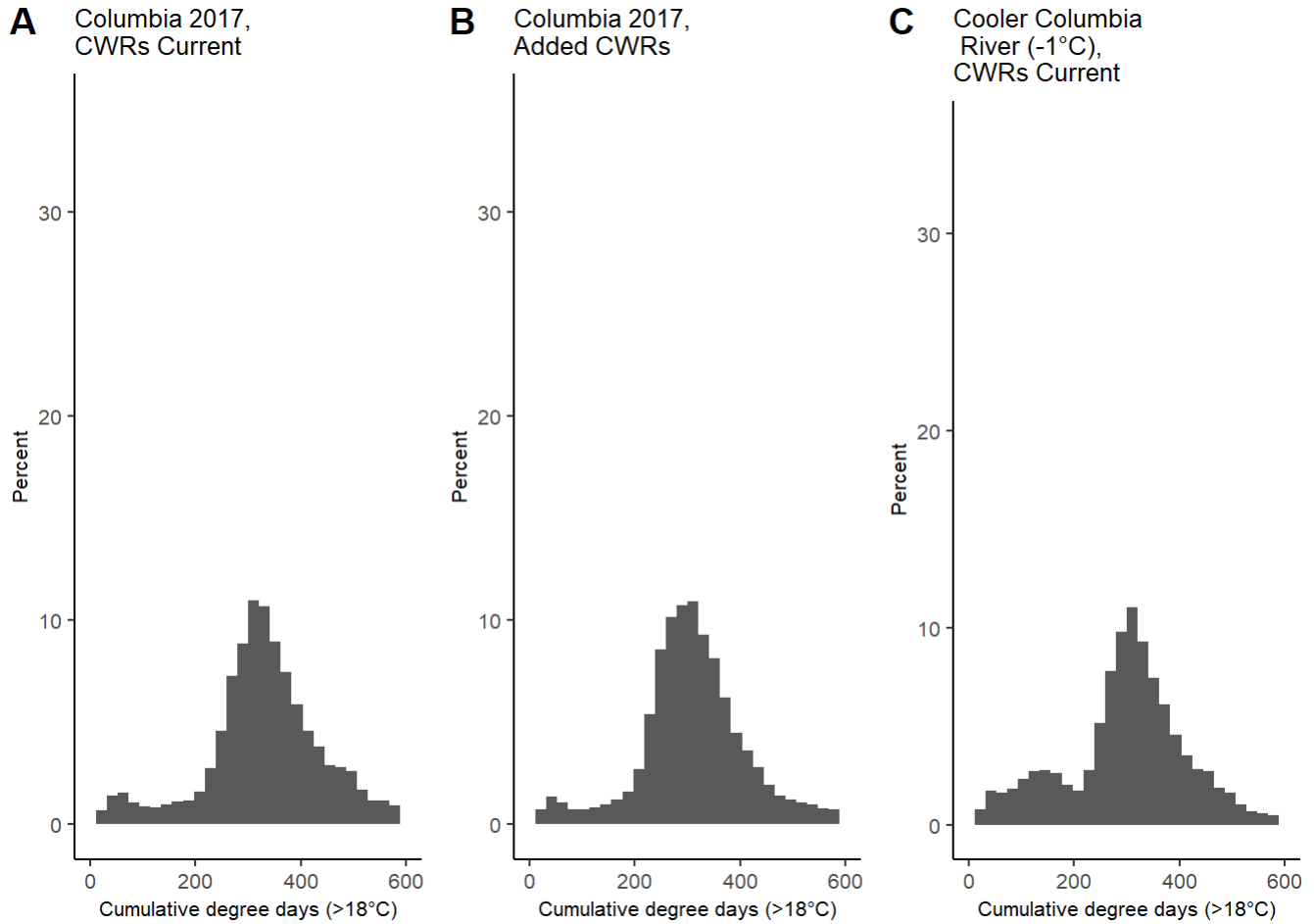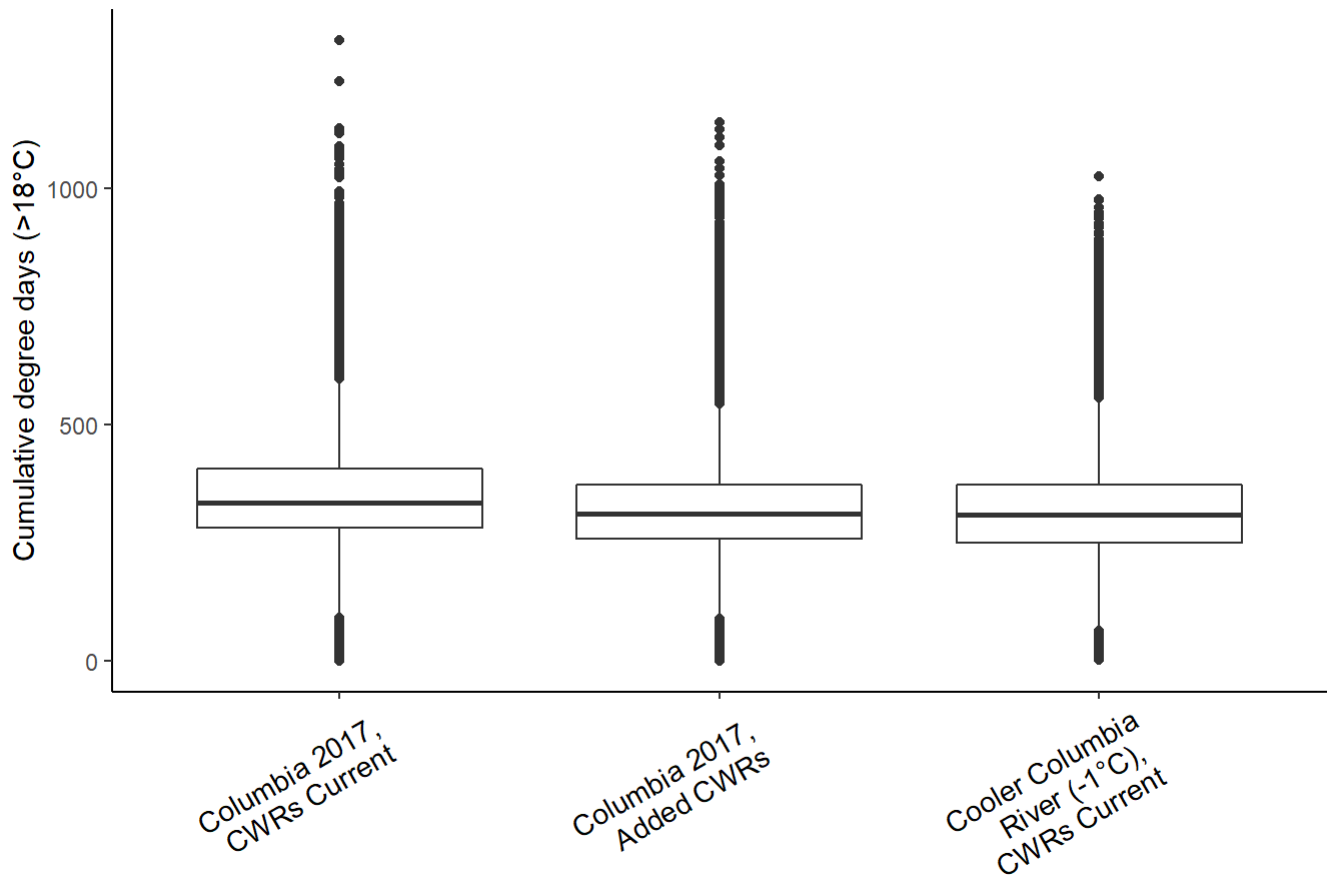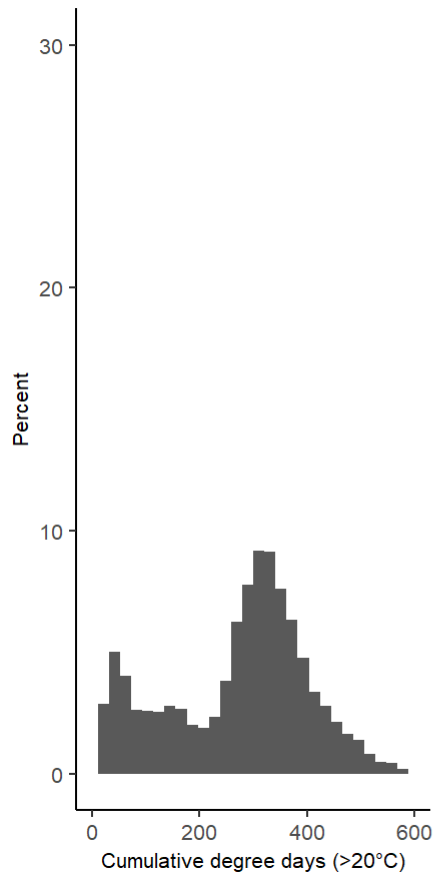

