Draft Technical Memorandum

To: Columbia River CWR Project Team

From: Marcía Snyder, Nathan Schumaker, and Joe Ebersole

Date: September 30, 2019

Subject: HexSim migration corridor simulation model preliminary results

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Background

To explore how cold water refuge 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 fish. We simulated the migration performance of four fish populations under differing thermal conditions. 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 1. 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

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

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

For the scenarios based on current Columbia River long term average (1992-2016) temperatures we simulated four populations- Tucannon River summer steelhead, Grande Ronde summer steelhead, Hanford Reach Fall Chinook salmon, and Snake River Fall Chinook salmon. For the scenarios based on

Columbia River recent condition (2017) temperatures we simulated two populations- Grande Ronde summer steelhead and Snake River Fall Chinook.

Results

The following figures and tables summarize some of the preliminary 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 recent condition scenarios for each population.

Grande Ronde summer steelhead cumulative DD

MNSnyder

8/29/2019

DD > 18 °C

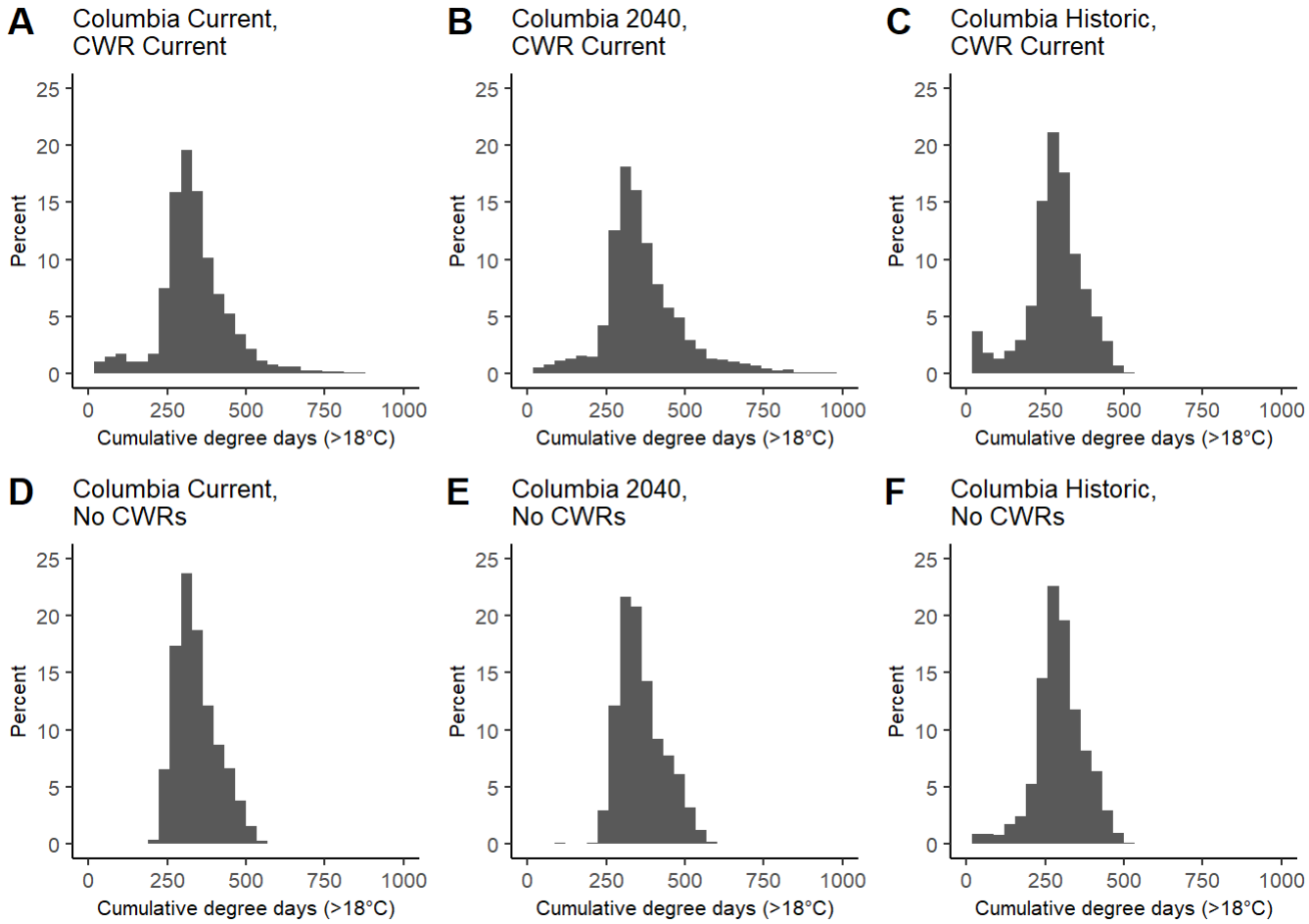


Fig. 1. Histograms of modeled Grande Ronde River summer steelhead accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.

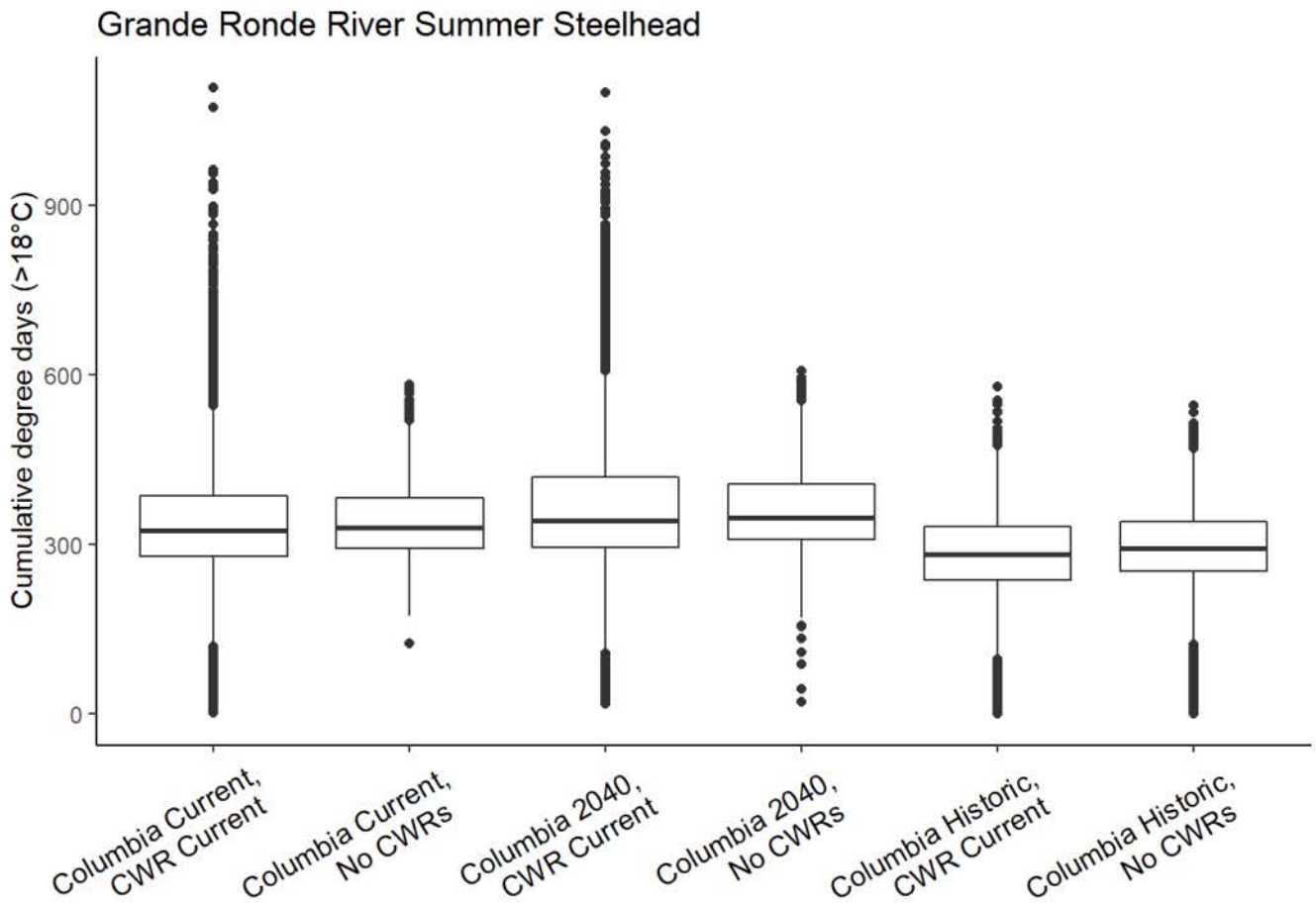


Fig. 2. Boxplots of modeled Grande Ronde River summer steelhead accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.

Table 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

Degree Days > 20°C

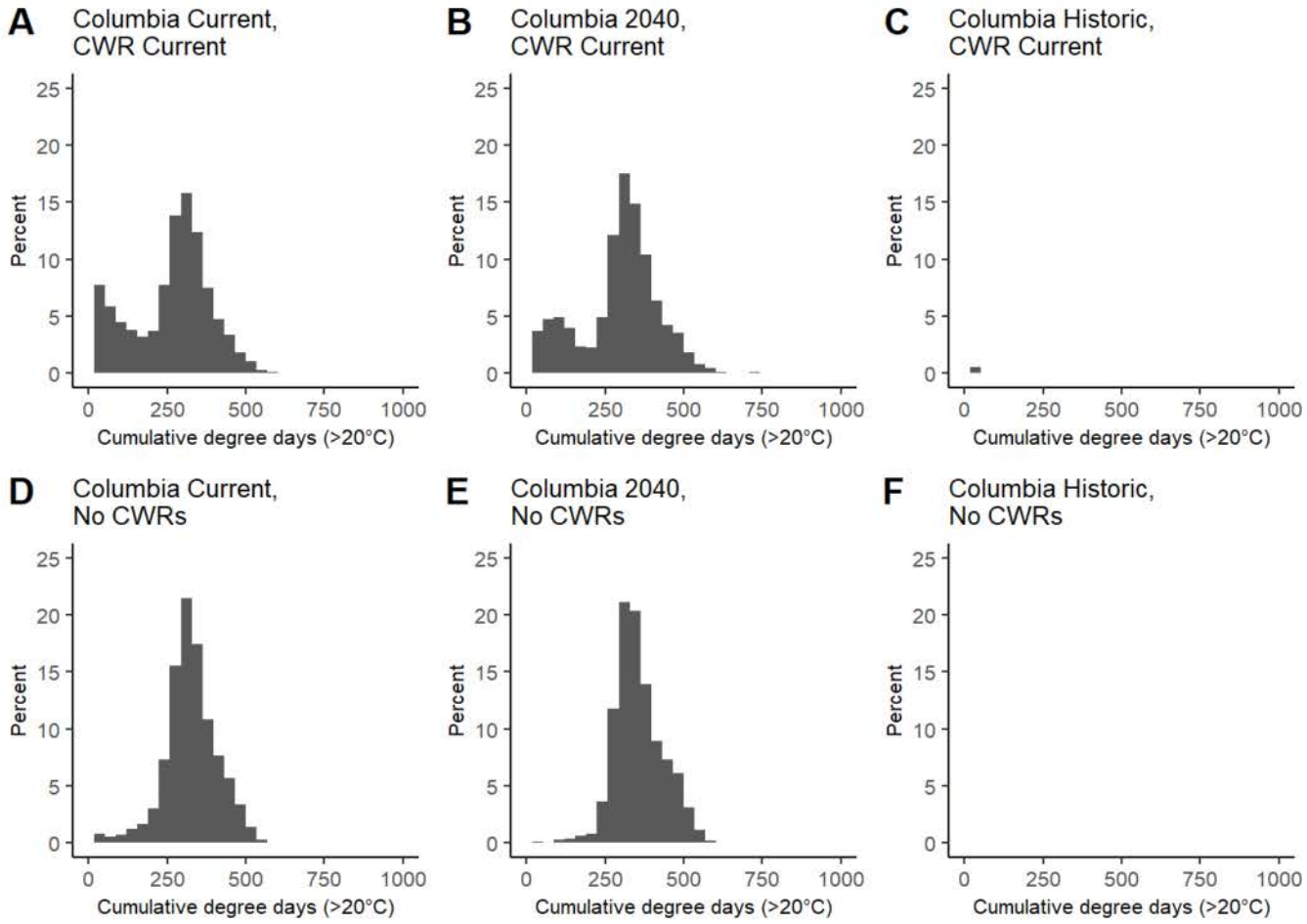


Fig. 3. Histograms of modeled Grande Ronde River summer steelhead accumulated degrees day over 20°C from Bonneville to the Snake River confluence in the Columbia River.

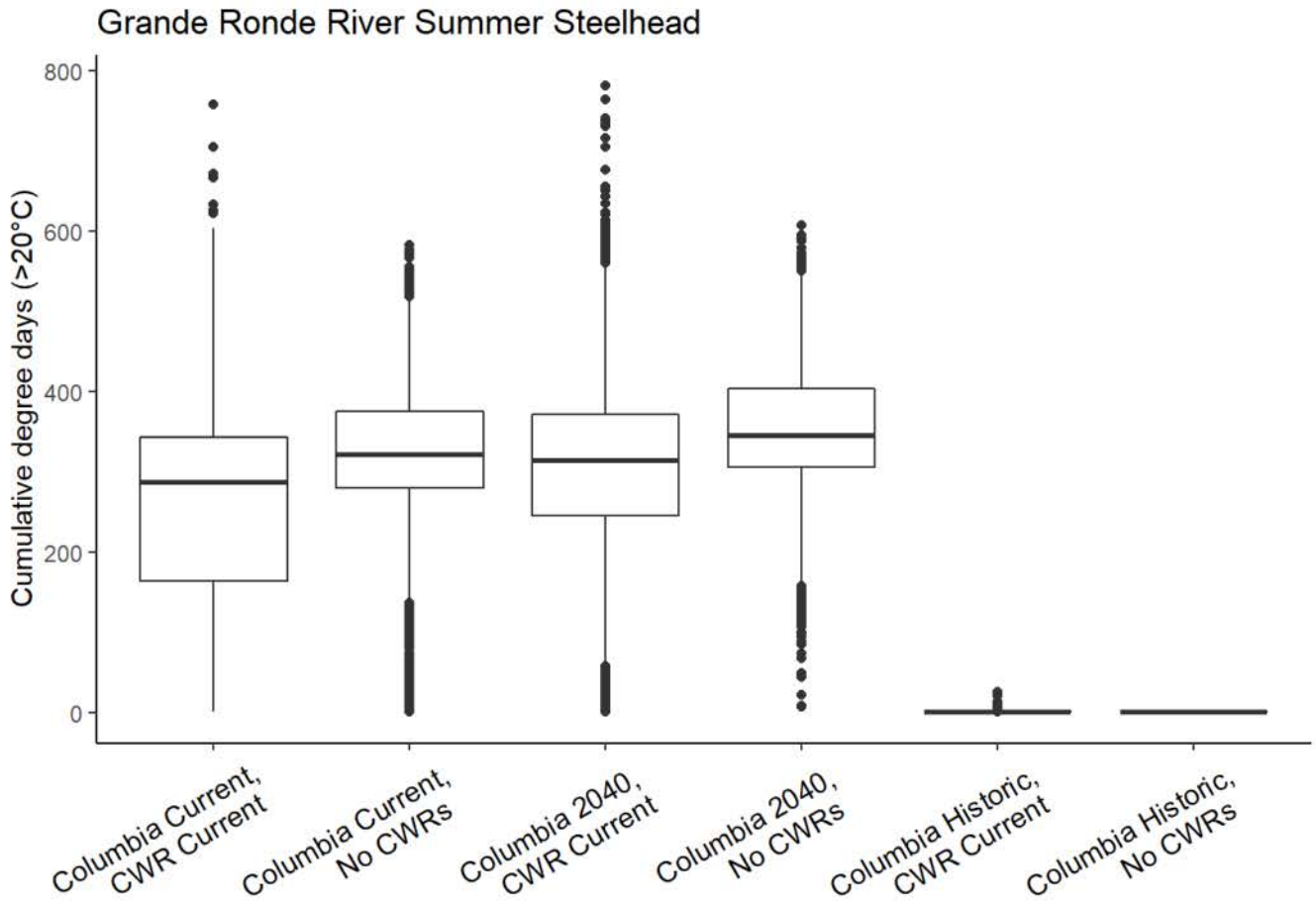


Fig. 4. Boxplots of modeled Grande Ronde River summer steelhead accumulated degrees day over 20°C from Bonneville to the Snake River confluence in the Columbia River.

Table 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

Degree Days > 21°C

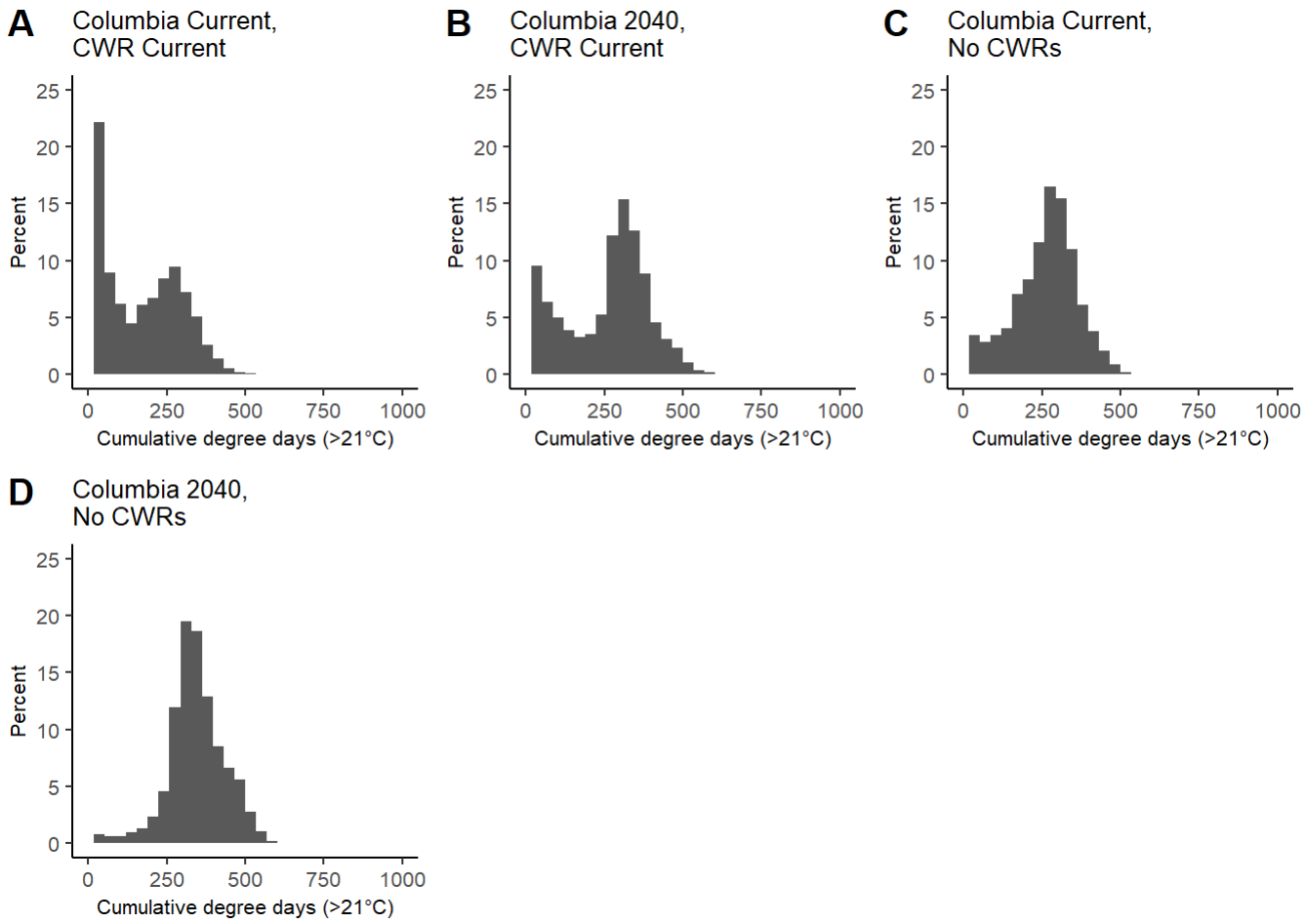


Fig. 5. Histograms of modeled Grande Ronde River summer steelhead accumulated degrees day over 21°C from Bonneville to the Snake River confluence in the Columbia River.

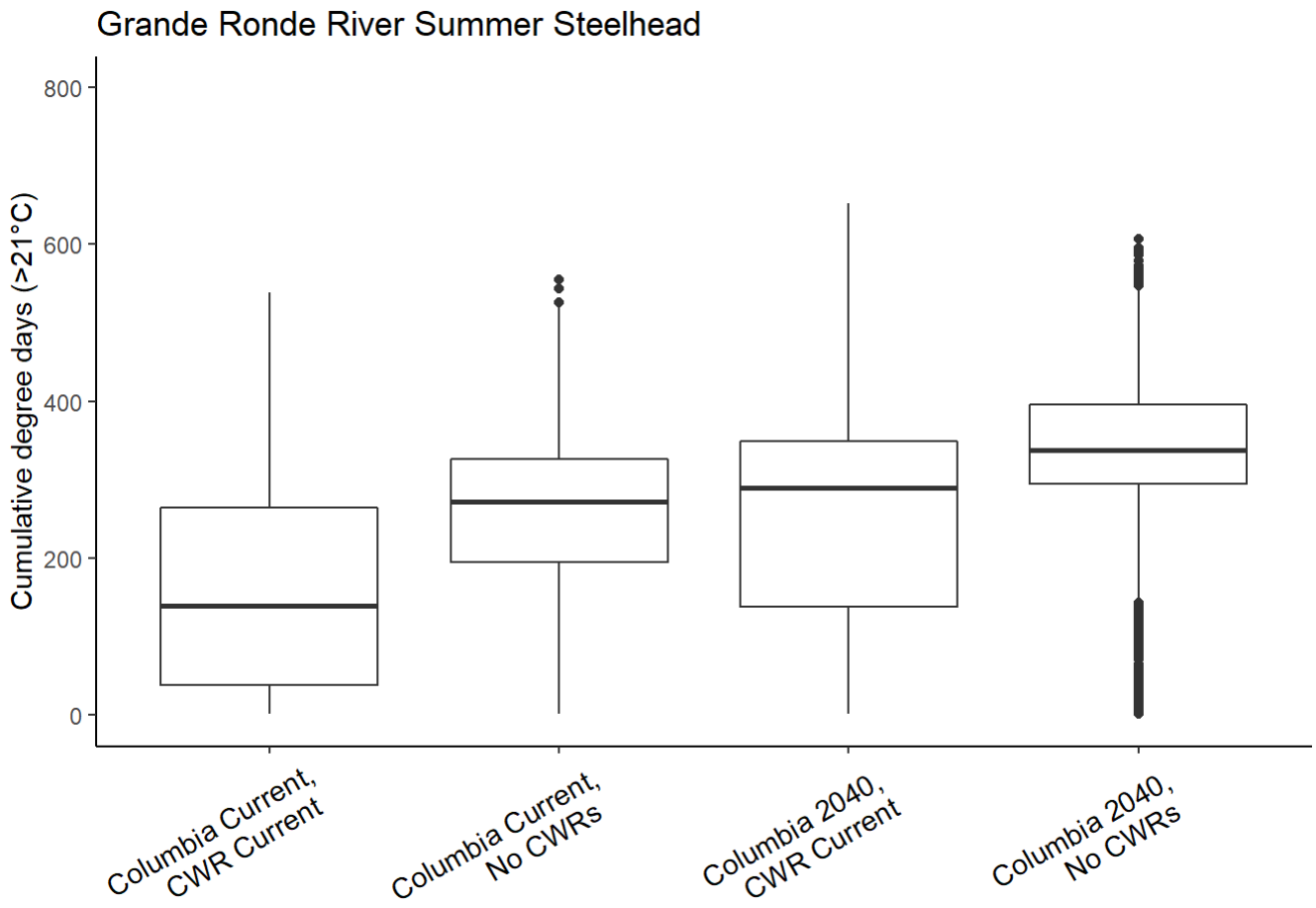


Fig. 6. Boxplots of modeled Grande Ronde River summer steelhead accumulated degrees day over 21°C from Bonneville to the Snake River confluence in the Columbia River.

Table 3. 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

Degree Days > 22°C

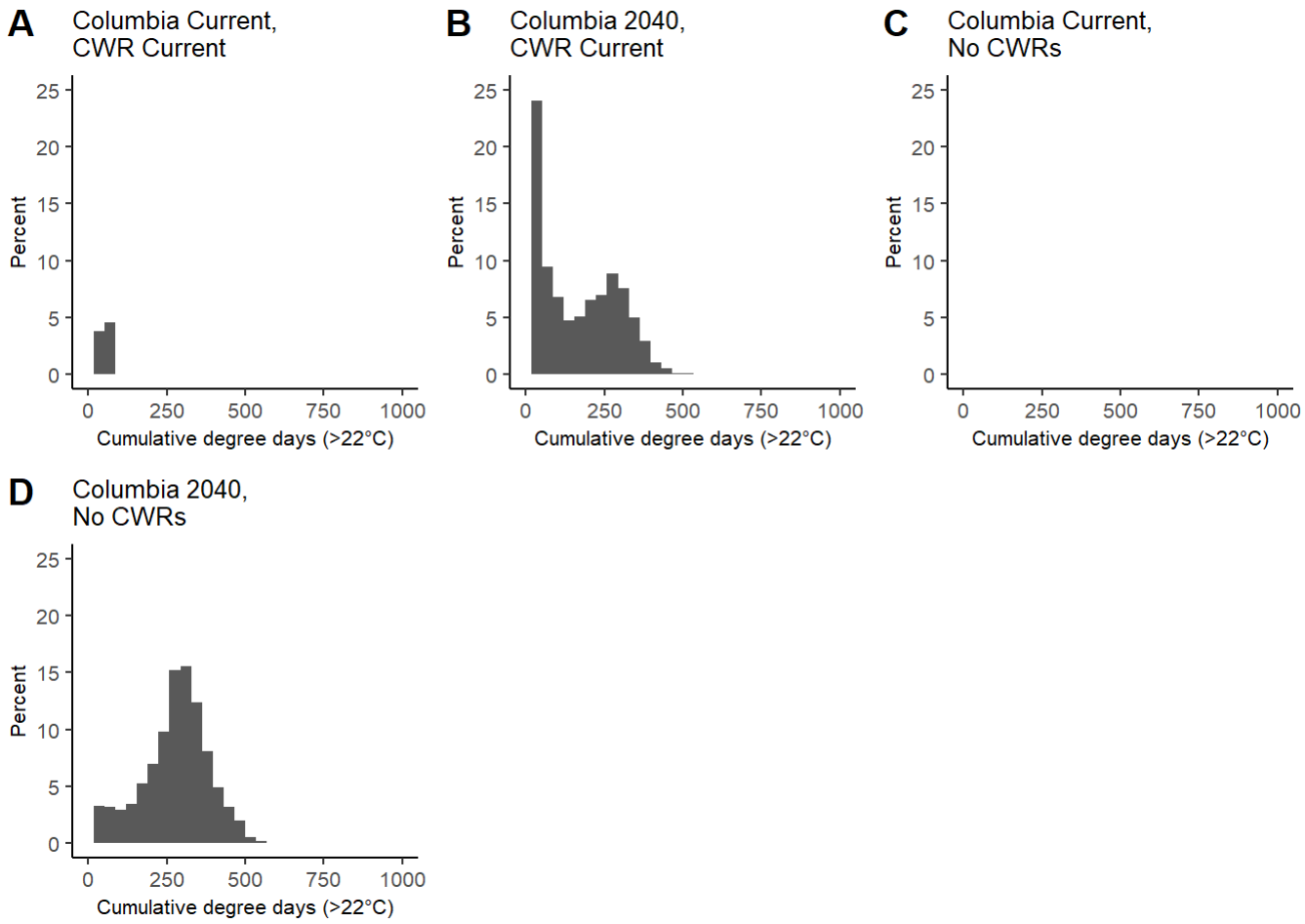


Fig. 5. Histograms of modeled Grande Ronde River summer steelhead accumulated degrees day over 22°C from Bonneville to the Snake River confluence in the Columbia River.

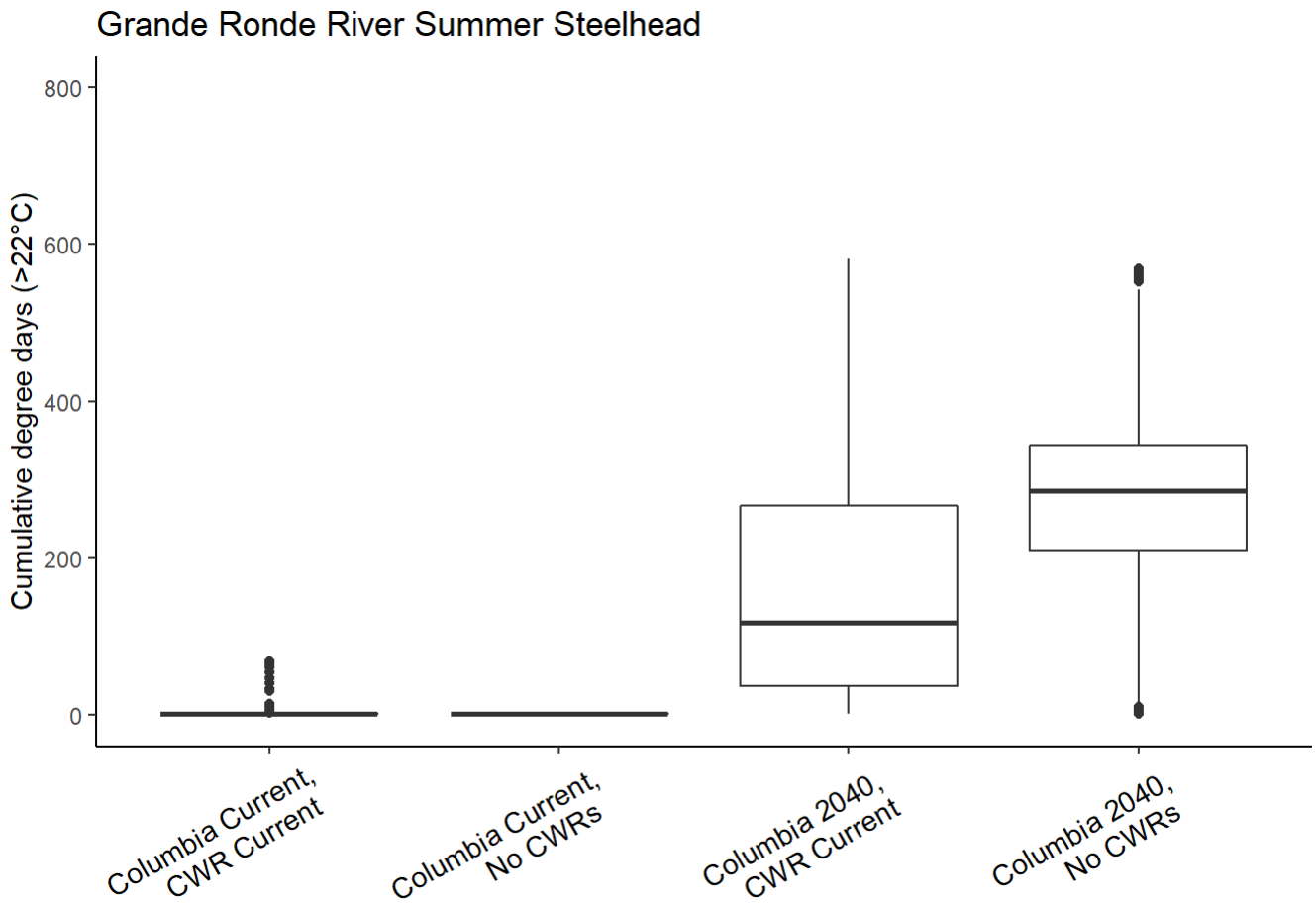


Fig. 6. Boxplots of modeled Grande Ronde River summer steelhead accumulated degrees day over 22°C from Bonneville to the Snake River confluence in the Columbia River.

Table 3. 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

Grande Ronde summer steelhead summarized fitness outcomes

MNSnyder

8/30/2019

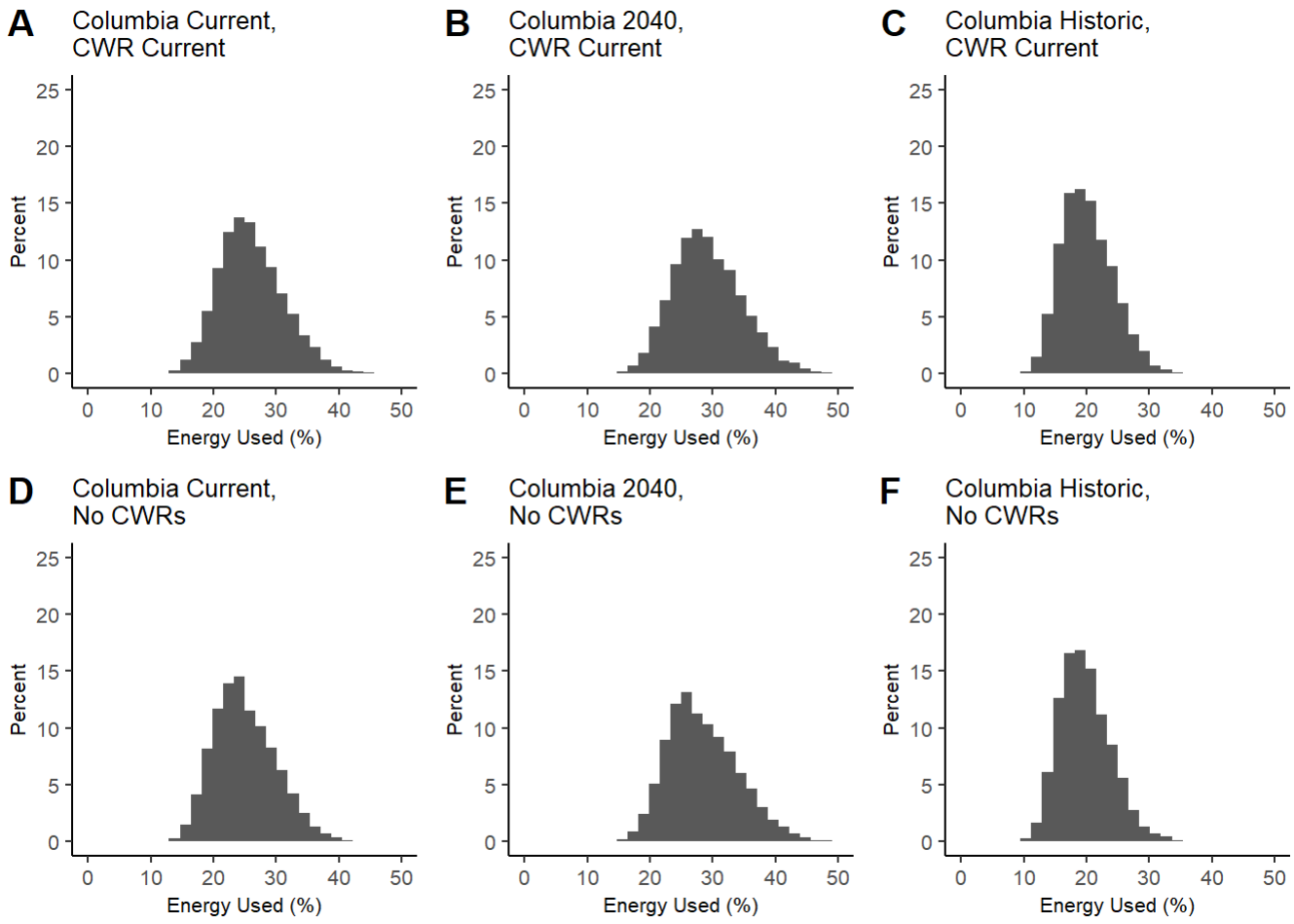


Fig. 1. Histogram of percent energy lost for modeled Grande Ronde summer steelhead migrating through different modeled thermalscapes.