Fig. 14.1 Histograms of modeled Grande Ronde River summer steelhead accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.
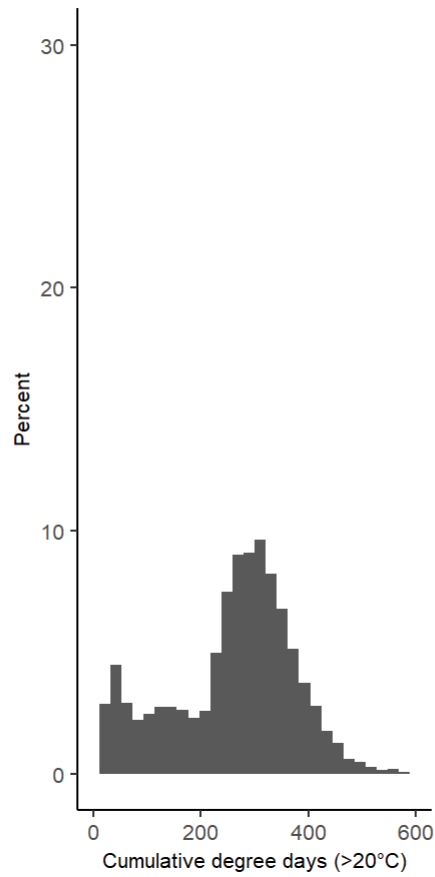
Fig. 14.2 Boxplots of modeled Grande Ronde River summer steelhead accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.

Table 14.1 Cumulative degree days (>18°C) used across different HexSim thermalscapes summarized for Grande Ronde River summer steelhead.

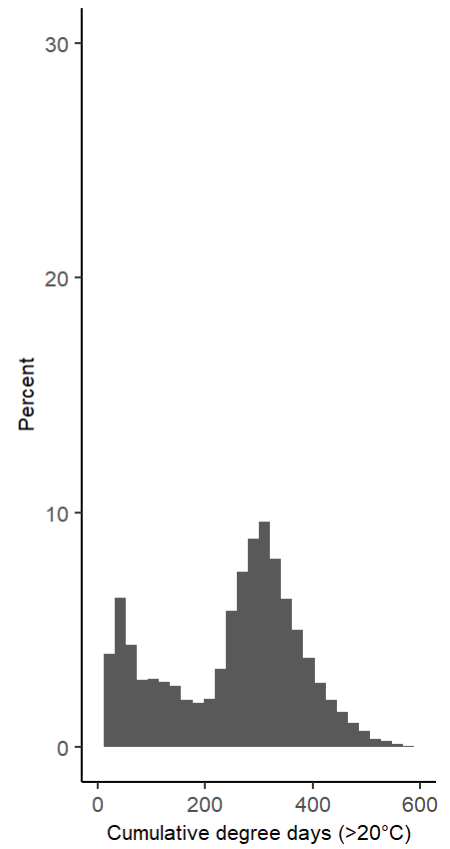| Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2017, CWRs Current	1	282	335	408	1315
Cooler Columbia River (-1°C), CWRs Current	3	250	310	373	1025
Columbia 2017, Added CWRs	1	259	311	374	1142

Fig. 14.3 Histograms of modeled Grande Ronde River summer steelhead accumulated degrees day over 20°C from Bonneville to the Snake River confluence in the Columbia River.
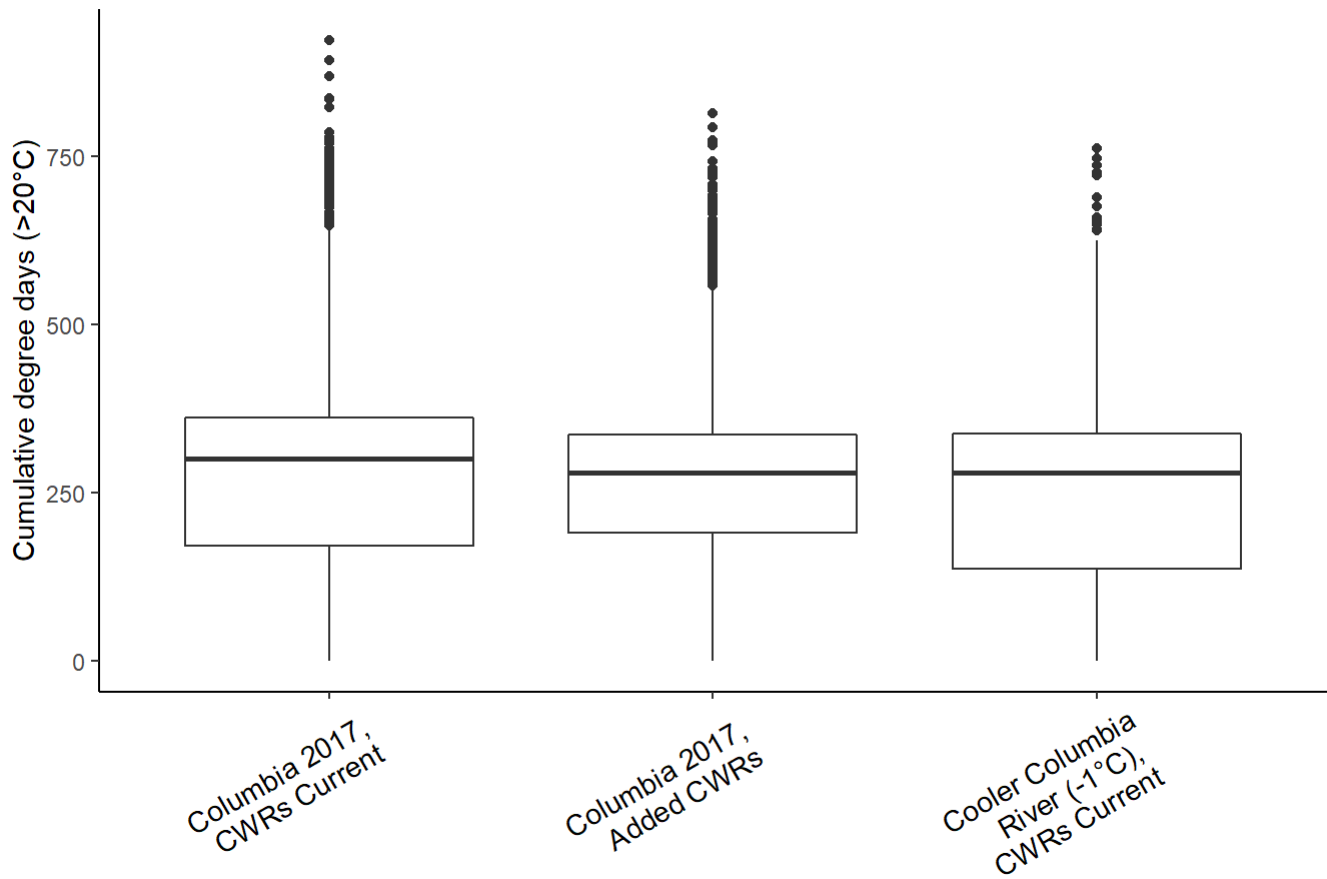
Fig. 14.4 Boxplots of modeled Grande Ronde River summer steelhead accumulated degrees day over 20°C from Bonneville to the Snake River confluence in the Columbia River.

Table 14.2 Cumulative degree days (>20°C) used across different HexSim thermalscapes summarized for Grande Ronde River summer steelhead.