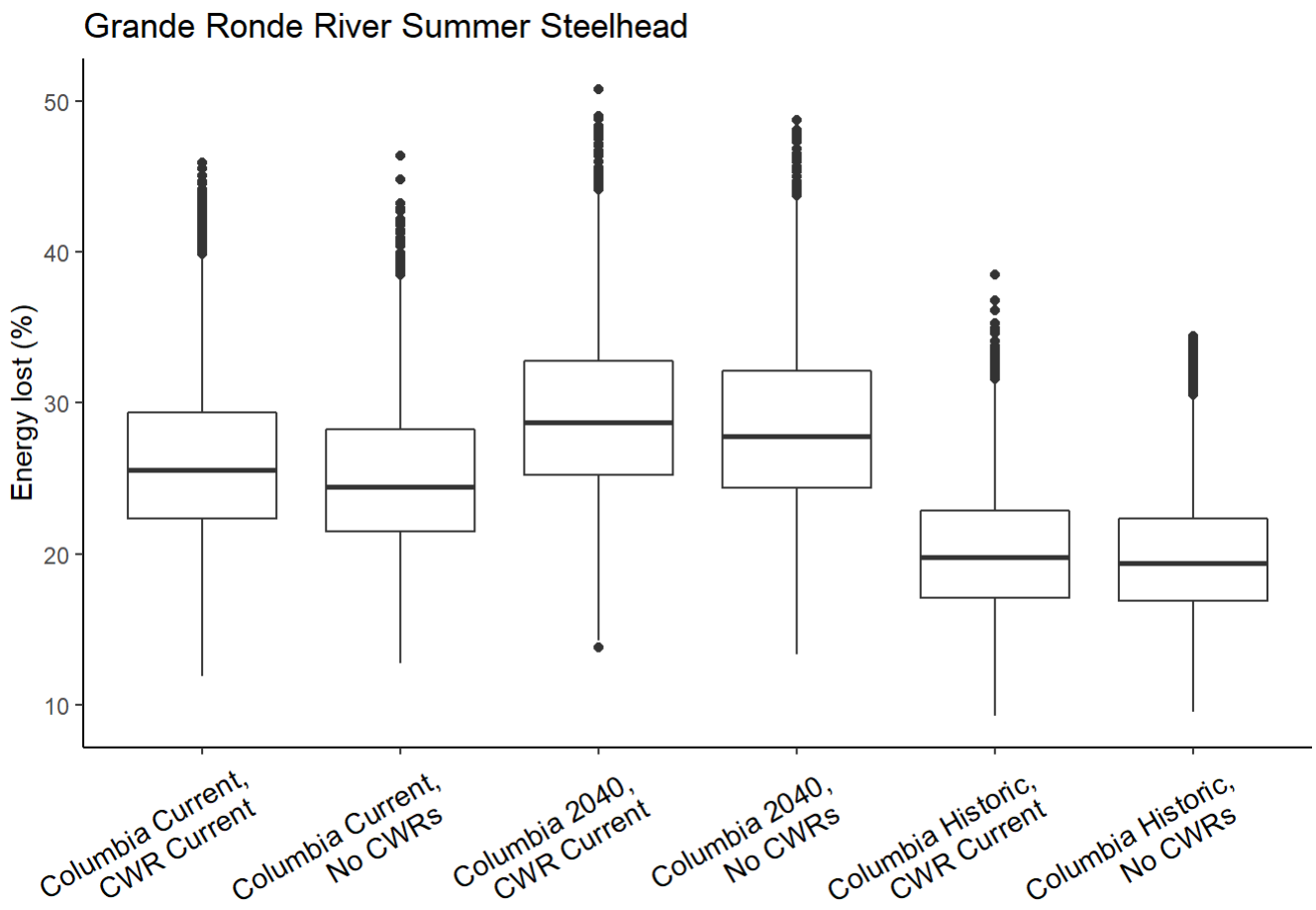


Fig. 2. Boxplot of percent energy lost for modeled Grande Ronde summer steelhead migrating through different modeled thermalscapes.

Table 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

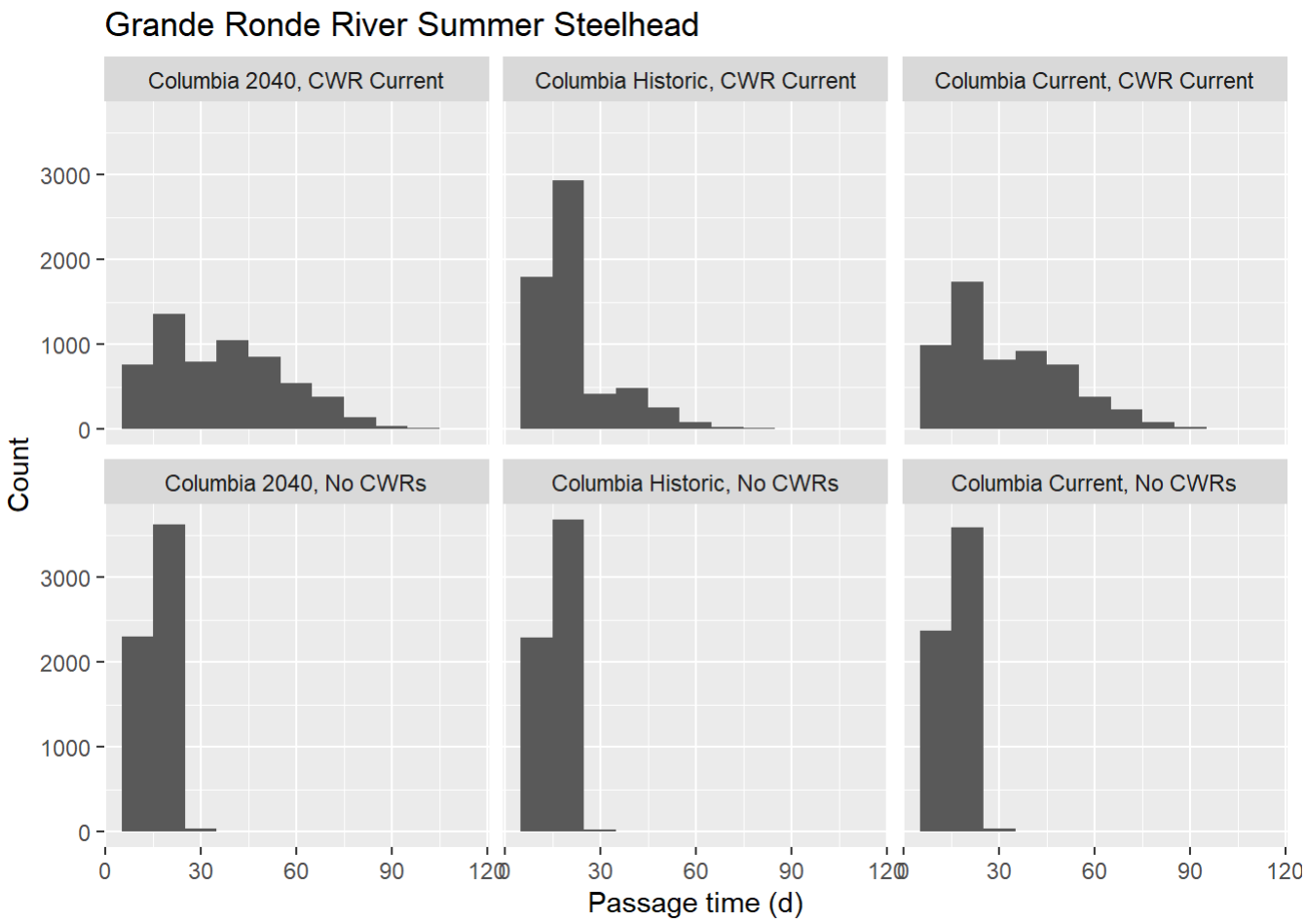
Table 3. Model output for total hours residing in cold water refuges summarized for Grande Ronde River Summer Steelhead.

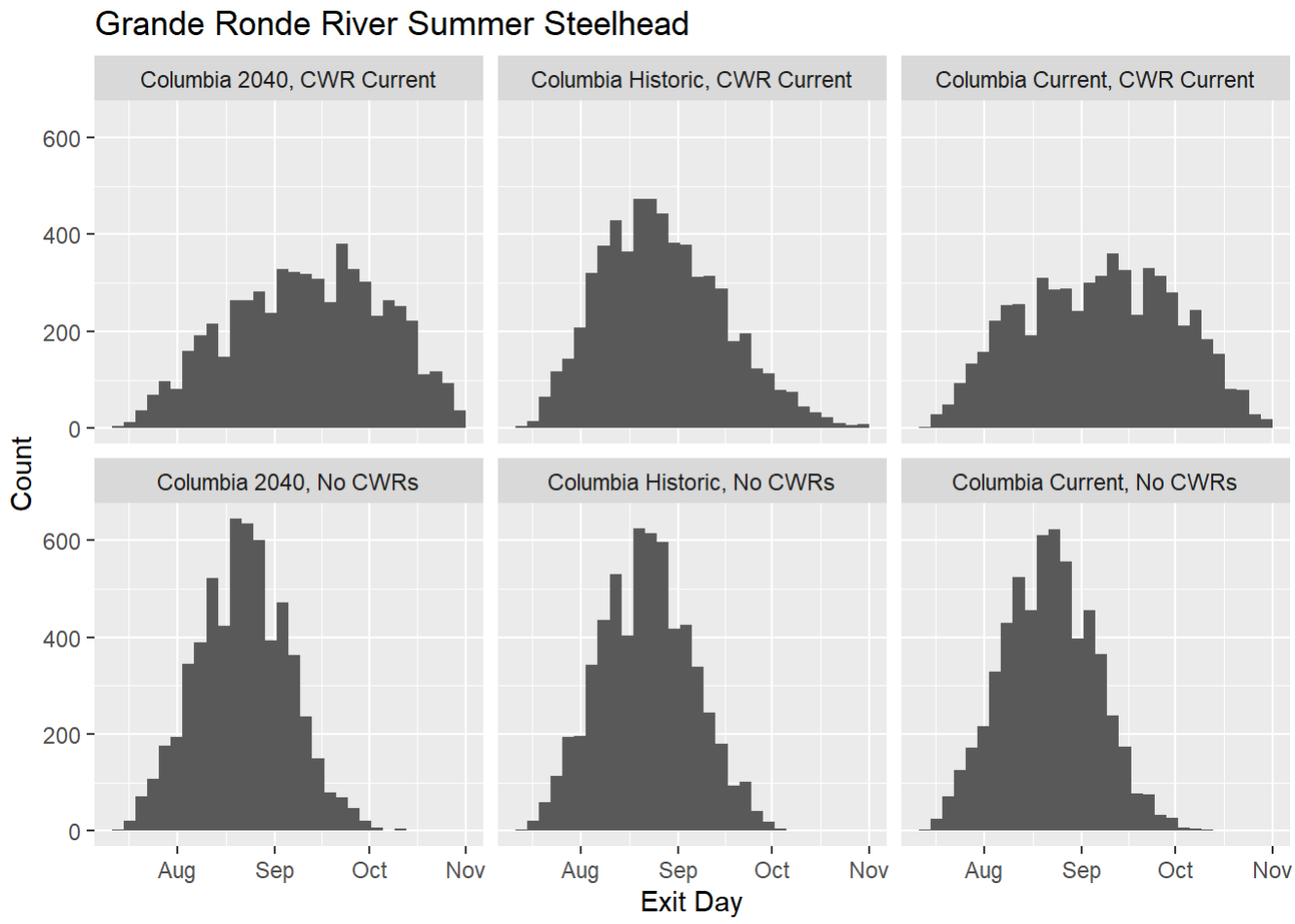
Scenario	Total CWR Residence (h)
Columbia Current,CWR Current	2331586
Columbia Current, No CWRs	16

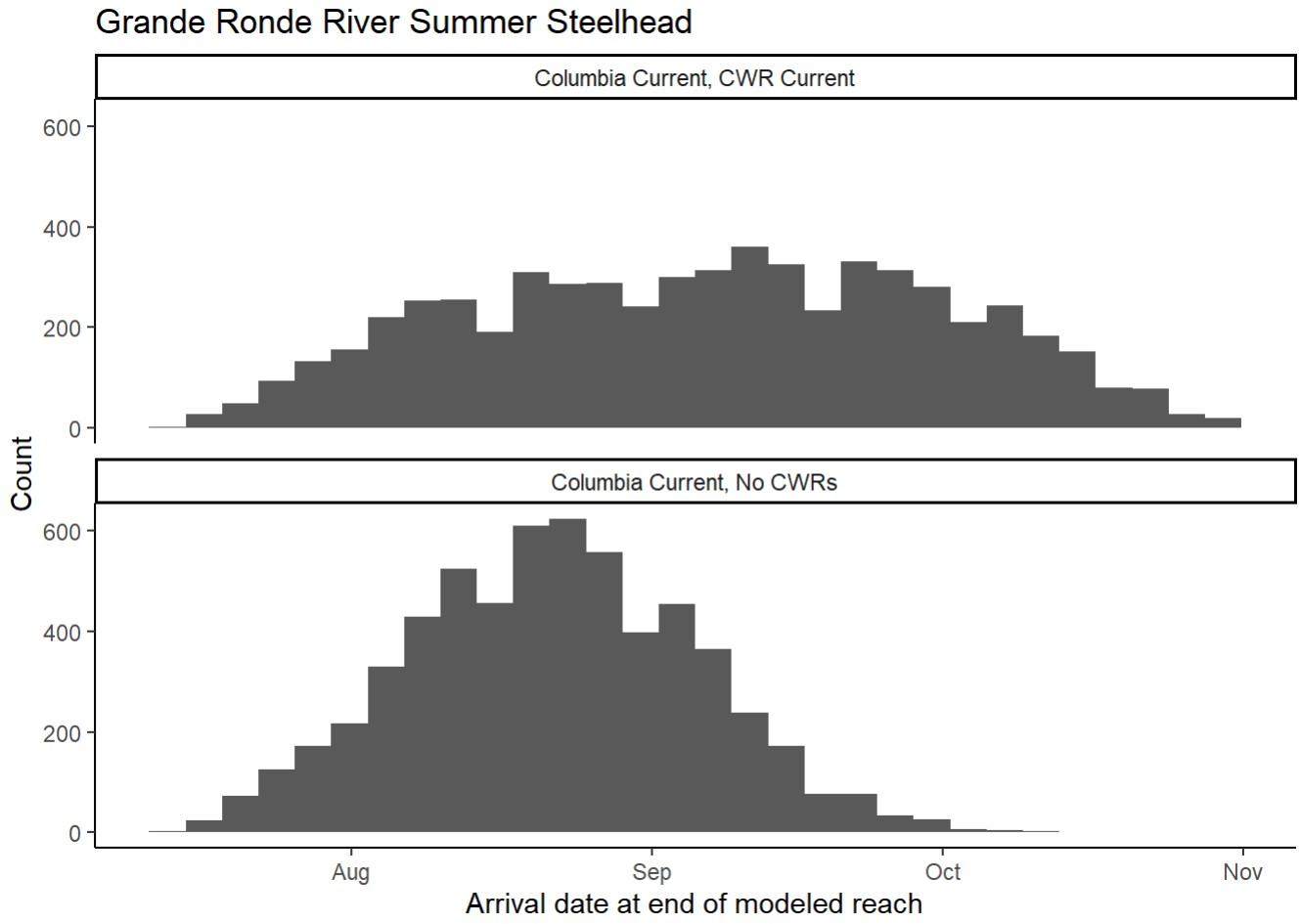
Scenario	Total CWR Residence (h)
Columbia 2040, Current	2982933
Columbia 2040, No CWRs	25
Columbia Historic, Current	744979
Columbia Historic, No CWRs	10

Table 4. 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	0.05
Columbia Current, No CWRs	0.05
Columbia 2040, Current	0.95
Columbia 2040, No CWRs	1.6
Columbia Historic, Current	0
Columbia Historic, No CWRs	0




Grande Ronde River Summer Steelhead
Columbia 2040, CWR Current
Columbia Historic, CWR Current
Columbia Current, CWR Current
Columbia 2040, No CWRs
Columbia Historic, No CWRs
Columbia Current, No CWRs
Count
0
200
400
600
Aug
Sep
Oct
Nov
Exit Day


Grande Ronde River Summer Steelhead
Columbia Current, CWR Current
Columbia Current, No CWRs
Count
0
200
400
600
Aug
Sep
Oct
Nov
Arrival date at end of modeled reach

Tucannon summer steelhead cumulative DD

MNSnyder

8/29/2019

DD > 18 °C

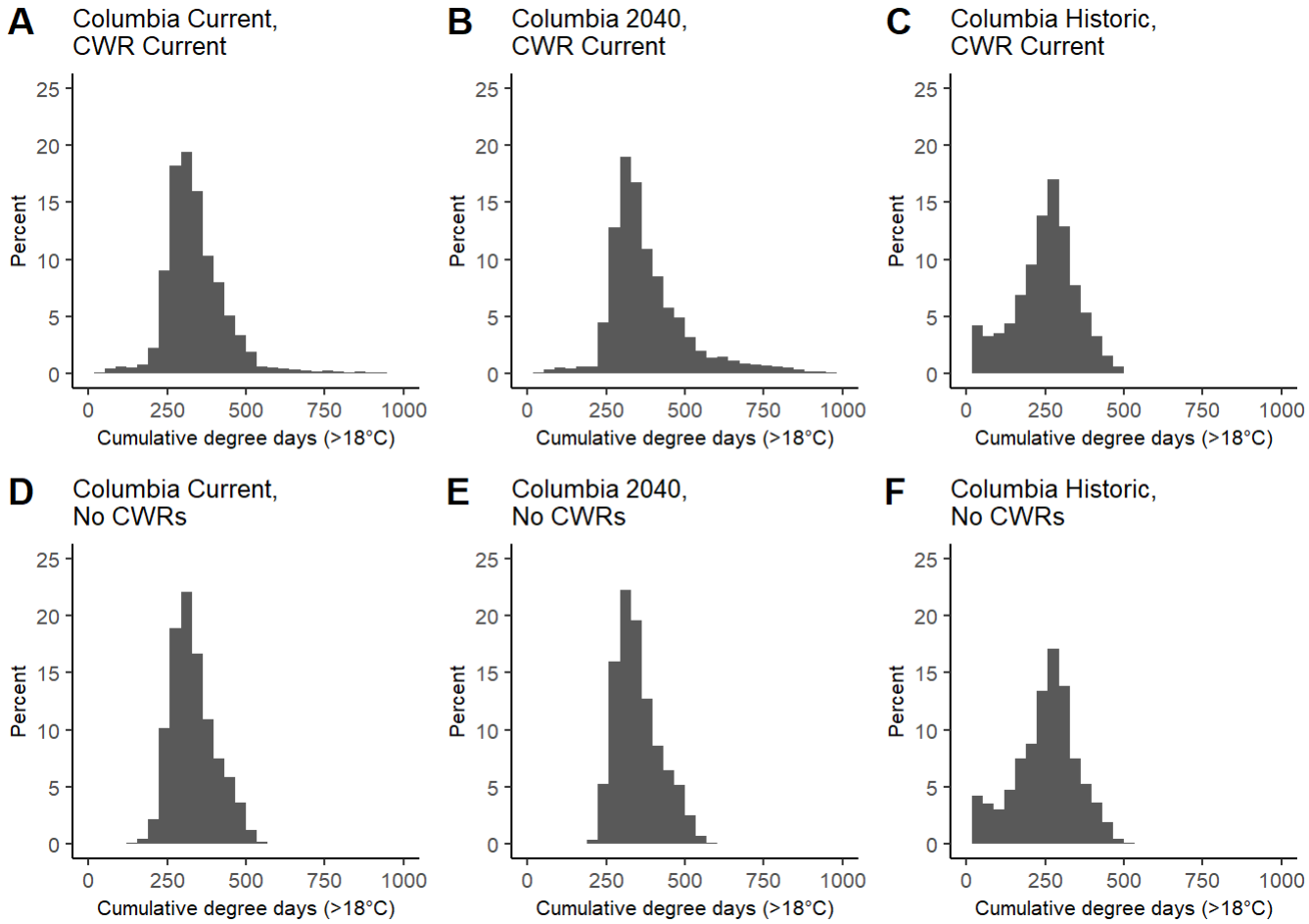


Fig. 1. Histograms of modeled Tucannon River summer steelhead accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.

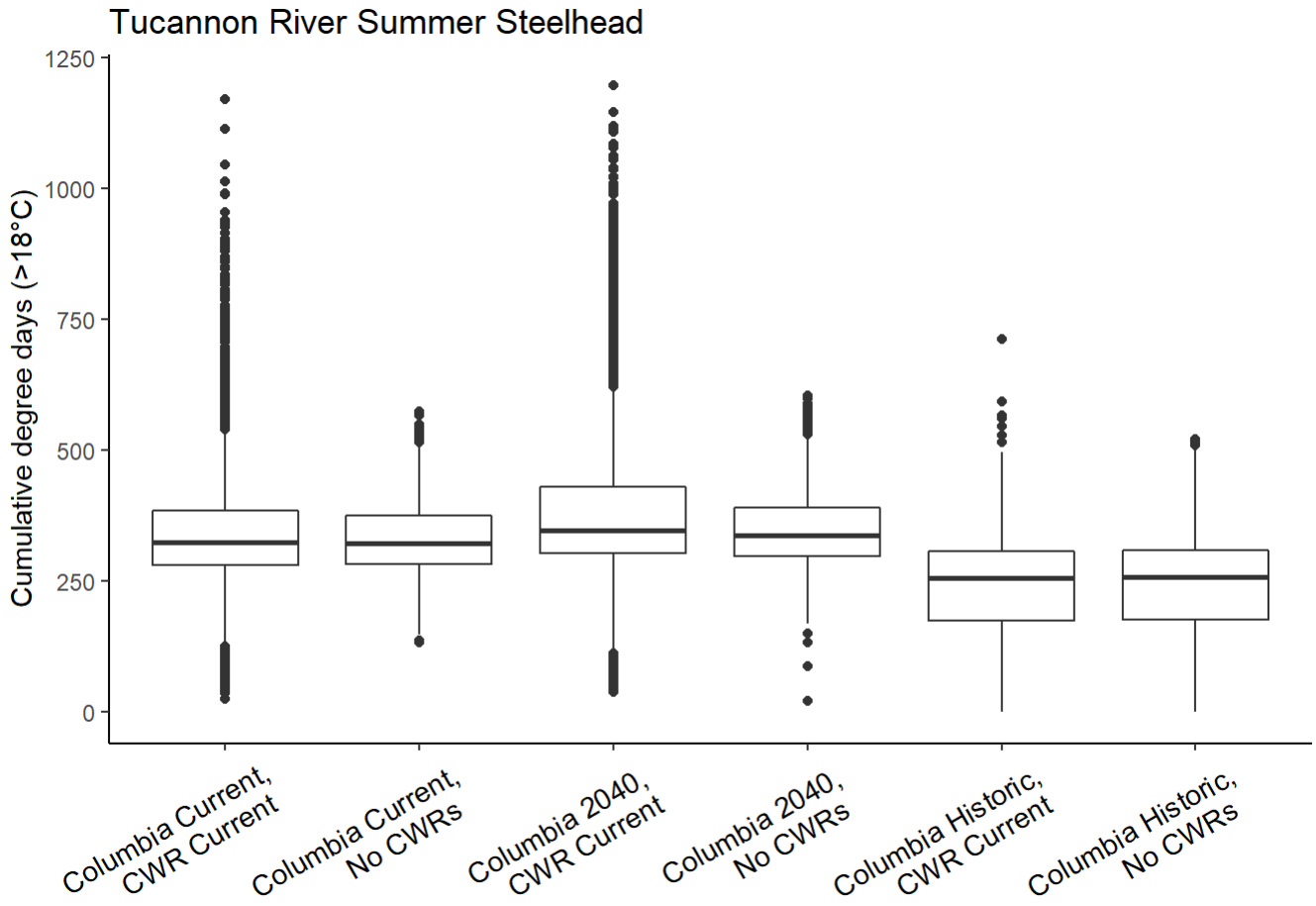


Fig. 2. Boxplots of modeled Tucannon River summer steelhead accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.

Table 1. 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

Degree Days > 20°C

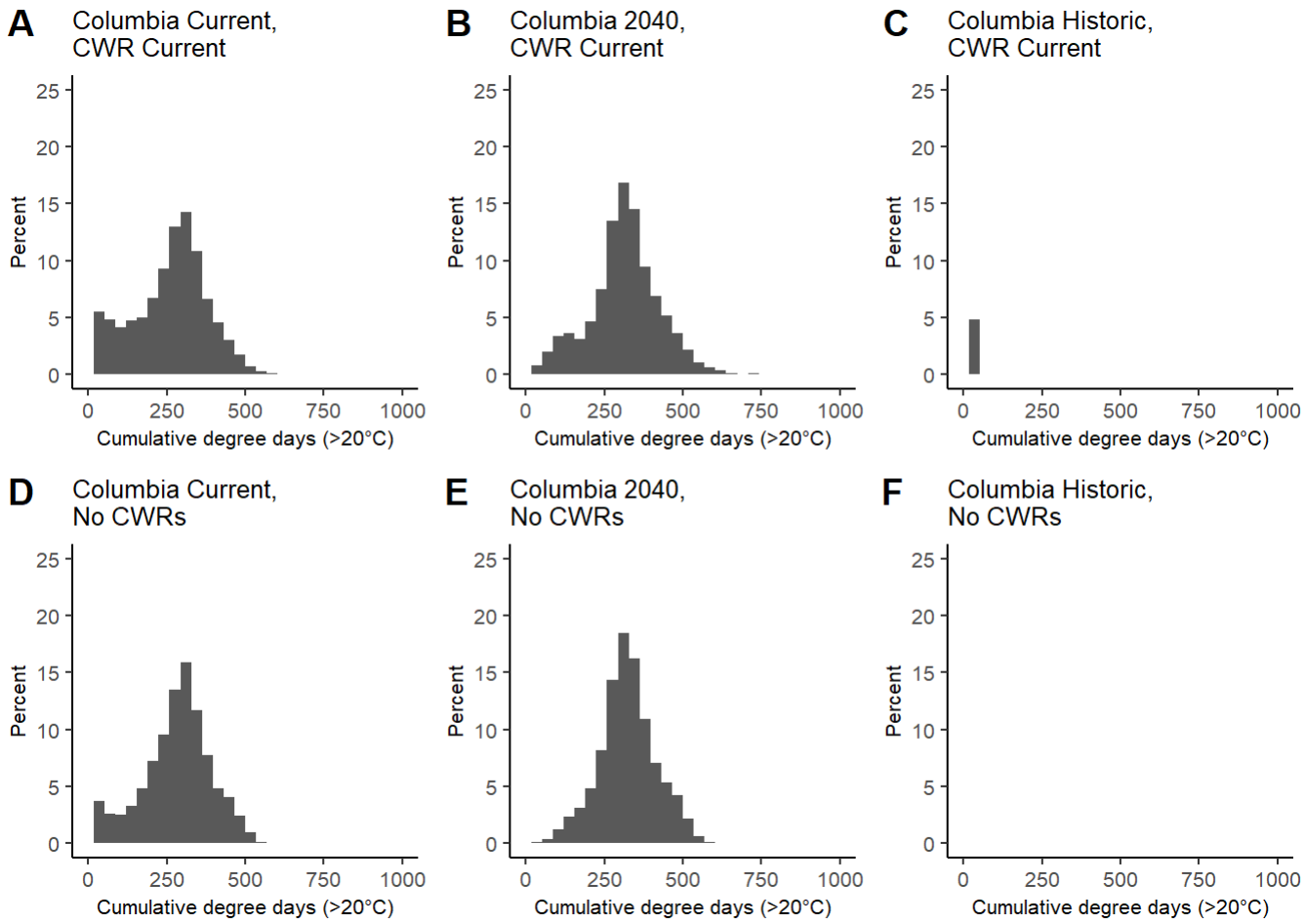


Fig. 3. Histograms of modeled Tucannon River summer steelhead accumulated degrees day over 20°C from Bonneville to the Snake River confluence in the Columbia River.

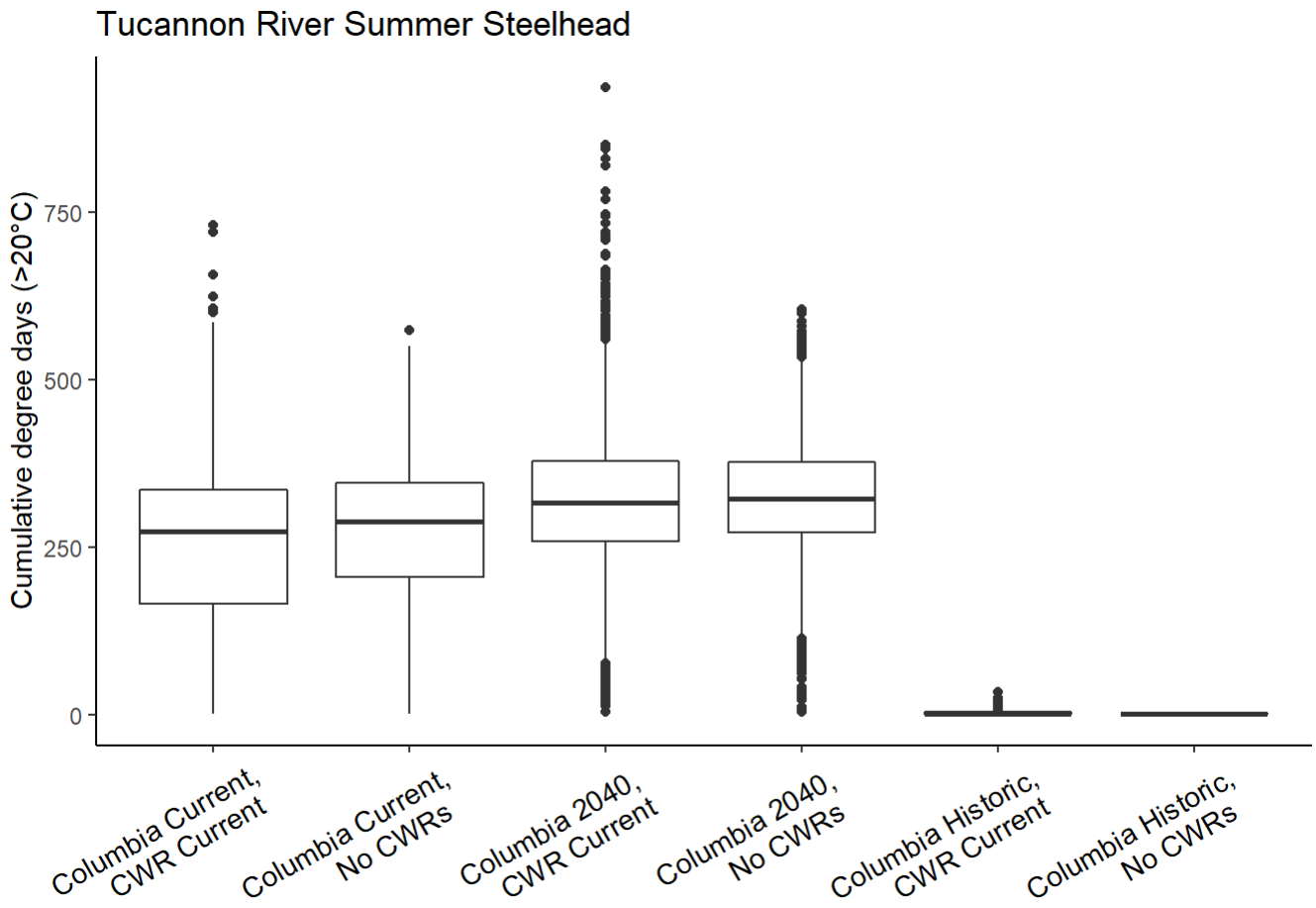
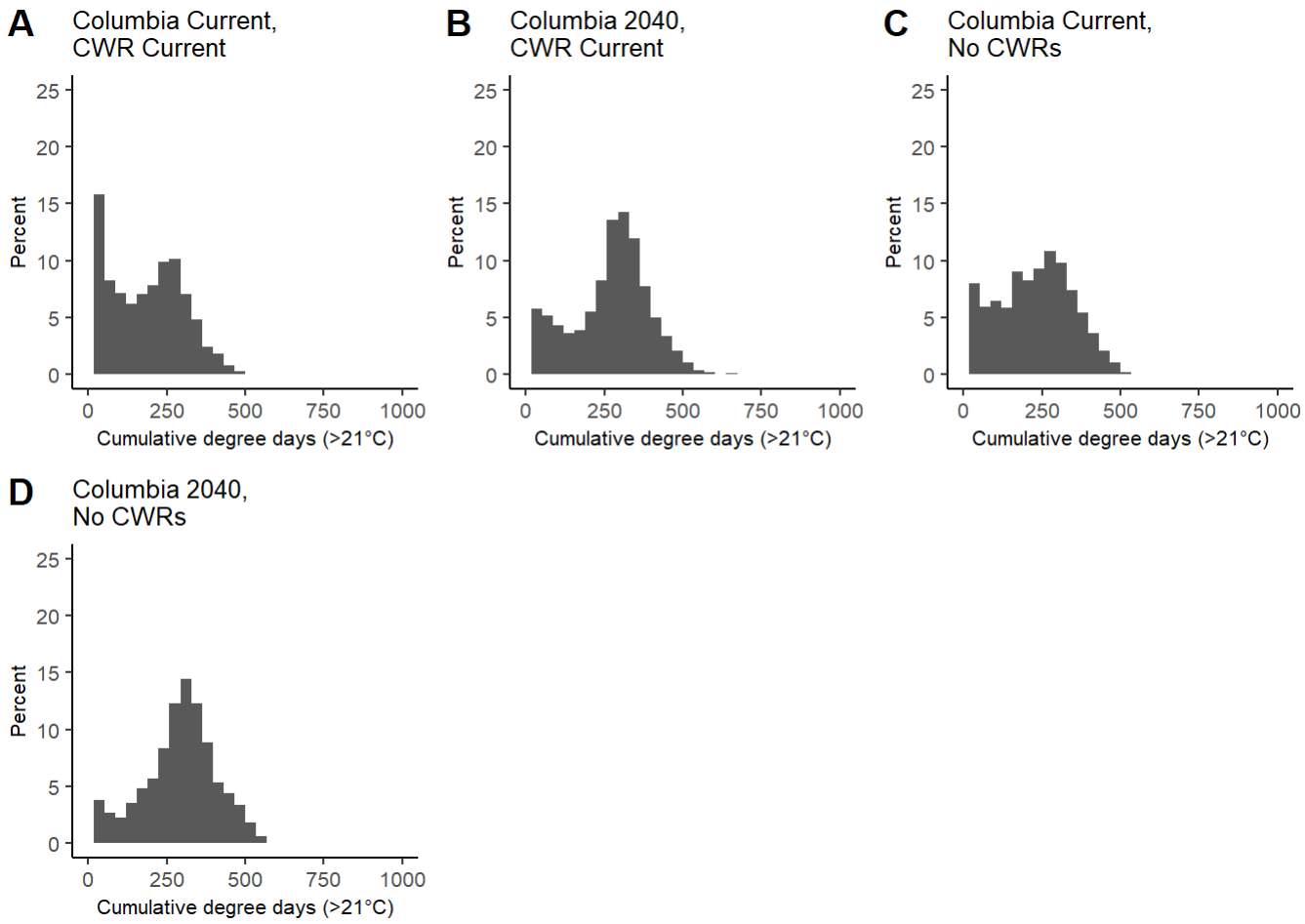


Fig. 4. Boxplots of modeled Tucannon River summer steelhead accumulated degrees day over 20°C from Bonneville to the Snake River confluence in the Columbia River.