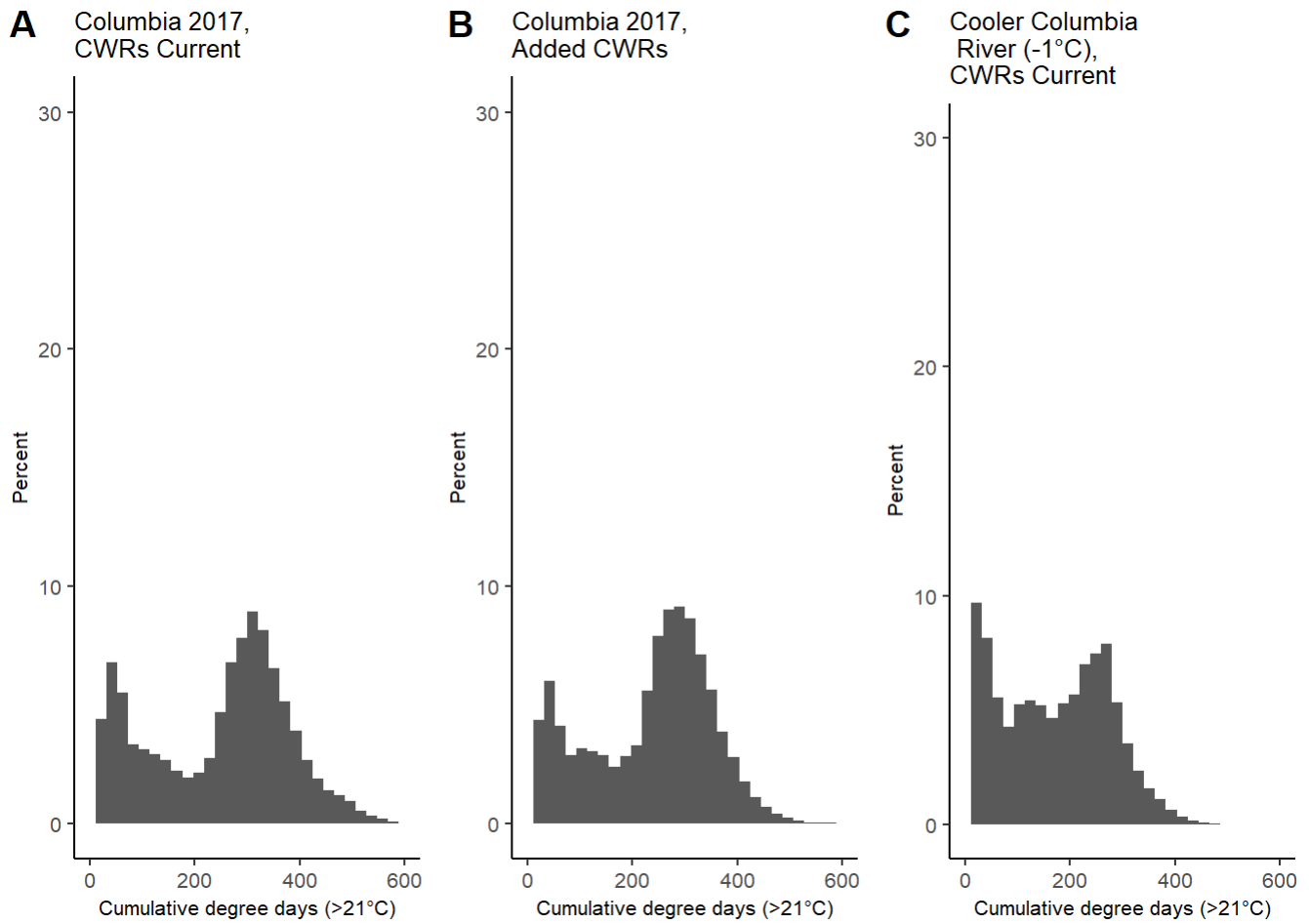| Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2017, CWRs Current	1	172	302	362	924
Cooler Columbia River (-1°C), CWRs Current	1	138	280	338	762
Columbia 2017, Added CWRs	1	190	280	337	814

Fig. 14.5 Histograms of modeled Grande Ronde River summer steelhead accumulated degrees day over 21°C from Bonneville to the Snake River confluence in the Columbia River.
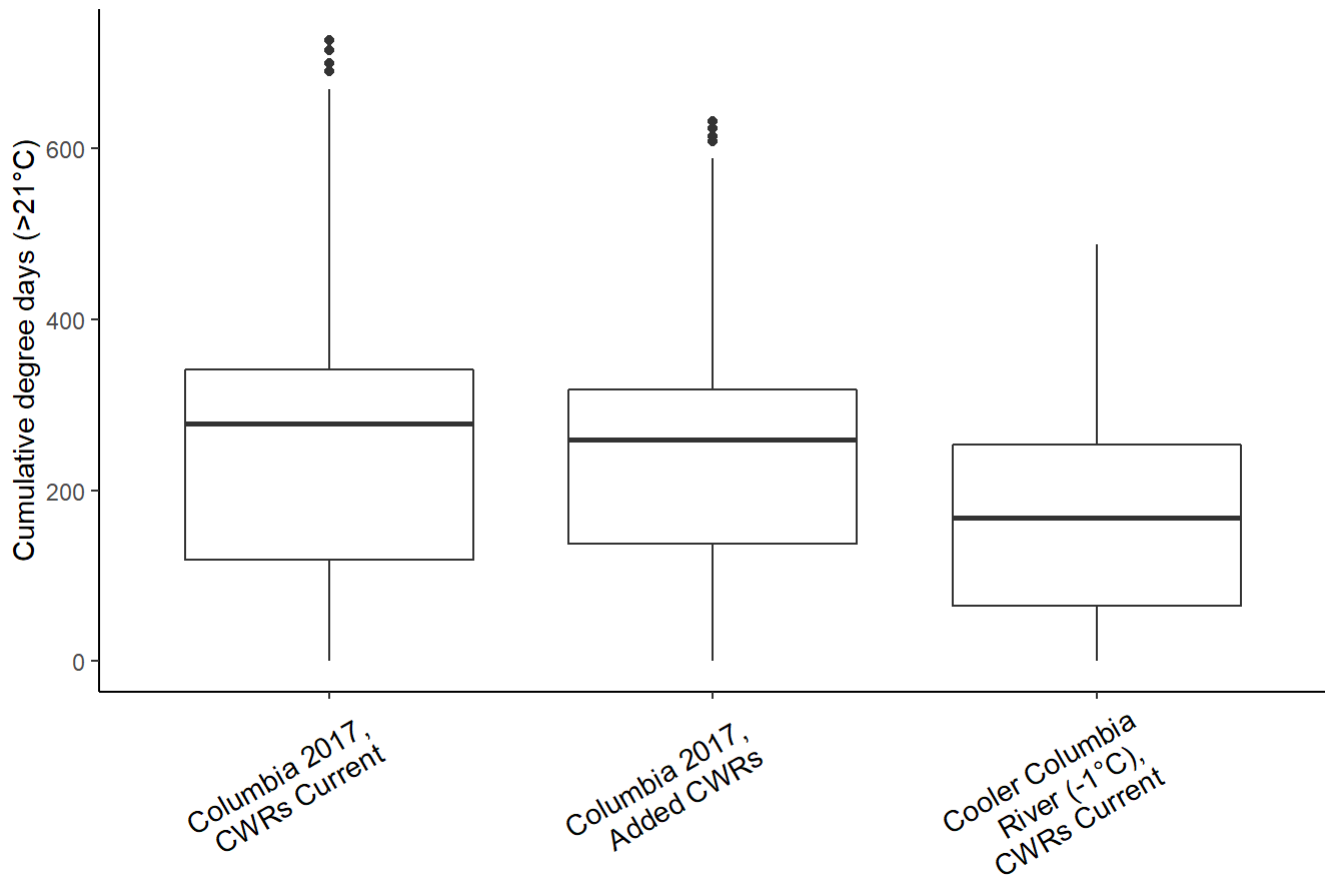
Grande Ronde River summer steelhead

Fig. 14.6 Boxplots of modeled Grande Ronde River summer steelhead accumulated degrees day over 21°C from Bonneville to the Snake River confluence in the Columbia River.