Table 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

Degree Days > 21°C



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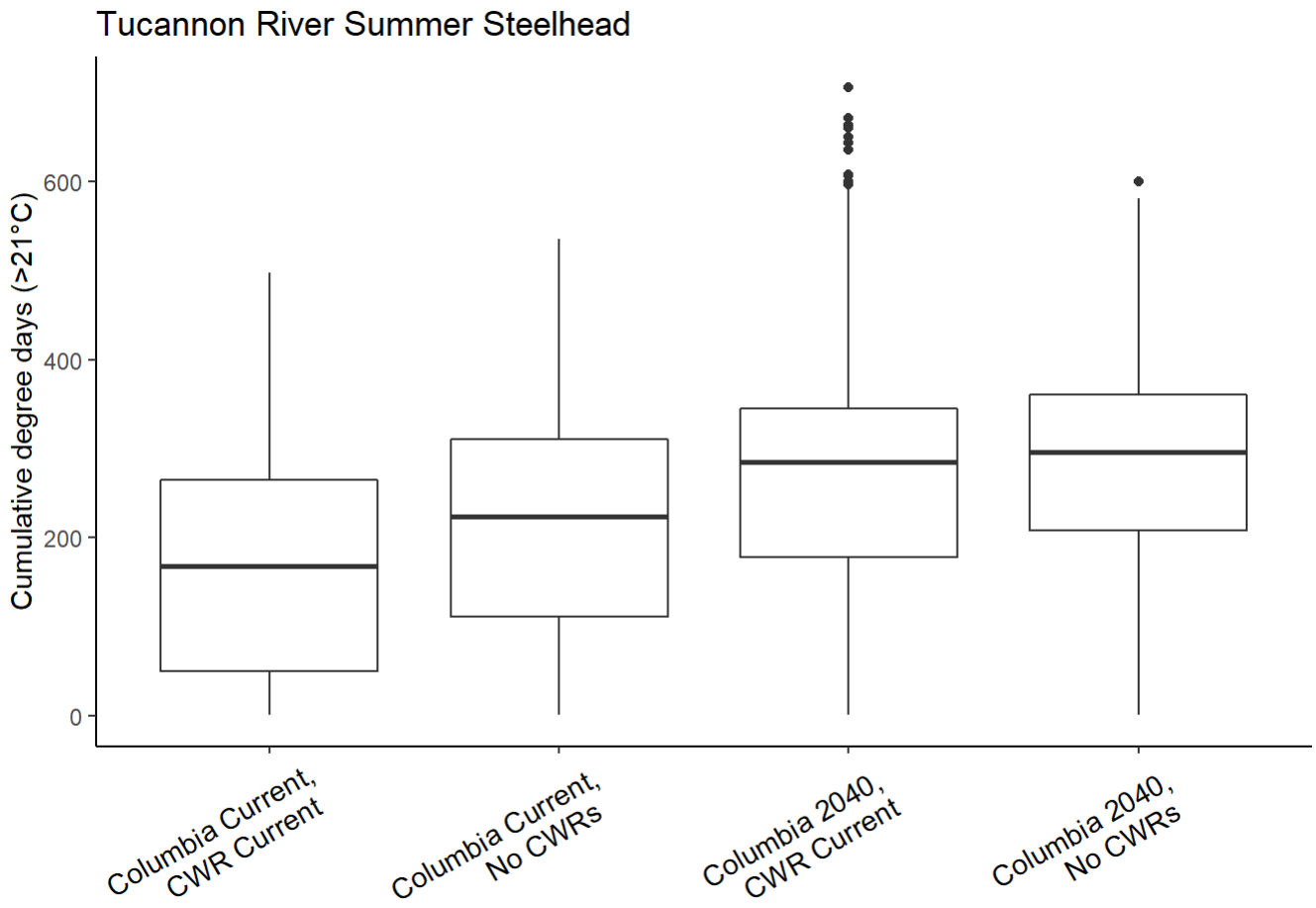

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Table 3. Cumulative degree days (>21°C) used across different HexSim thermalscapes summarized for Tucannon River Summer Steelhead.

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

Tucannon summer steelhead summarized fitness outcomes

MNSnyder

8/26/2019

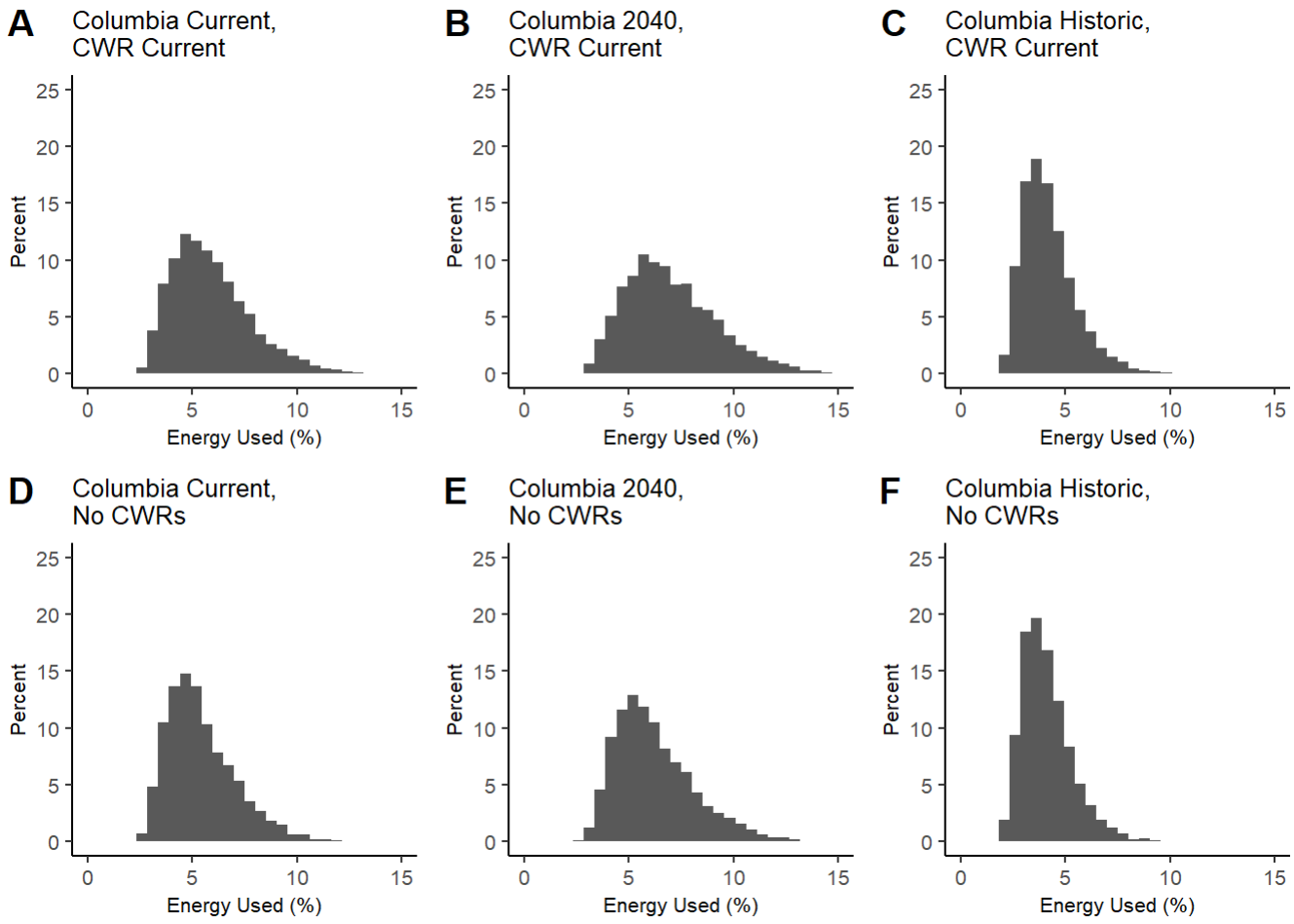


Fig. 1. Histogram of percent energy lost for modeled Grande Ronde summer steelhead migrating through different modeled thermalscapes.

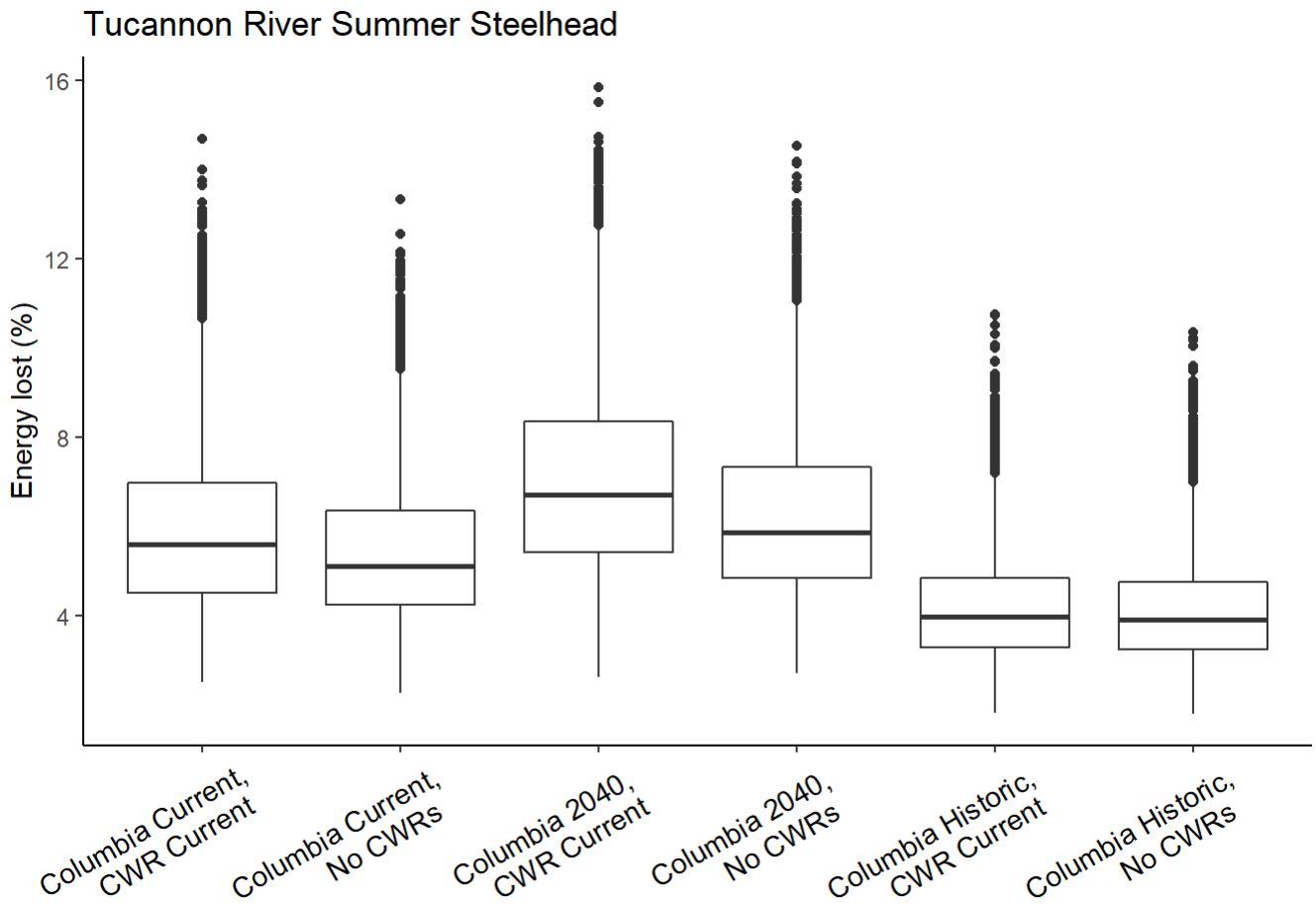


Fig. 2. Boxplot of percent energy lost for modeled Grande Ronde summer steelhead migrating through different modeled thermalscapes.

Table 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 3. Model output for total hours residing in cold water refuges summarized for Tucannon River Summer Steelhead.

Scenario	Total CWR Residence (h)
Columbia Current,CWR Current	1772101
Columbia Current, No CWRs	9

Scenario	Total CWR Residence (h)
Columbia 2040, Current	2667476
Columbia 2040, No CWRs	12
Columbia Historic, Current	435933
Columbia Historic, No CWRs	3

Table 4. 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
Columbia Current, No CWRs	0
Columbia 2040, Current	0.45
Columbia 2040, No CWRs	0.4
Columbia Historic, Current	0
Columbia Historic, No CWRs	0

Hanford Reach Fall Chinook cumulative DD

MNSnyder

8/29/2019

DD > 18 °C

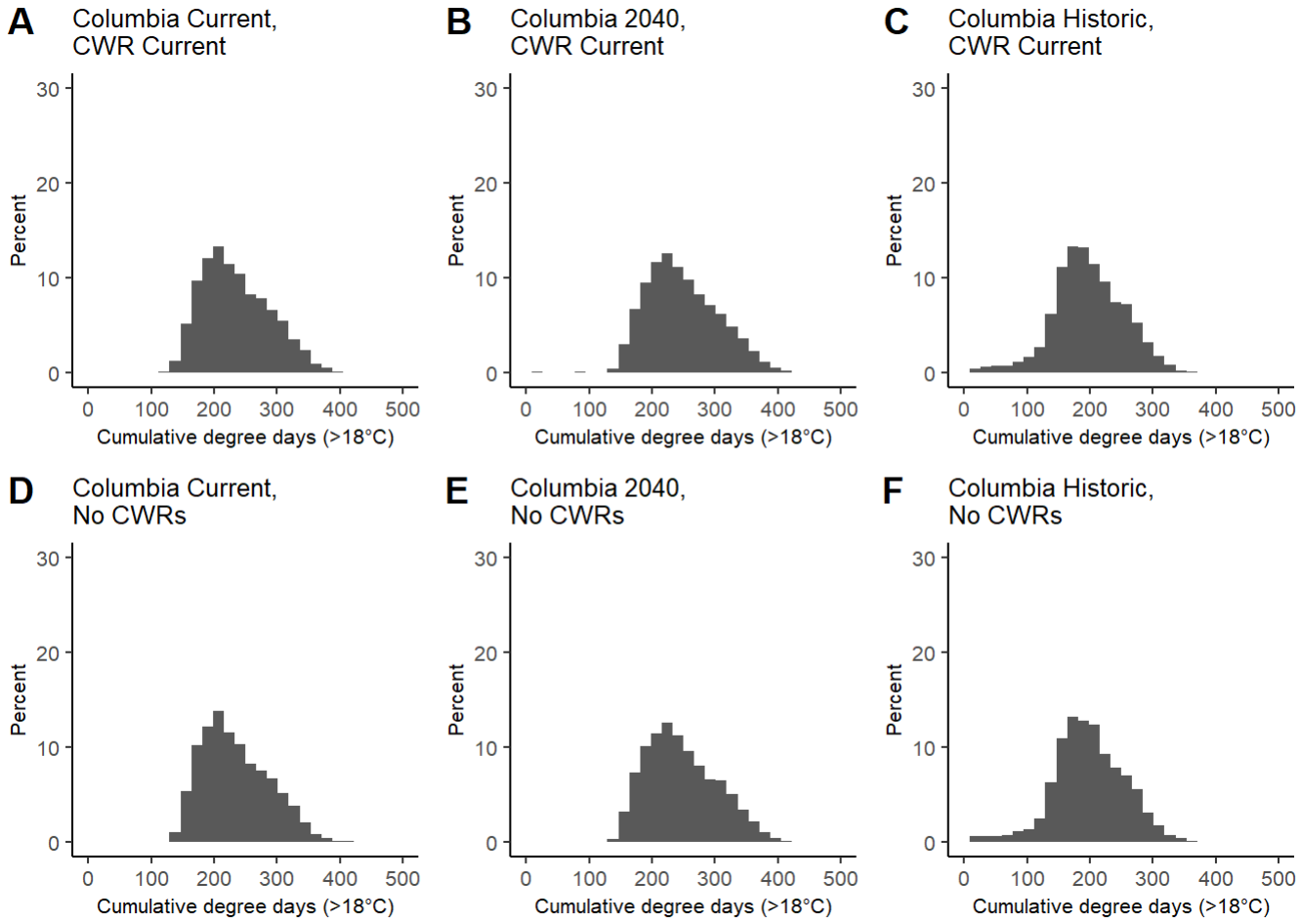


Fig. 1. Histograms of modeled Hanford Reach fall Chinook accumulated degrees day over 18°C from Bonneville to the Hanford Reach confluence in the Columbia River.

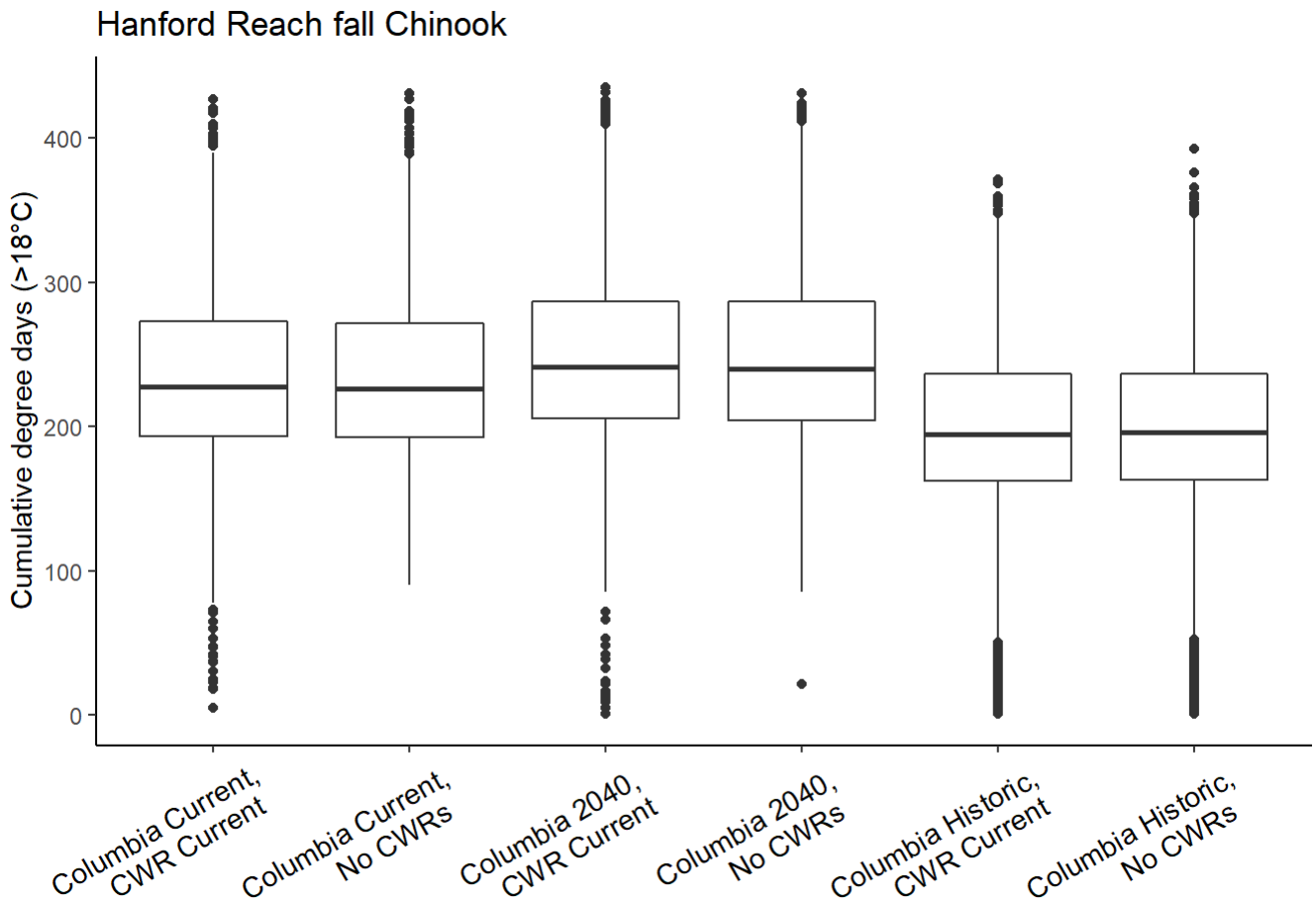
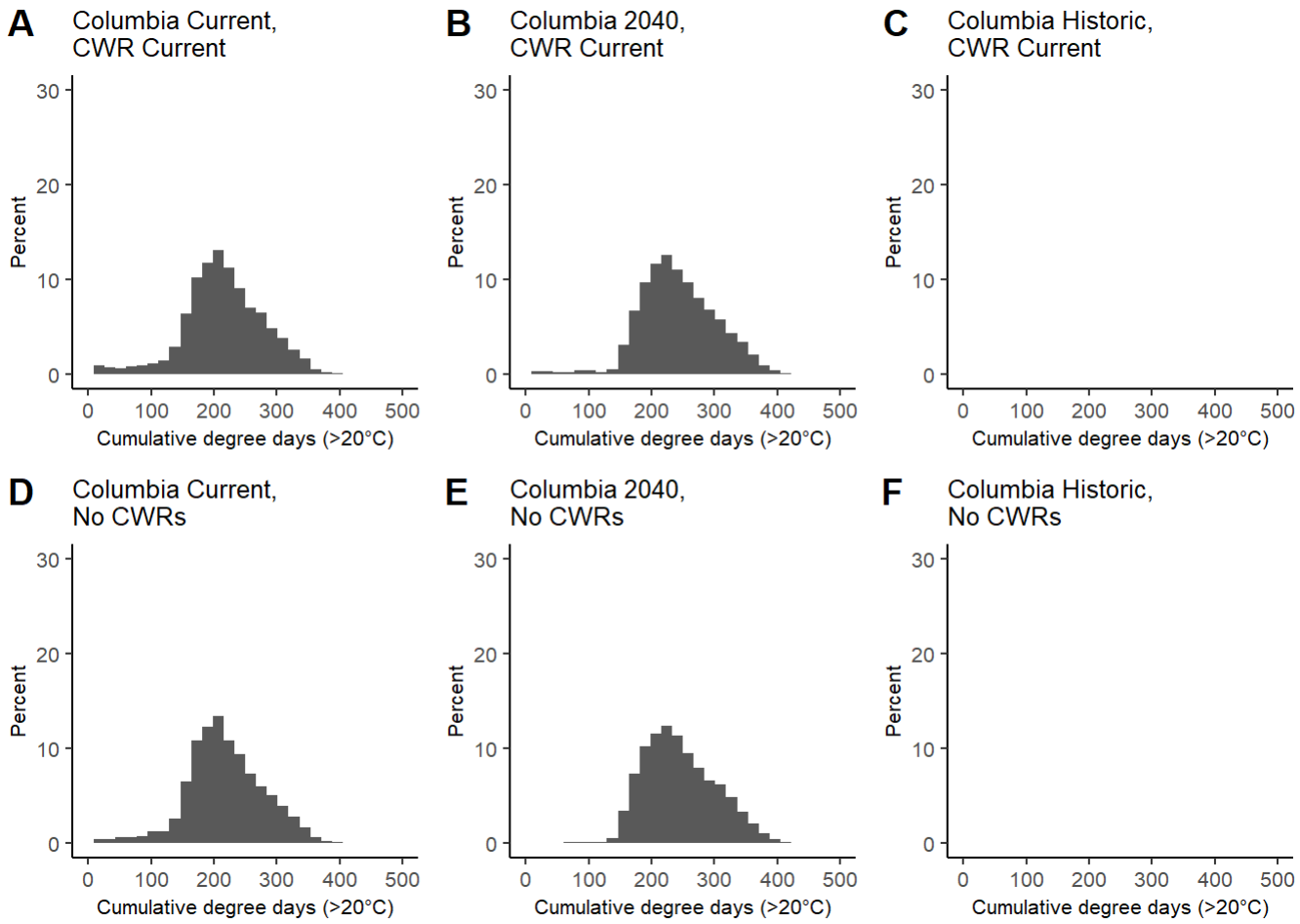


Fig. 2. Boxplots of modeled Hanford Reach fall Chinook accumulated degrees day over 18°C from Bonneville to the Hanford Reach confluence in the Columbia River.

Table 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

Degree Days > 20°C



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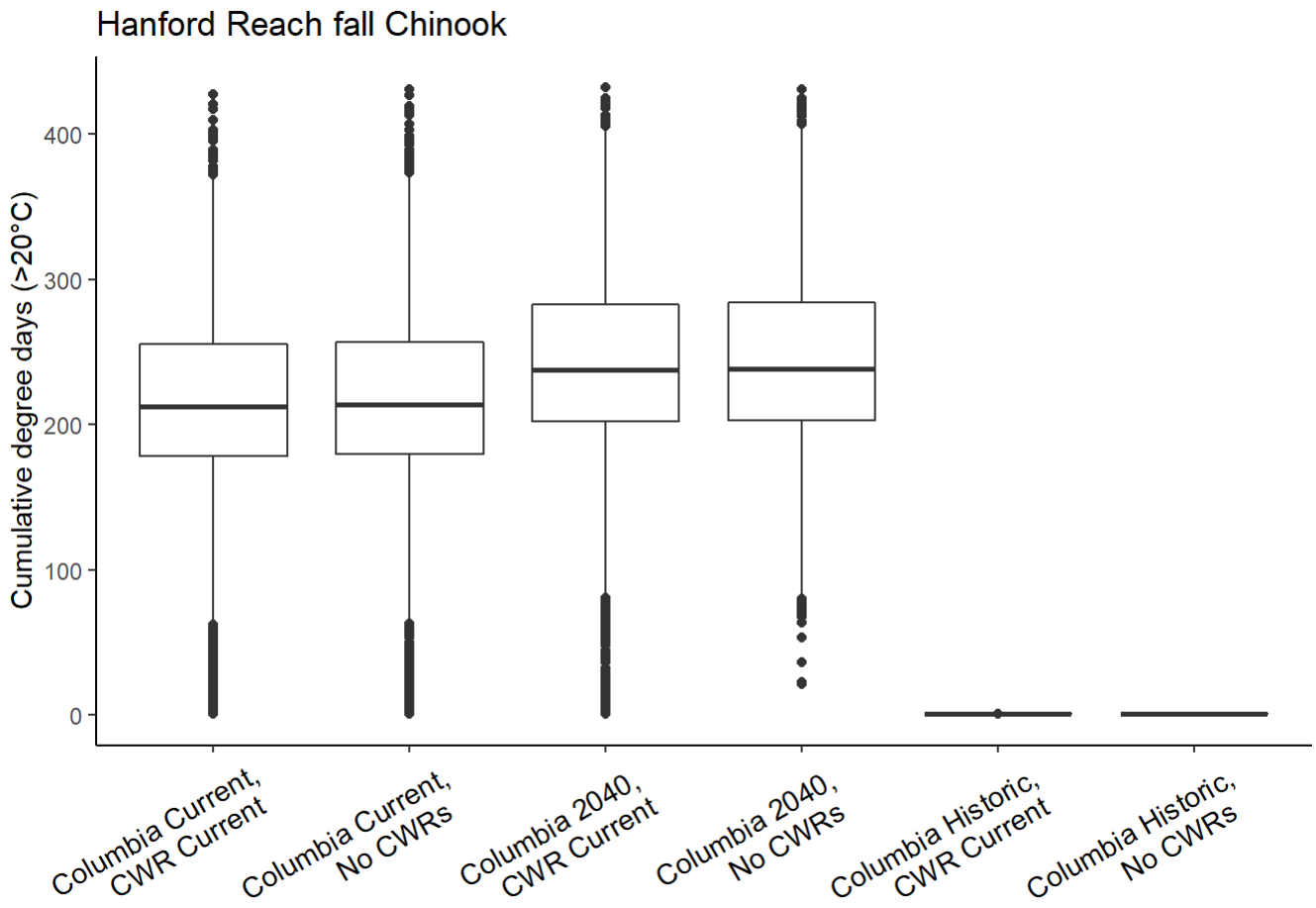


Fig. 4. Boxplots of modeled Hanford Reach fall Chinook accumulated degrees day over 20°C from Bonneville to the Hanford Reach confluence in the Columbia River.

Table 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

Degree Days > 21°C

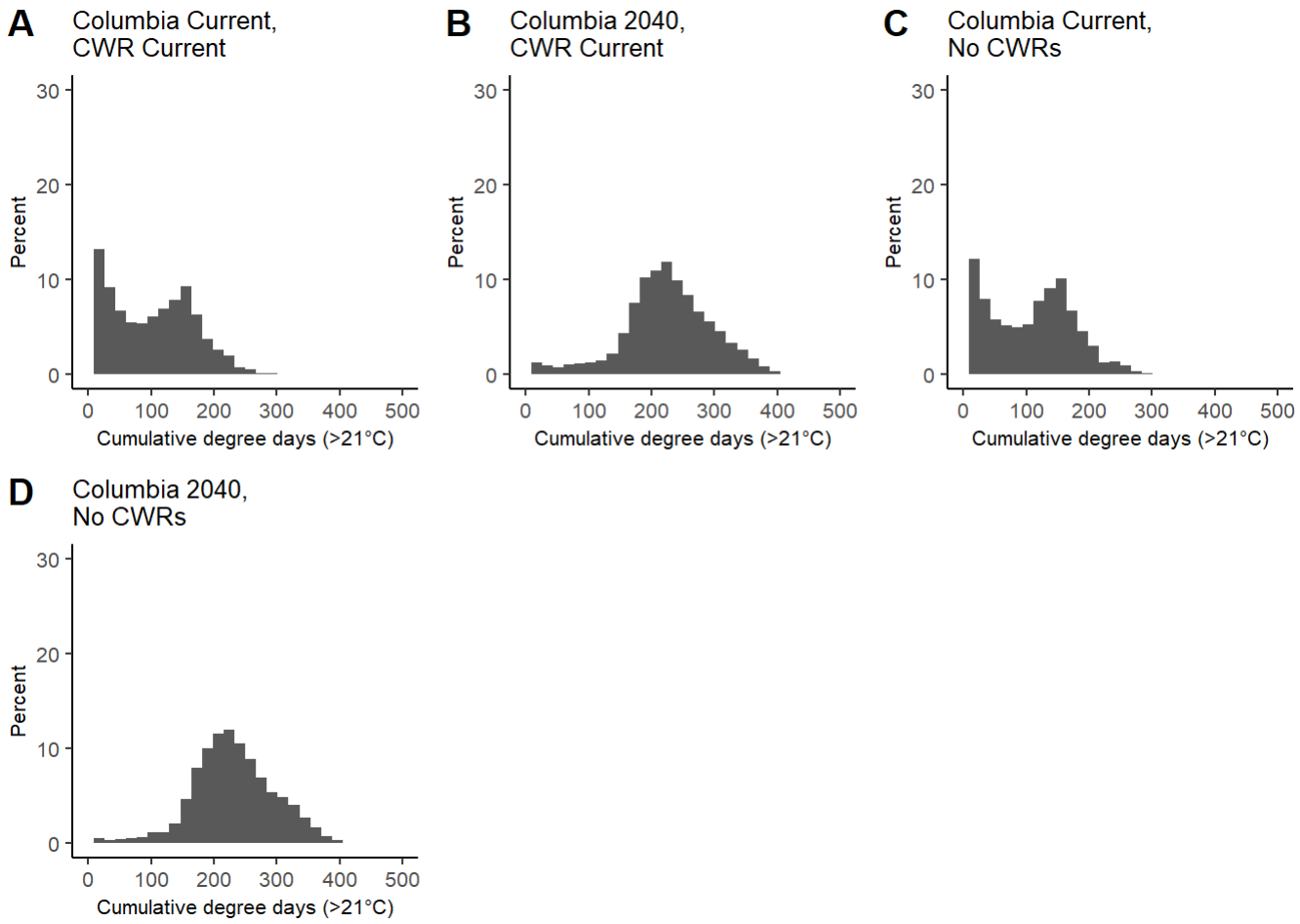


Fig. 5. Histograms of modeled Hanford Reach fall Chinook accumulated degrees day over 21°C from Bonneville to the Hanford Reach confluence in the Columbia River.

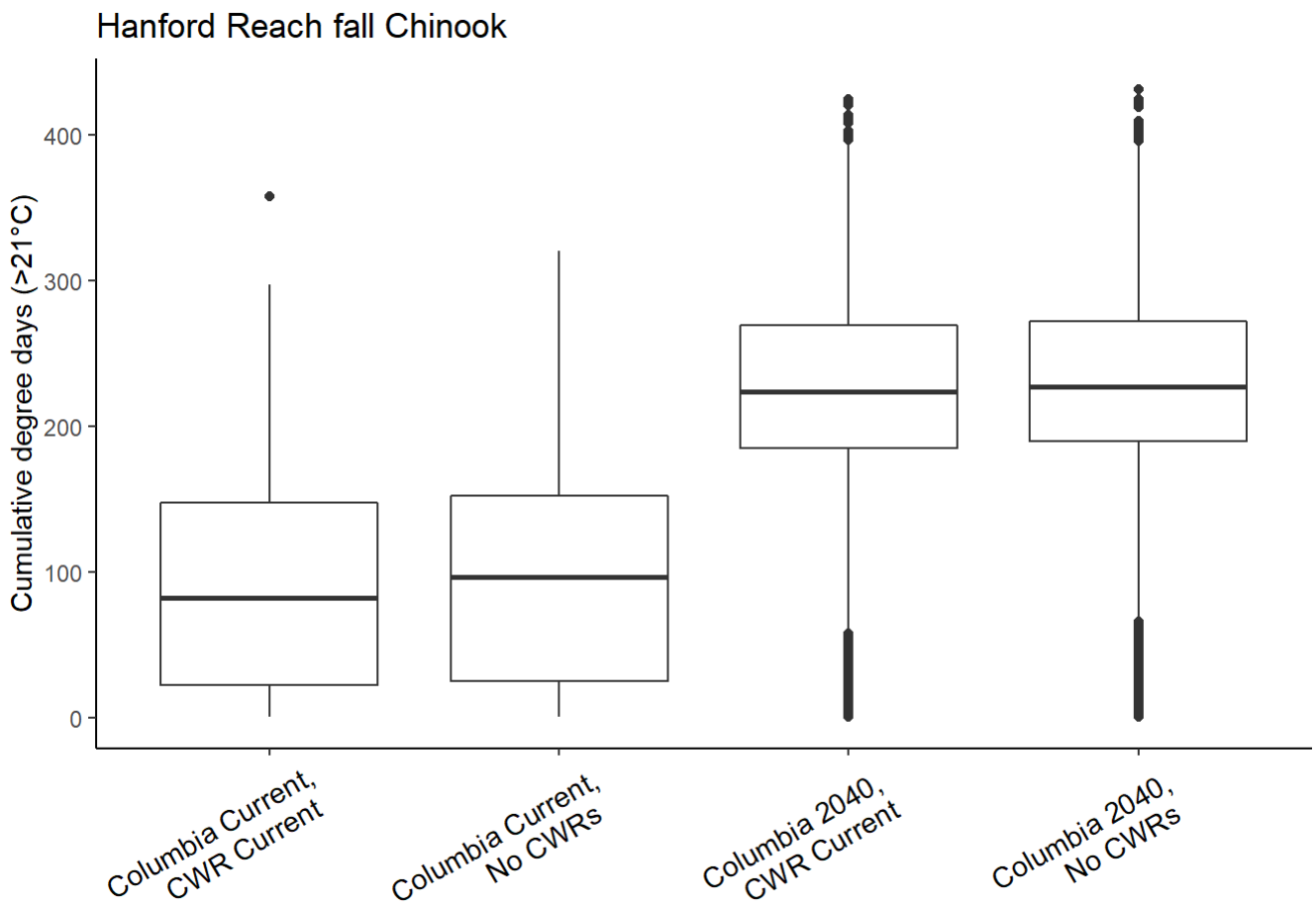


Fig. 6. Boxplots of modeled Hanford Reach fall Chinook accumulated degrees day over 21°C from Bonneville to the Hanford Reach confluence in the Columbia River.

Table 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

Hanford Reach Fall Chinook summarized fitness outcomes

MNSnyder

8/26/2019

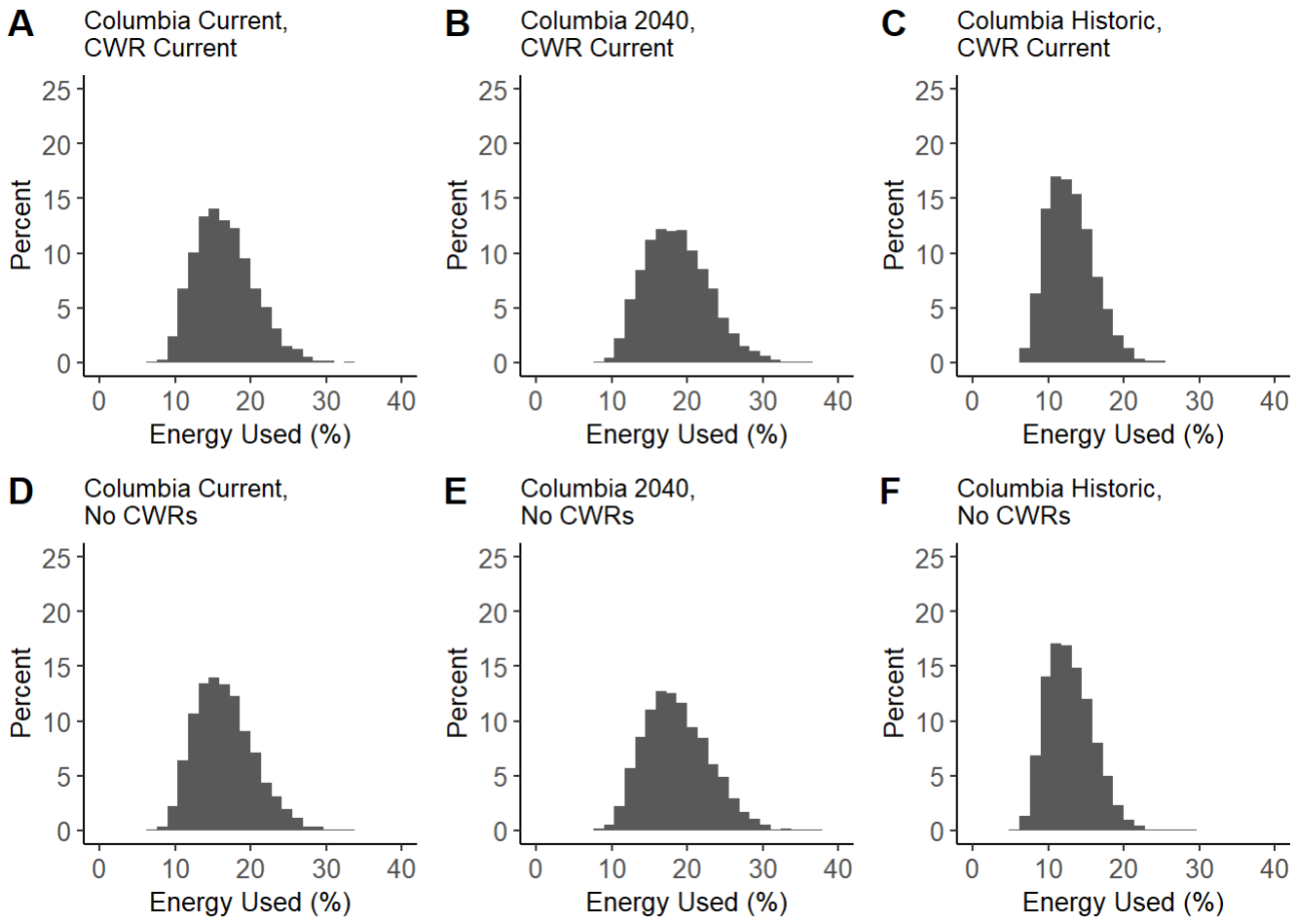


Fig. 1. Histogram of percent energy lost for modeled Hanford Reach Fall Chinook salmon migrating through four different modeled thermalscapes.