Table 14.3 Cumulative degree days (>21°C) used across different HexSim thermalscapes summarized for Grande Ronde River summer steelhead.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2017, CWRs Current	1	118	278	341	727
Cooler Columbia River (-1°C), CWRs Current	1	65	168	253	487
Columbia 2017, Added CWRs	1	137	260	318	632

15. Energy use, CWR use, and survivorship results for Grande Ronde River summer steelhead under year 2017 temperatures for the Columbia River with simulated additional coldwater refuges
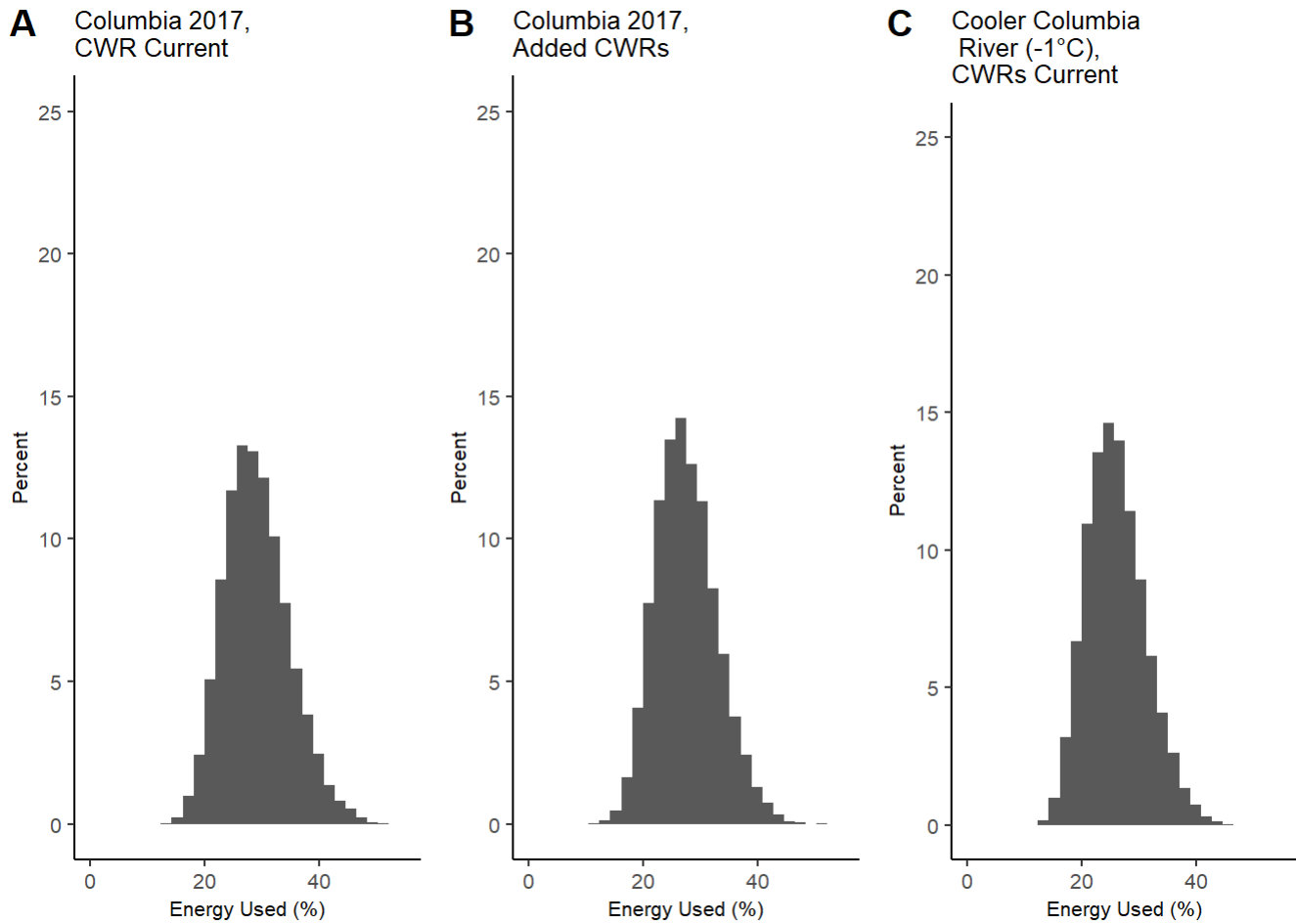

Fig. 15.1 Histogram of percent energy lost for modeled Grande Ronde River summer steelhead migrating through four different modeled thermalscapes.
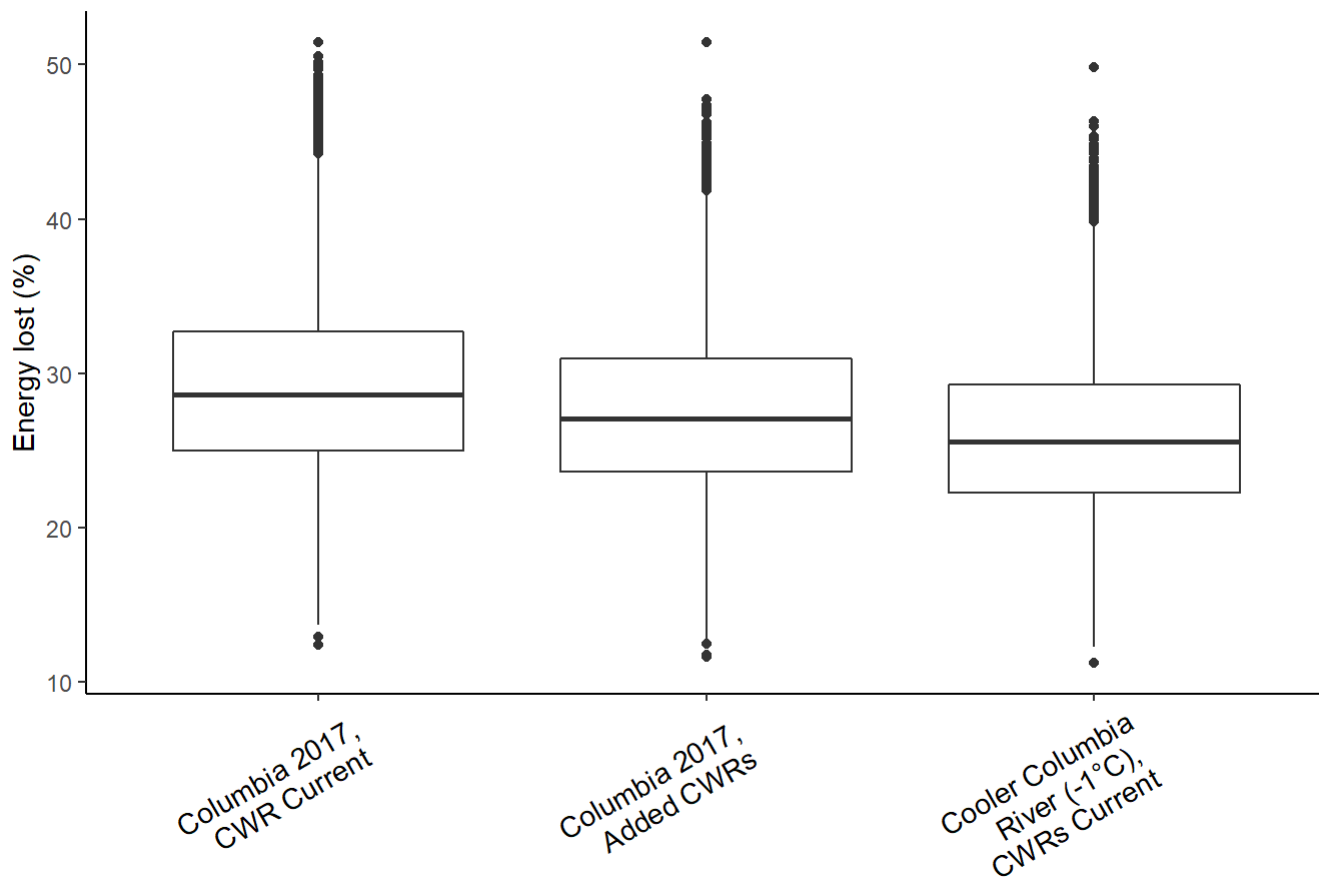
Fig. 15.2 Boxplot of percent energy lost for modeled Grande Ronde River summer steelhead migrating through four different modeled thermalscapes.

Table 15.1 Percent energy used across different HexSim thermalscapes summarized for Grande Ronde River summer steelhead.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2017, CWR Current	12	25	29	33	51
Cooler Columbia River (-1°C), CWRs Current	11	22	26	29	50
Columbia 2017, Added CWRs	12	24	27	31	51

Table 15.2 Model output for hours residing in cold water refuges summarized for Grande Ronde River summer steelhead.

Scenario	CWR Residence (h/individual)
Columbia 2017,CWR Current	509
Cooler Columbia River (-1°C), CWRs Current	411
Columbia 2017, Added CWRs	523

Table 15.3 Model output for percent of individuals dying from acute temperature stress summarized for Grande Ronde River summer steelhead.

Scenario	Total mortality
Columbia 2017,CWR Current	0.32
Cooler Columbia River (-1°C), CWRs Current	0.02
Columbia 2017, Added CWRs	0.33

16. Cumulative degree days summary results for Snake River Fall Chinook Salmon under year 2017 temperatures for the Columbia River with simulated additional coldwater refuges
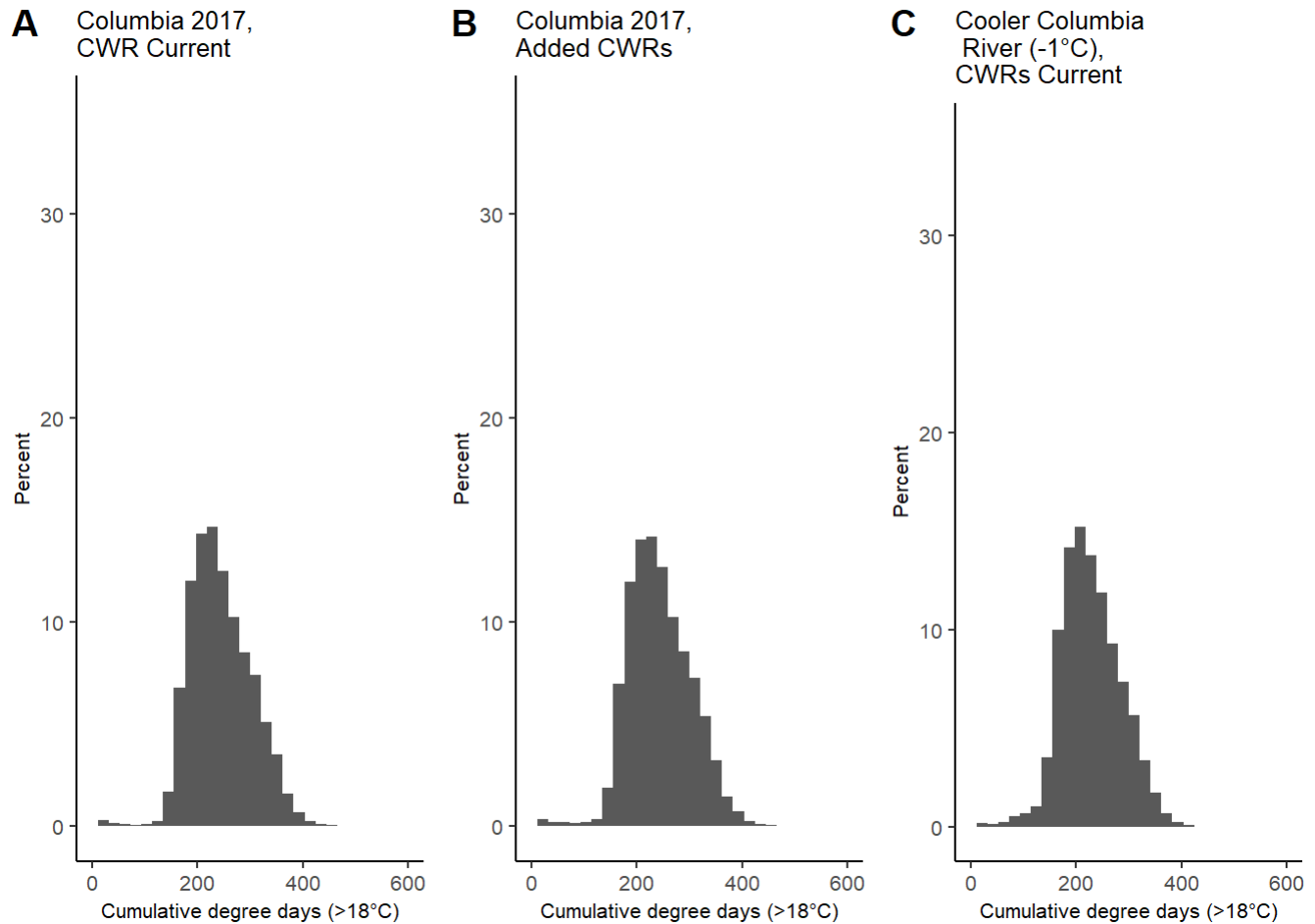

Fig. 16.1 Histograms of modeled Snake River Fall Chinook Salmon accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.
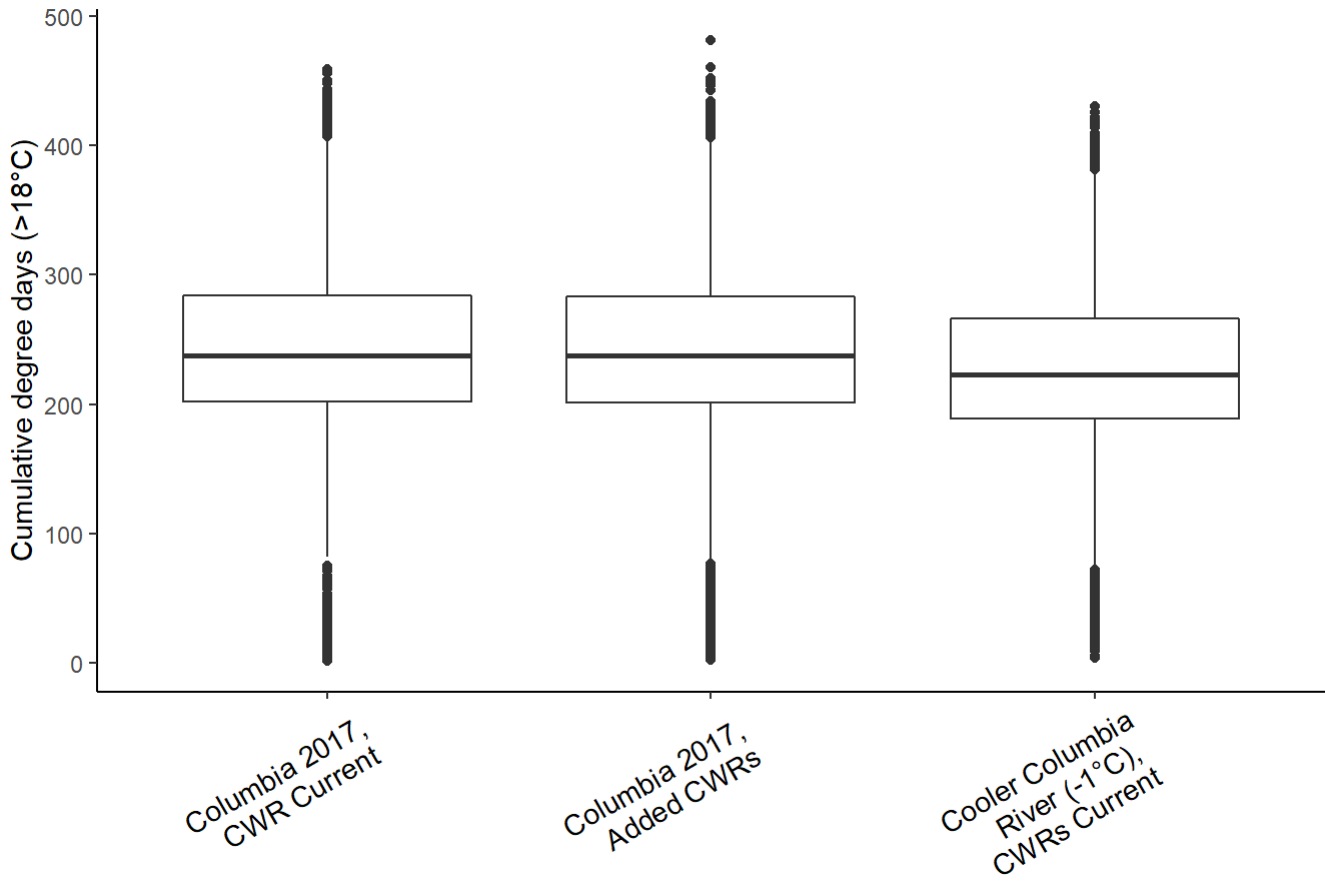
Fig. 16.2 Boxplots of modeled Snake River Fall Chinook Salmon accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.

Table 16.1 Cumulative degree days (>18°C) used across different HexSim thermalscapes summarized for Snake River Fall Chinook Salmon.