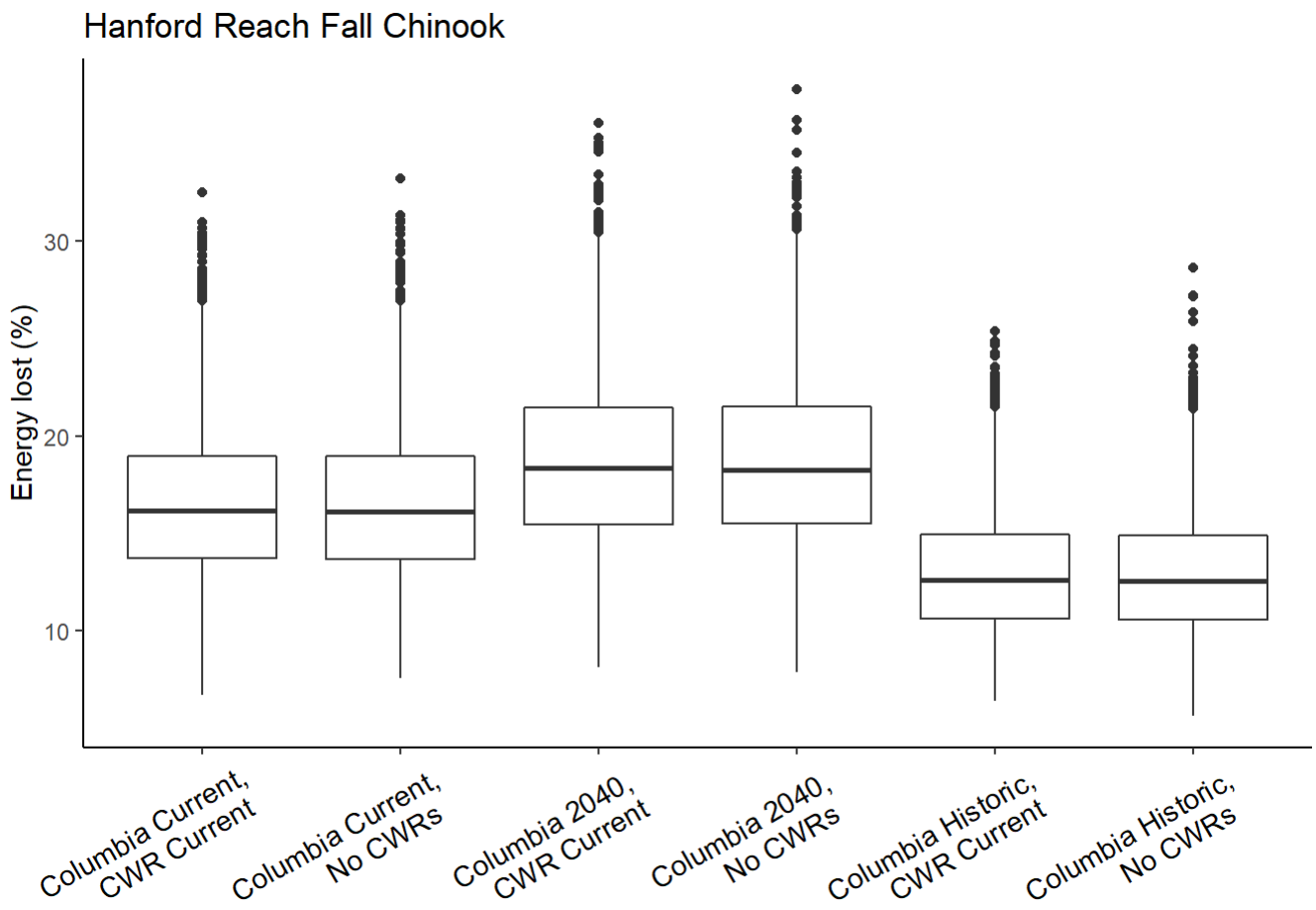


Fig. 2. Boxplot of percent energy lost for modeled Hanford Reach Fall Chinook migrating through four different modeled thermalscapes.

Table 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 3. Model output for total hours residing in cold water refuges summarized for Hanford Reach Fall Chinook.

Scenario	Total CWR Residence (h)
Columbia Current,CWR Current	48919
Columbia Current, No CWRs	1

Scenario	Total CWR Residence (h)
Columbia 2040, Current	98438
Columbia 2040, No CWRs	4
Columbia Historic, Current	5827
Columbia Historic, No CWRs	0

Table 4. 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
Columbia Current, No CWRs	0
Columbia 2040, Current	0
Columbia 2040, No CWRs	0.1
Columbia Historic, Current	0
Columbia Historic, No CWRs	0

Snake River Fall Chinook cumulative DD

MNSnyder

8/29/2019

DD > 18 °C

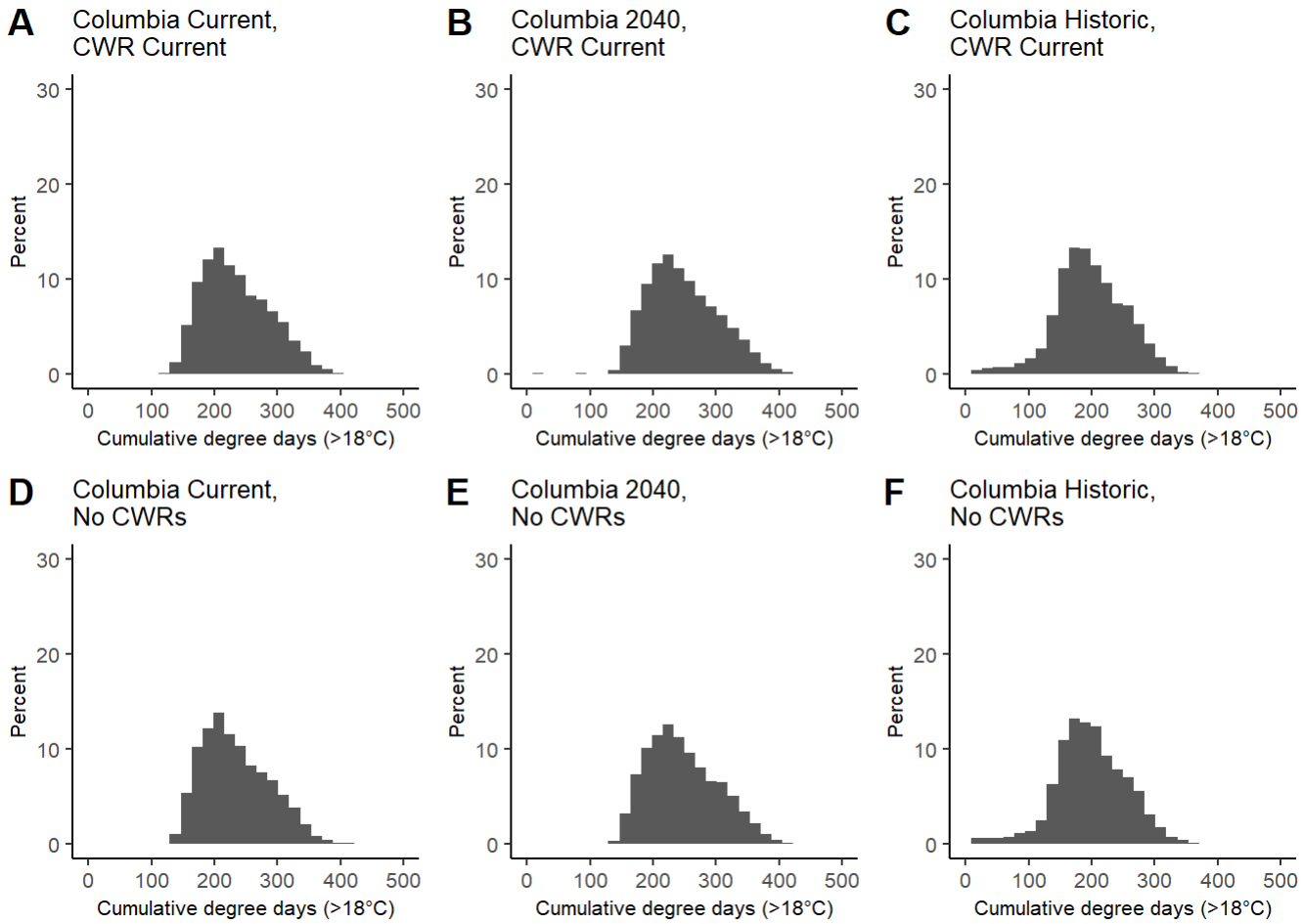


Fig. 1. Histograms of modeled Snake River fall Chinook accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.

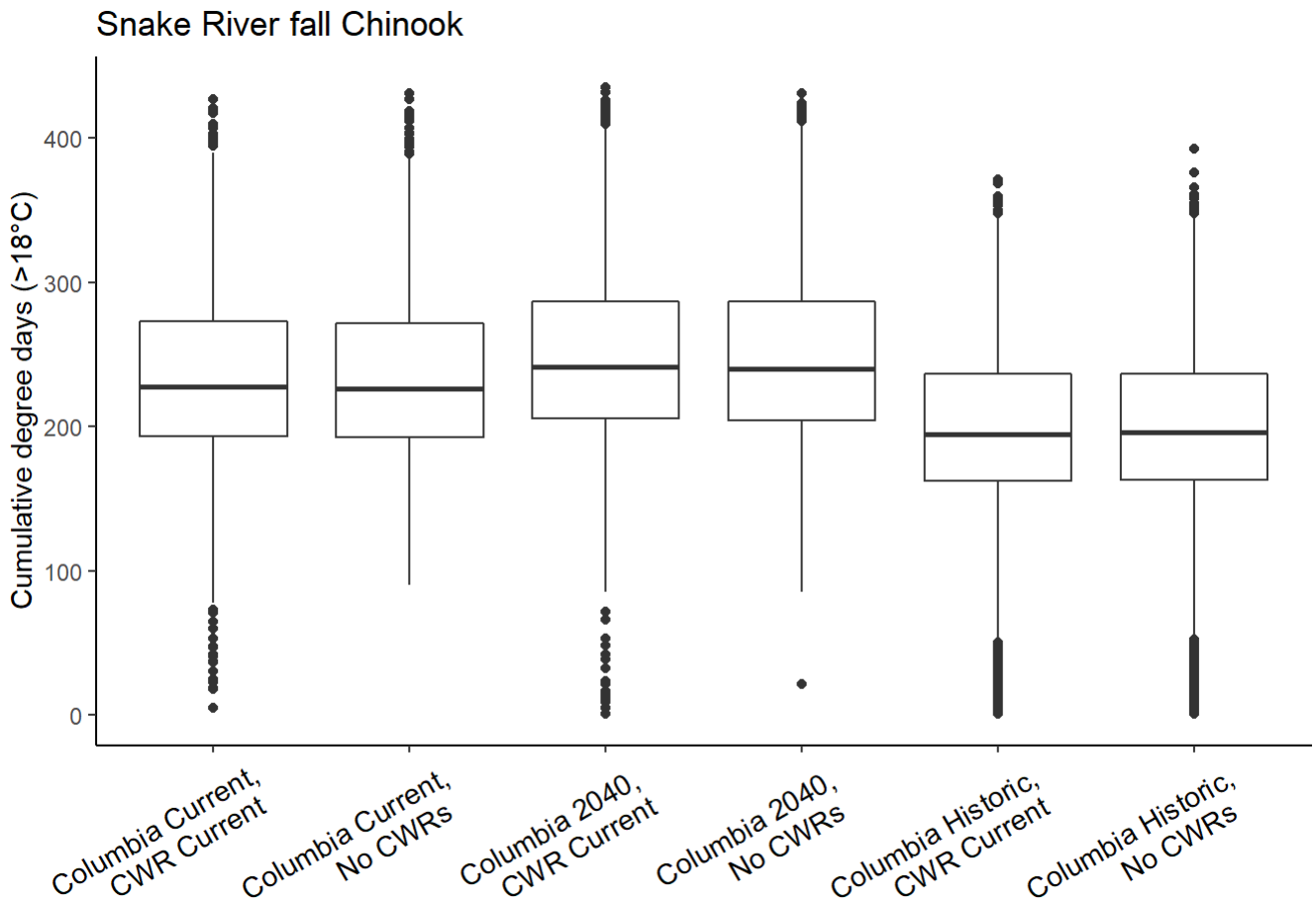


Fig. 2. Boxplots of modeled Snake River fall Chinook accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.

Table 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

Degree Days > 20°C

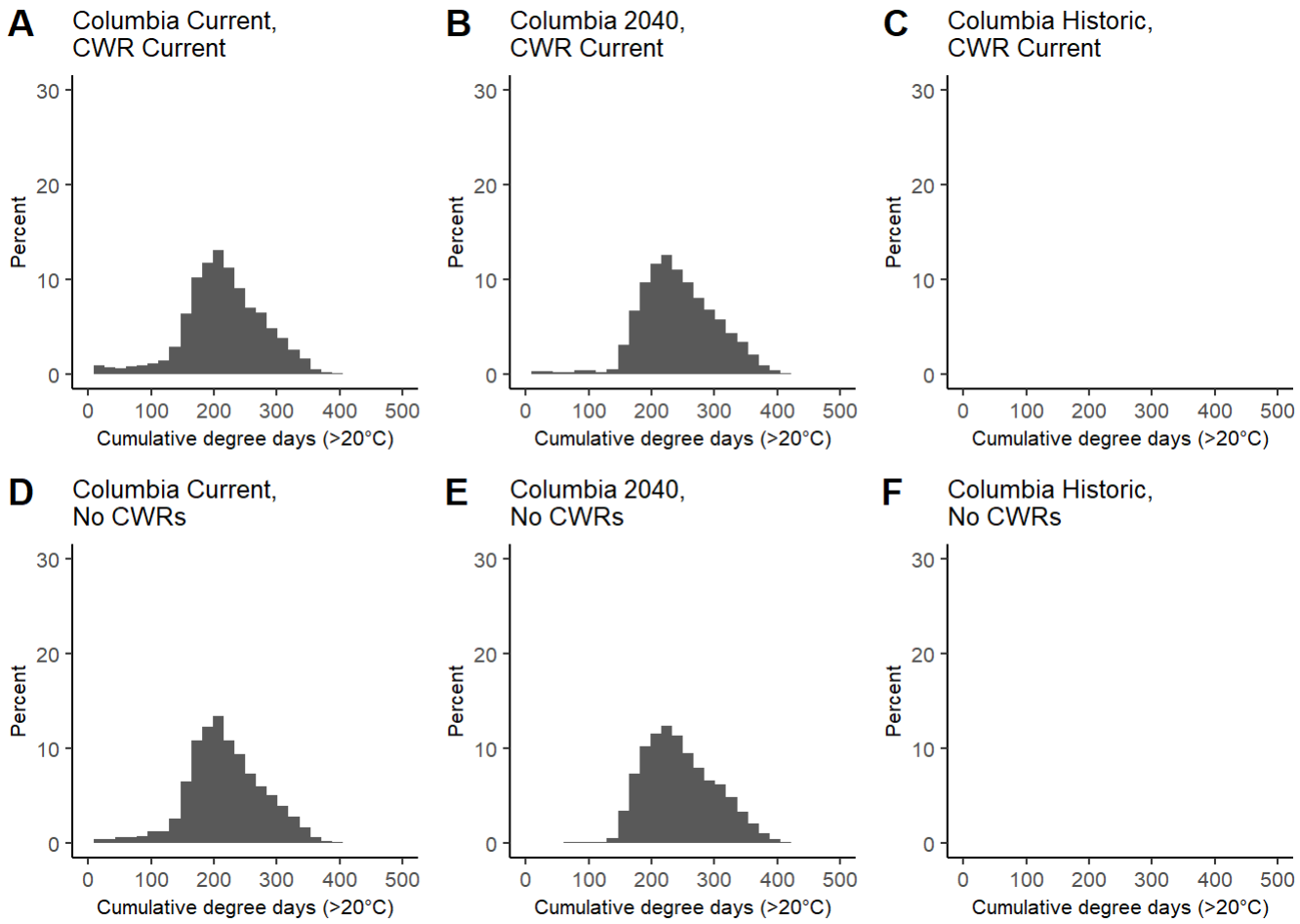


Fig. 3. Histograms of modeled Snake River fall Chinook accumulated degrees day over 20°C from Bonneville to the Snake River confluence in the Columbia River.