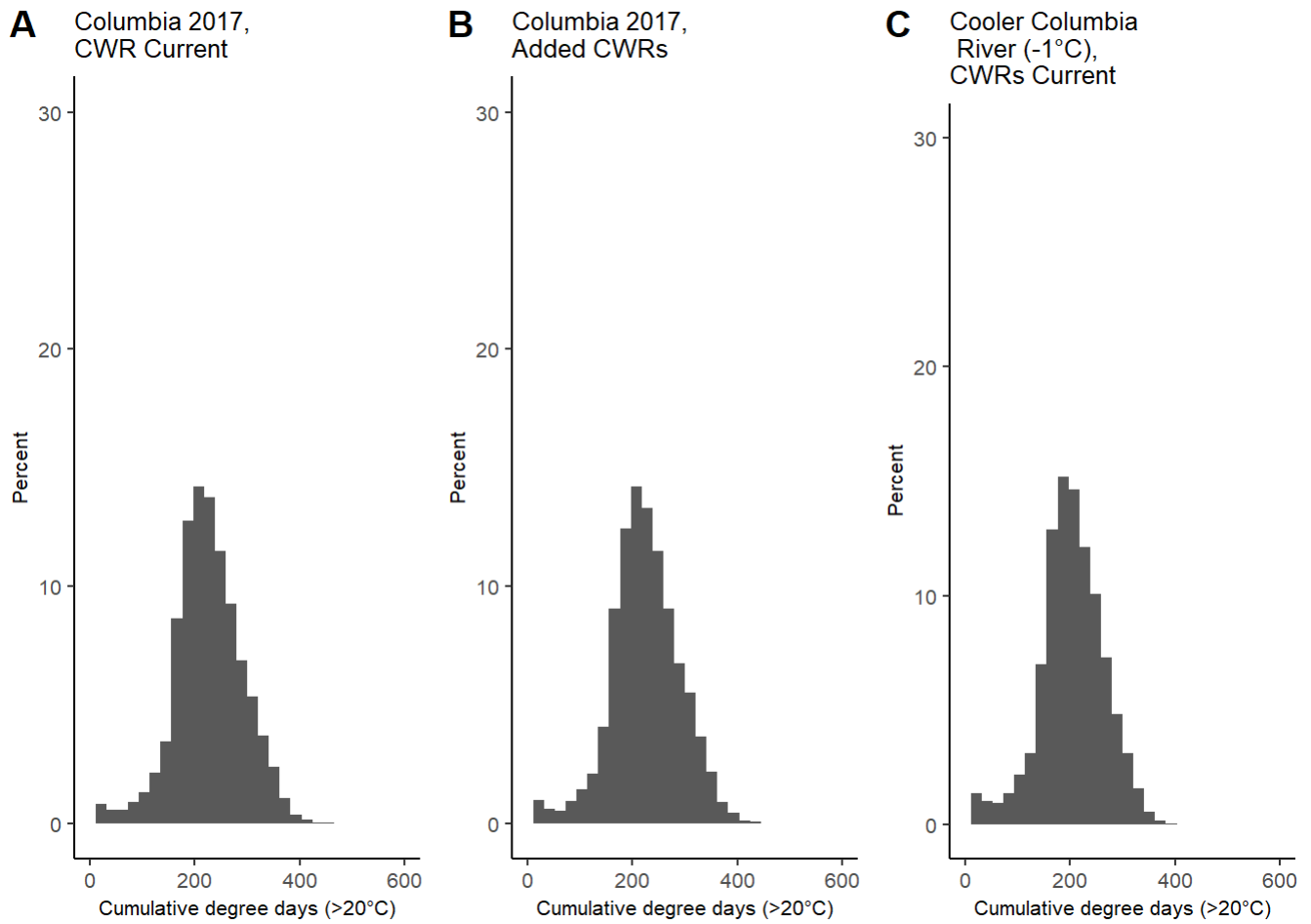| Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2017, CWR Current	2	202	238	284	459
Cooler Columbia River (-1°C), CWRs Current	3	189	223	266	431
Columbia 2017, Added CWRs	2	201	237	283	482

Fig. 16.3 Histograms of modeled Snake River Fall Chinook Salmon accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.
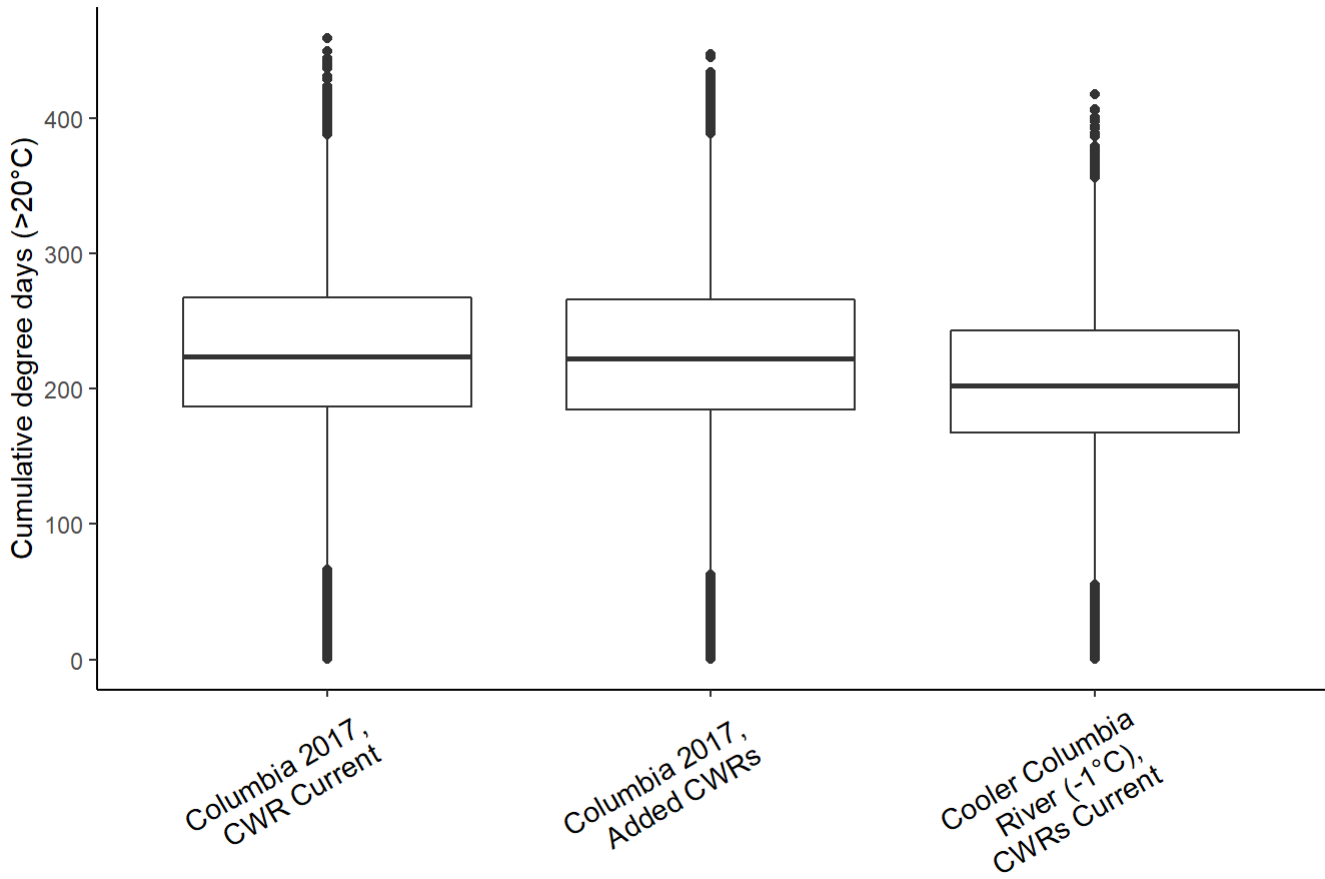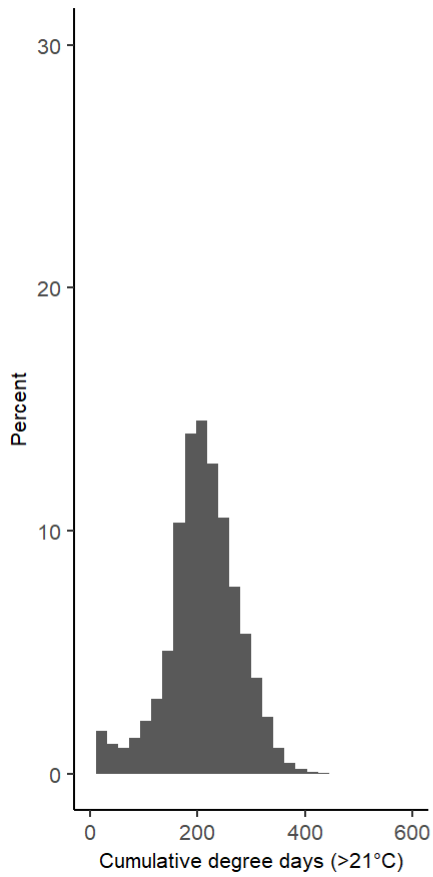
Fig. 16.4 Boxplots of modeled Snake River Fall Chinook Salmon accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.
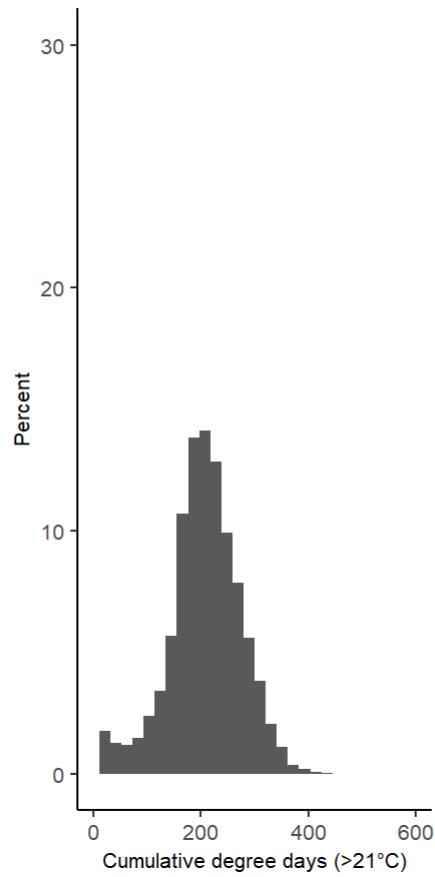
Table 16.2 Cumulative degree days (>20°C) used across different HexSim thermalscapes summarized for Snake River Fall Chinook Salmon.

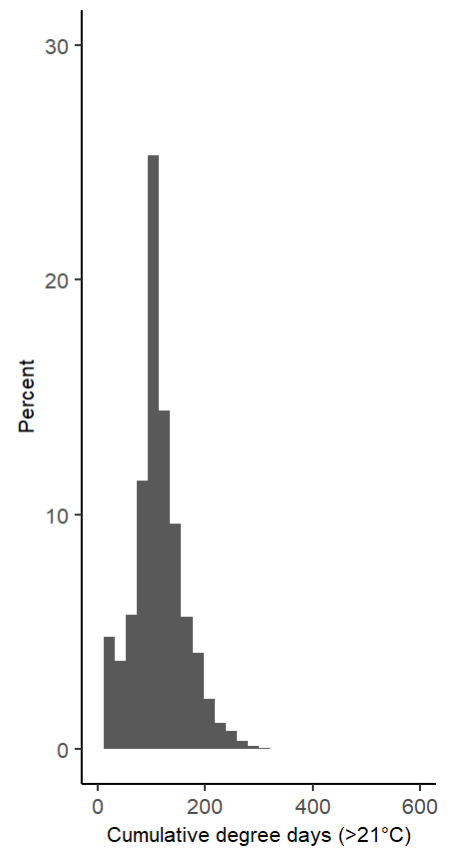| Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2017, CWR Current	1	187	224	267	459
Cooler Columbia River (-1°C), CWRs Current	1	168	203	243	417
Columbia 2017, Added CWRs	1	185	222	266	447

Fig. 16.5 Histograms of modeled Snake River Fall Chinook Salmon accumulated degrees day over 21°C from Bonneville to the Snake River confluence in the Columbia River.
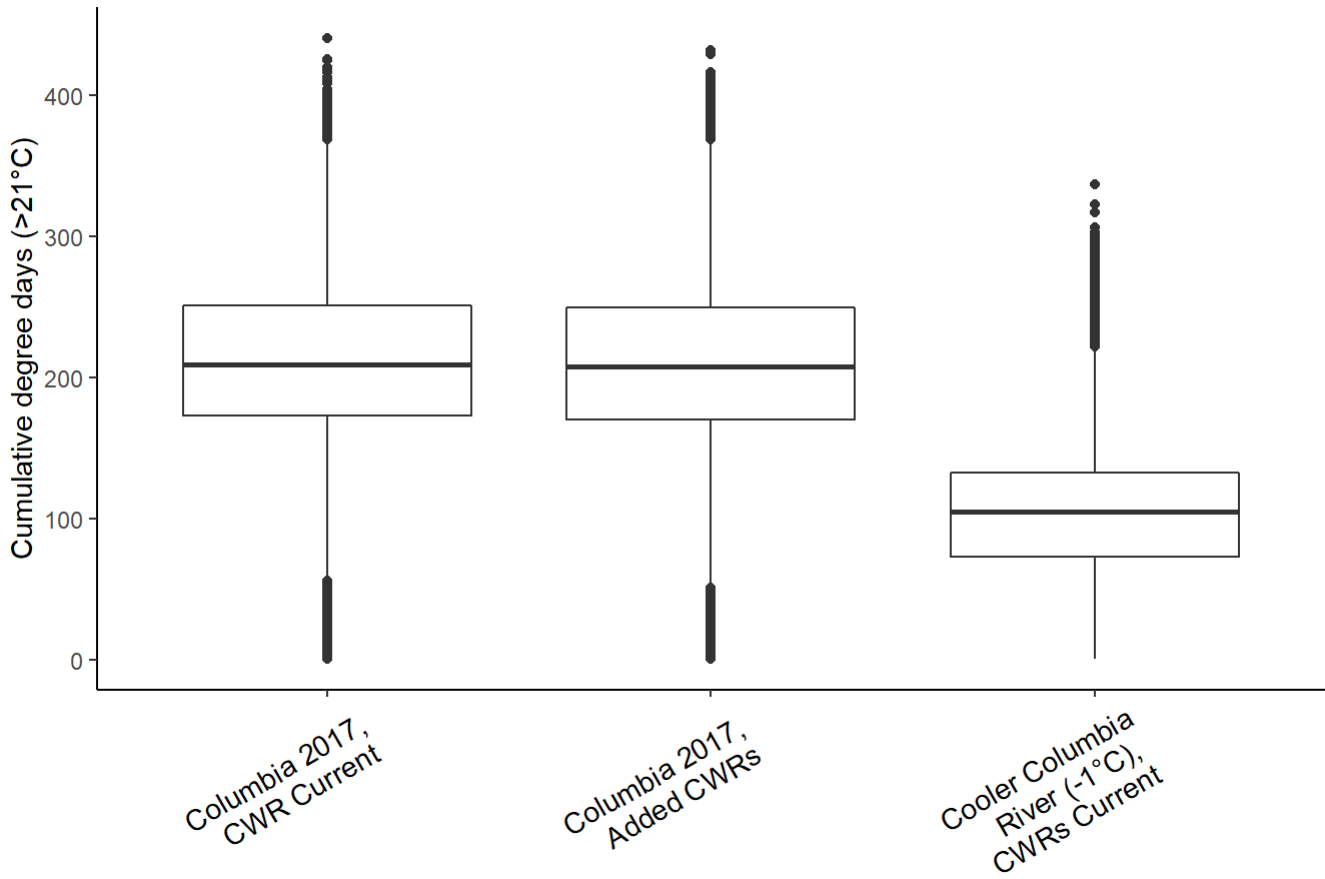
Fig. 16.6 Boxplots of modeled Snake River Fall Chinook Salmon accumulated degrees day over 21°C from Bonneville to the Snake River confluence in the Columbia River.

Table 16.3 Cumulative degree days (>21°C) used across different HexSim thermalscapes summarized for Snake River Fall Chinook Salmon.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2017, CWR Current	1	173	209	251	441
Cooler Columbia River (-1°C),CWRs Current	1	73	105	132	337
Columbia 2017, Added CWRs	1	170	208	250	432

17. Energy use, CWR use, and survivorship results for Snake River Fall Chinook Salmon under year 2017 temperatures for the Columbia River with simulated additional coldwater refuges
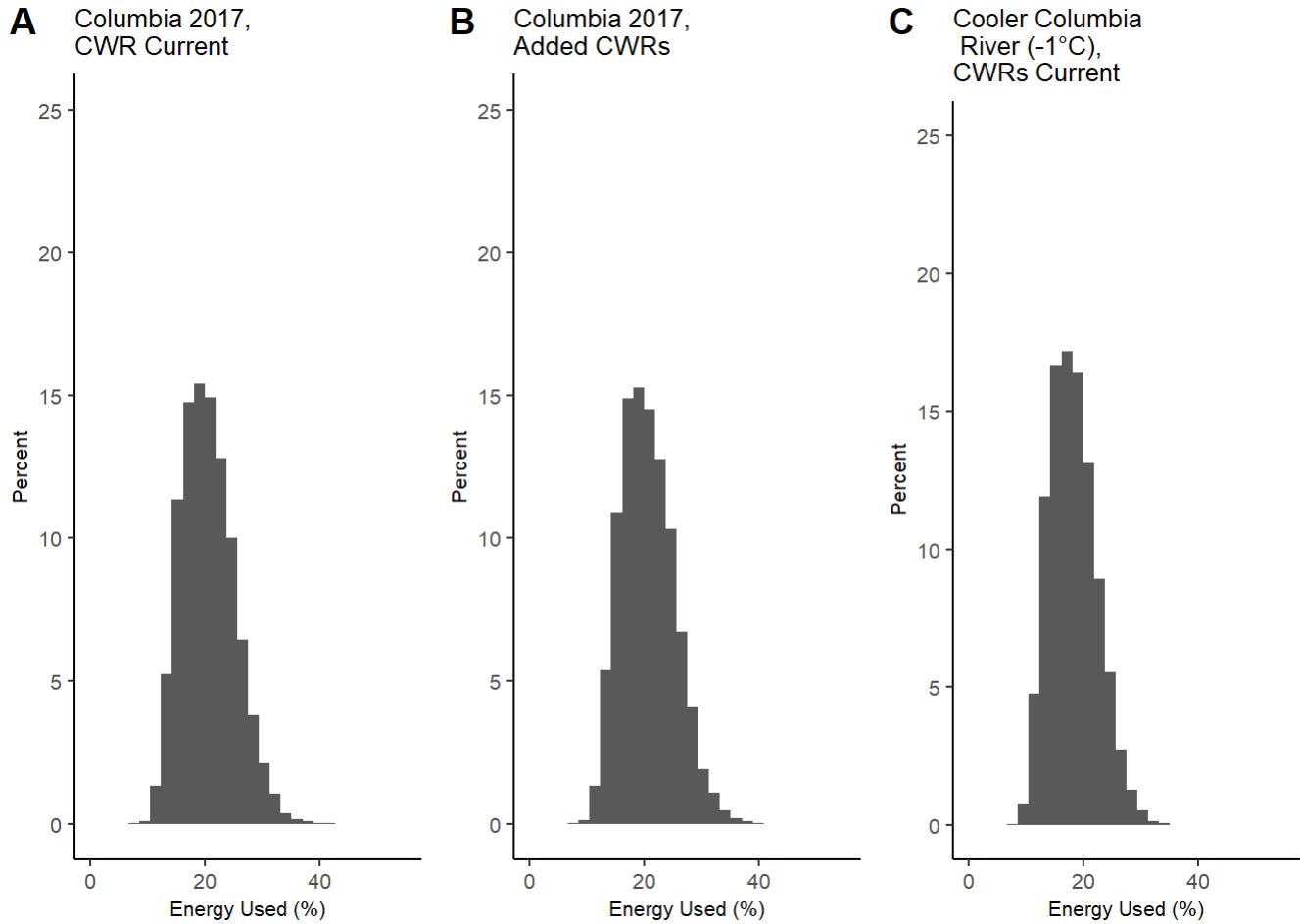

Fig. 17.1 Histogram of percent energy lost for modeled Snake River Fall Chinook Salmon migrating through four different modeled thermalscapes.
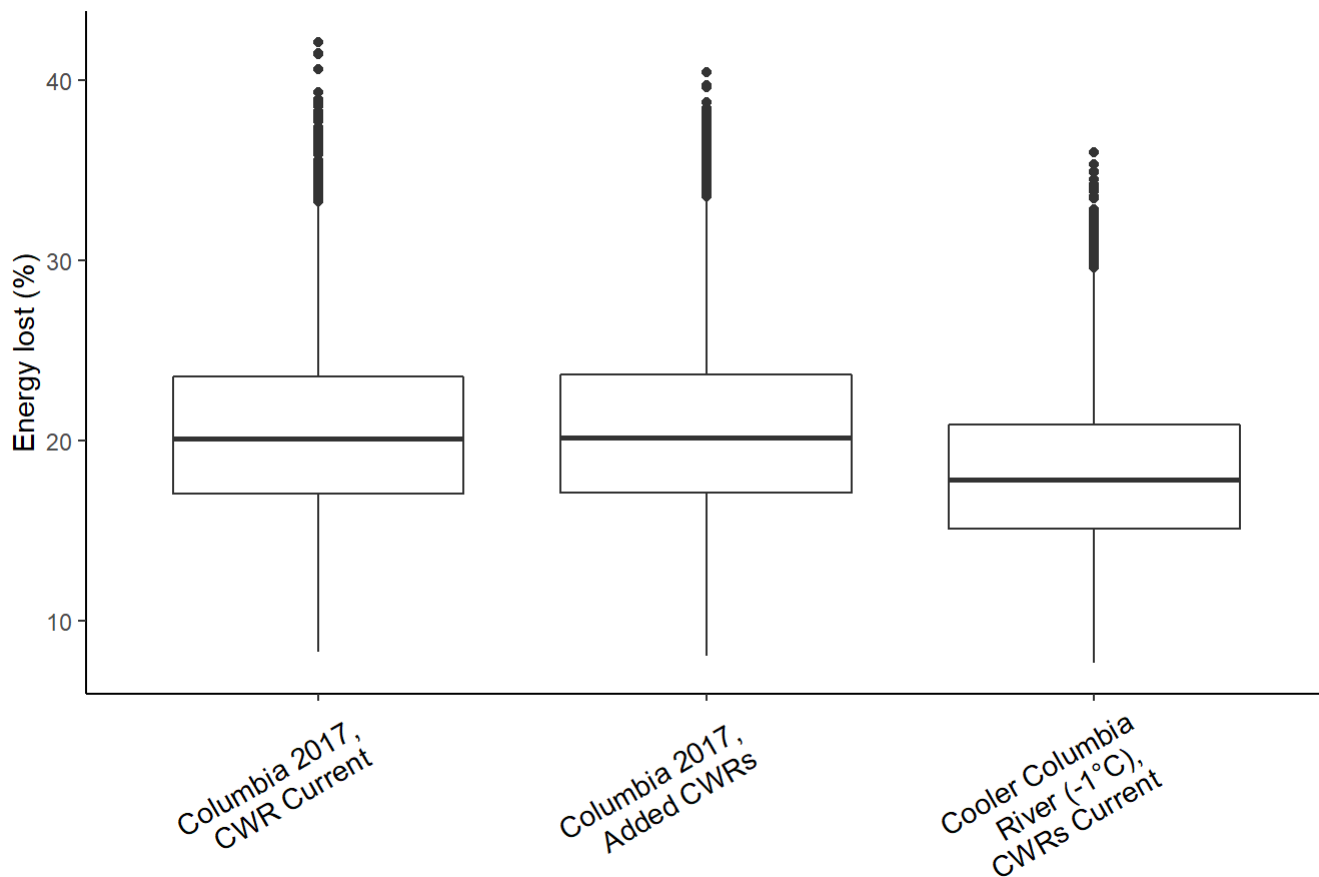
Snake River Fall Chinook Salmon

Fig. 17.2 Boxplot of percent energy lost for modeled Snake River Fall Chinook Salmon migrating through four different modeled thermalscapes.

Table 17.1 Percent energy used across different HexSim thermalscapes summarized for Snake River Fall Chinook Salmon.

Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2017, CWR Current	8.3	17.1	20.1	23.5	42.1
Cooler Columbia River (-1°C), CWRs Current	7.7	15.1	17.9	20.9	36.0
Columbia 2017, Added CWRs	8.1	17.1	20.2	23.7	40.4

Table 17.2 Model output for hours residing in cold water refuges summarized for Snake River Fall Chinook Salmon.

Scenario	CWR Residence (h/individual)
Columbia 2017,CWR Current	21
Cooler Columbia River (-1°C), CWRs Current	13
Columbia 2017, Added CWRs	38

Table 17.3 Model output for percent of individuals dying from acute temperature stress summarized for Snake River Fall Chinook Salmon.

Scenario	Total mortality
Columbia 2017,CWR Current	0.32
Cooler Columbia River (-1°C), CWRs Current	0.02
Columbia 2017, Added CWRs	0.33