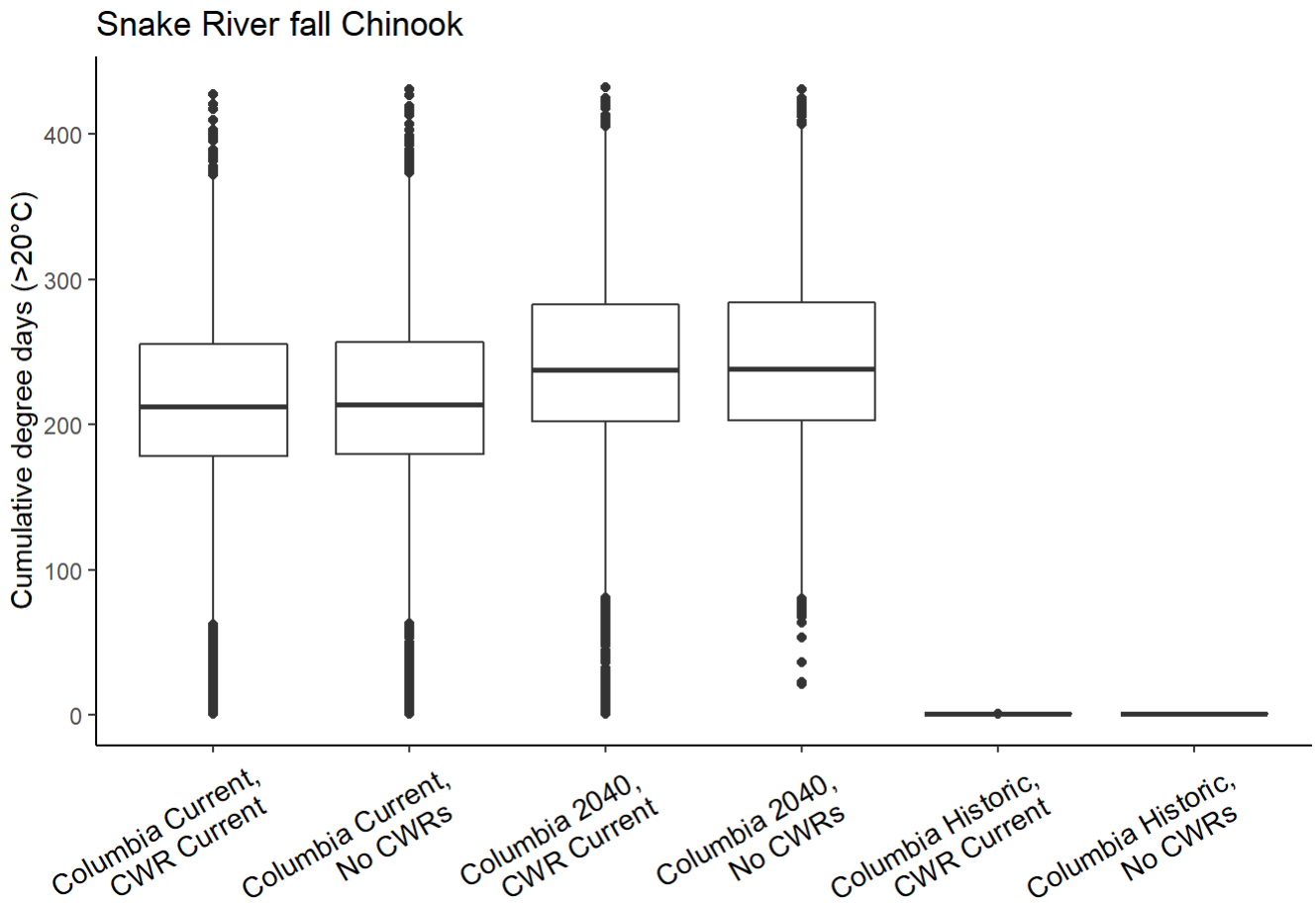


Fig. 4. Boxplots of modeled Snake River fall Chinook accumulated degrees day over 20°C from Bonneville to the Snake River confluence in the Columbia River.

Table 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

Degree Days > 21°C

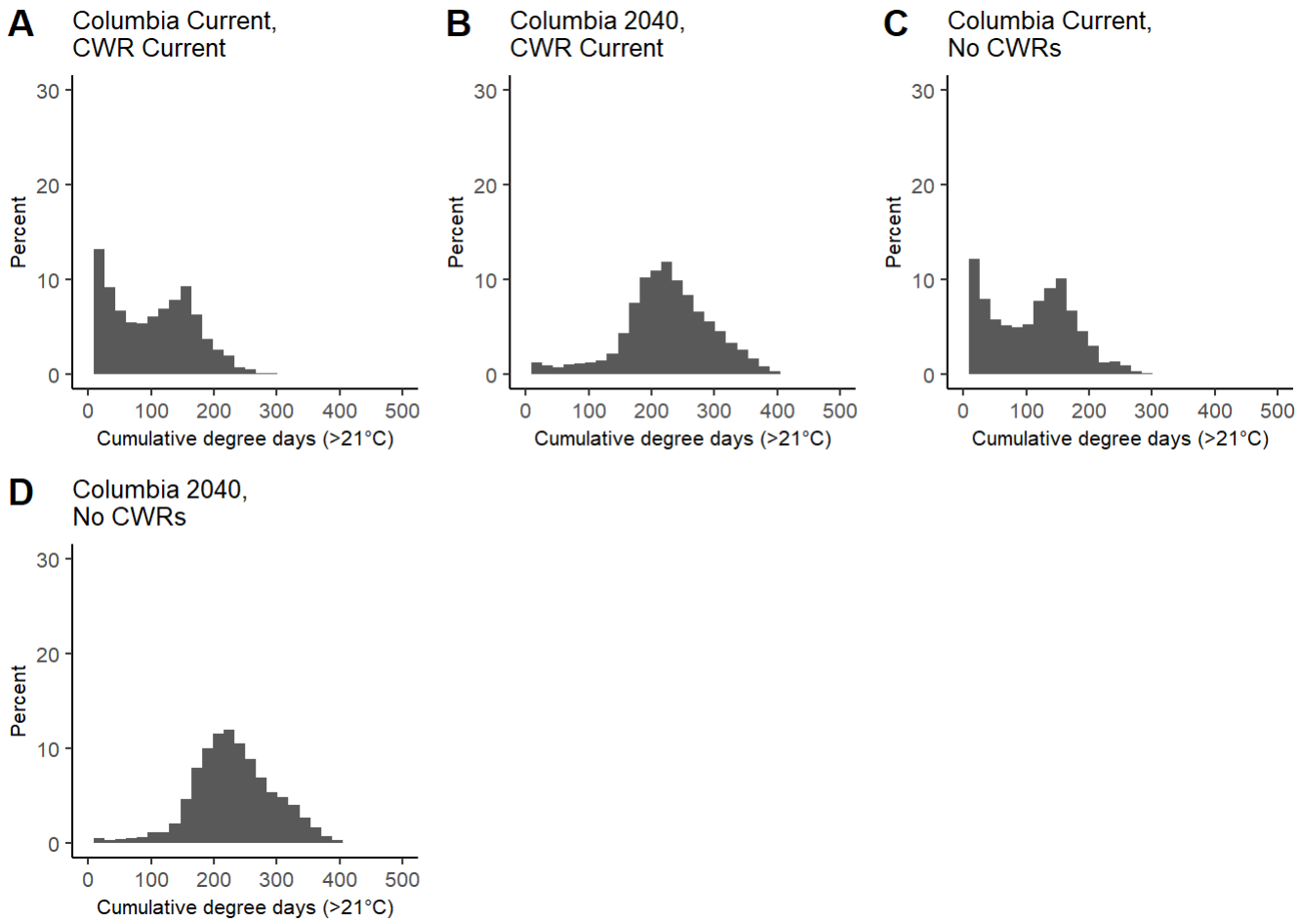


Fig. 5. Histograms of modeled Snake River fall Chinook accumulated degrees day over 21°C from Bonneville to the Snake River confluence in the Columbia River.

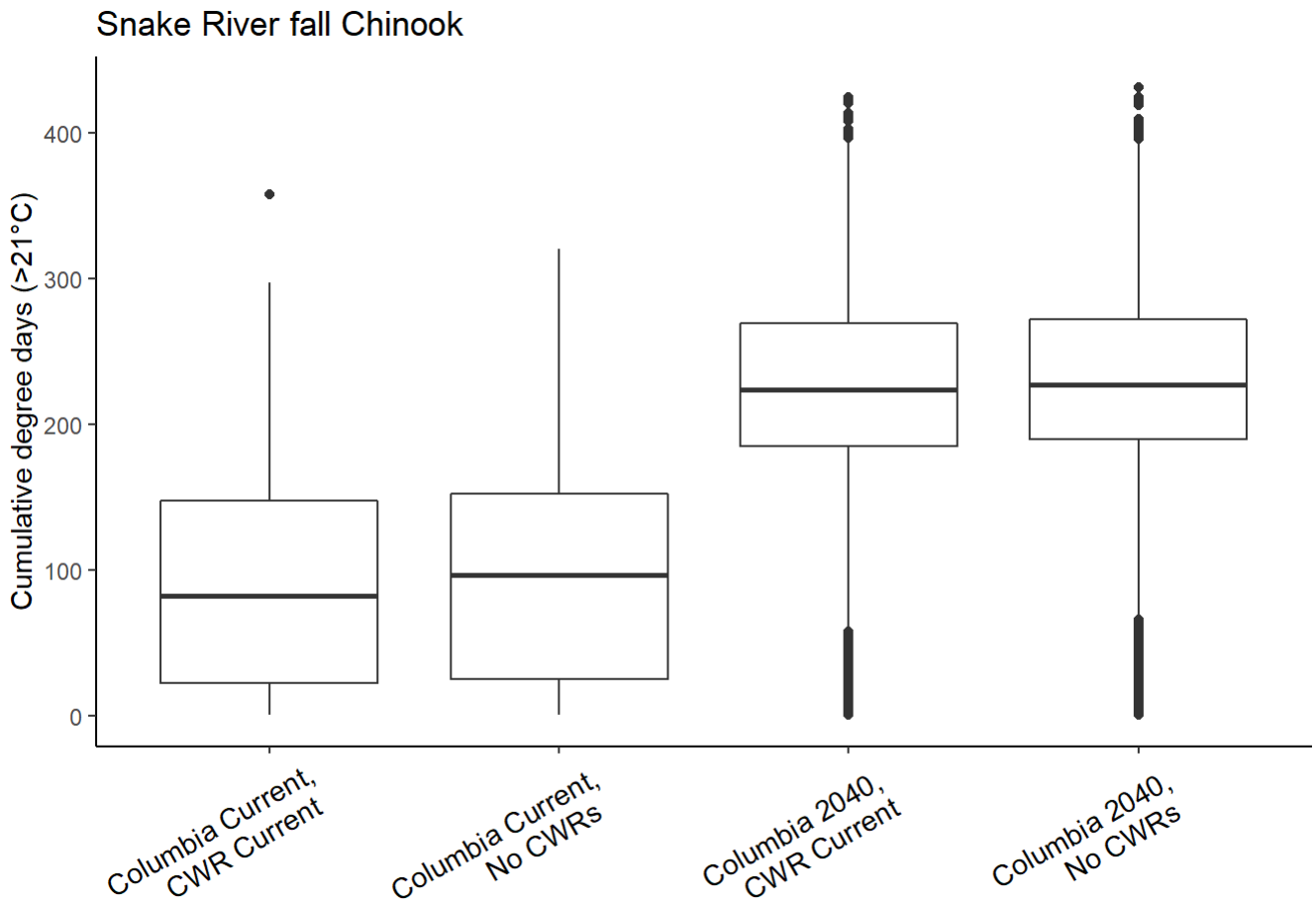


Fig. 6. Boxplots of modeled Snake River fall Chinook accumulated degrees day over 21°C from Bonneville to the Snake River confluence in the Columbia River.

Table 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

Degree Days > 22°C

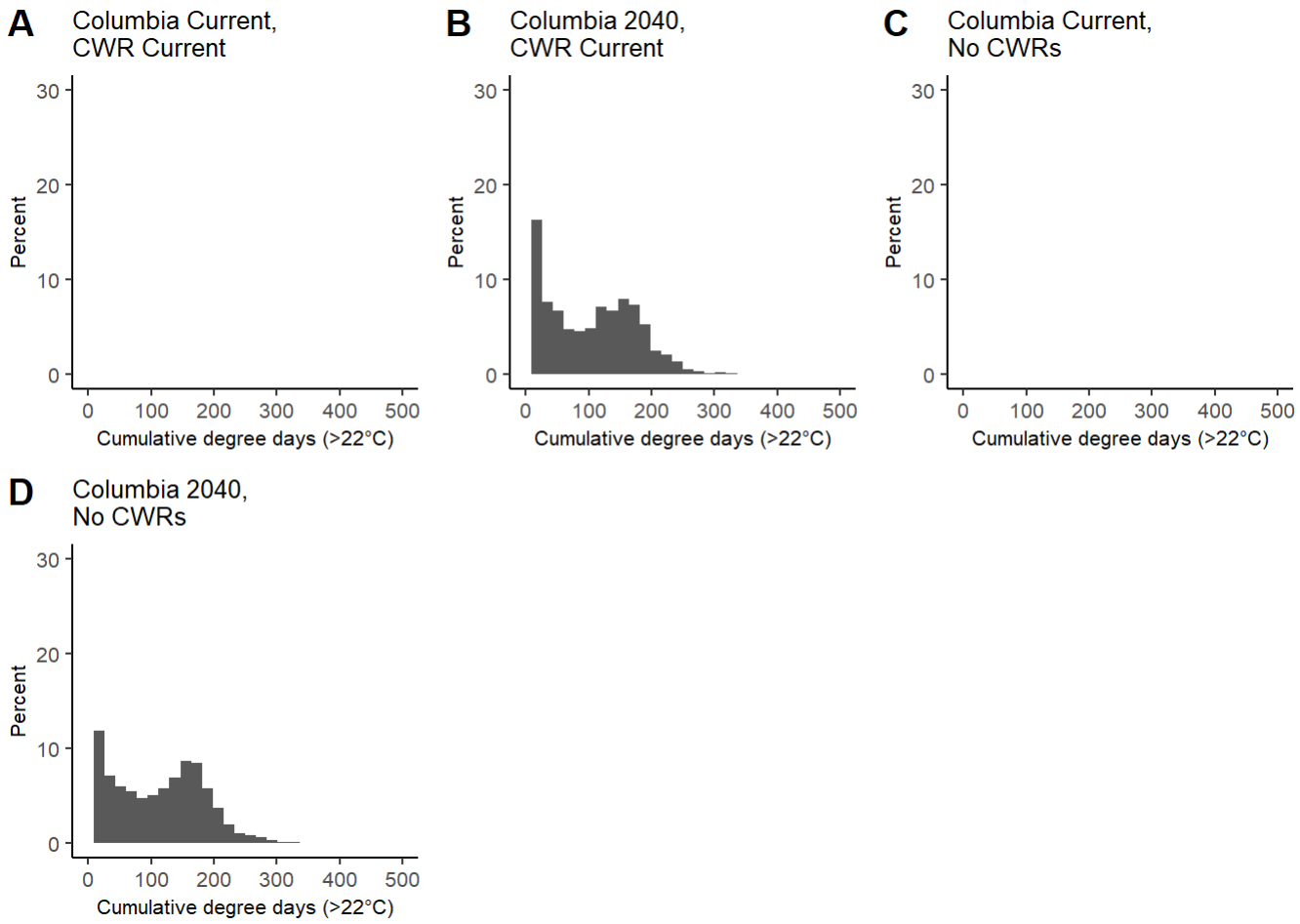


Fig. 5. Histograms of modeled Snake River fall Chinook accumulated degrees day over 22°C from Bonneville to the Snake River confluence in the Columbia River.

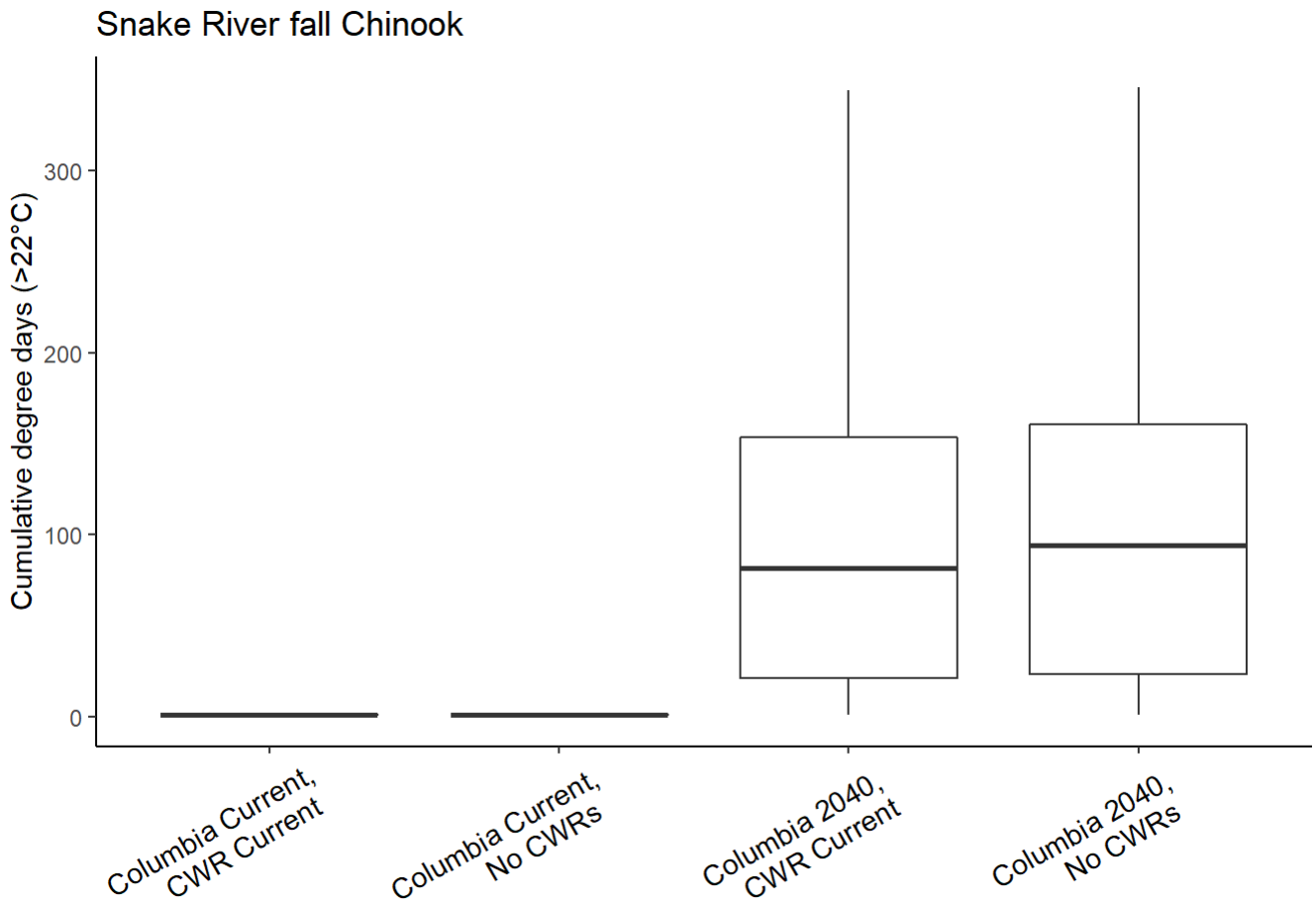


Fig. 6. Boxplots of modeled Snake River fall Chinook accumulated degrees day over 22°C from Bonneville to the Snake River confluence in the Columbia River.

Table 3. 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

Snake River Fall Chinook summarized fitness outcomes

MNSnyder

8/26/2019

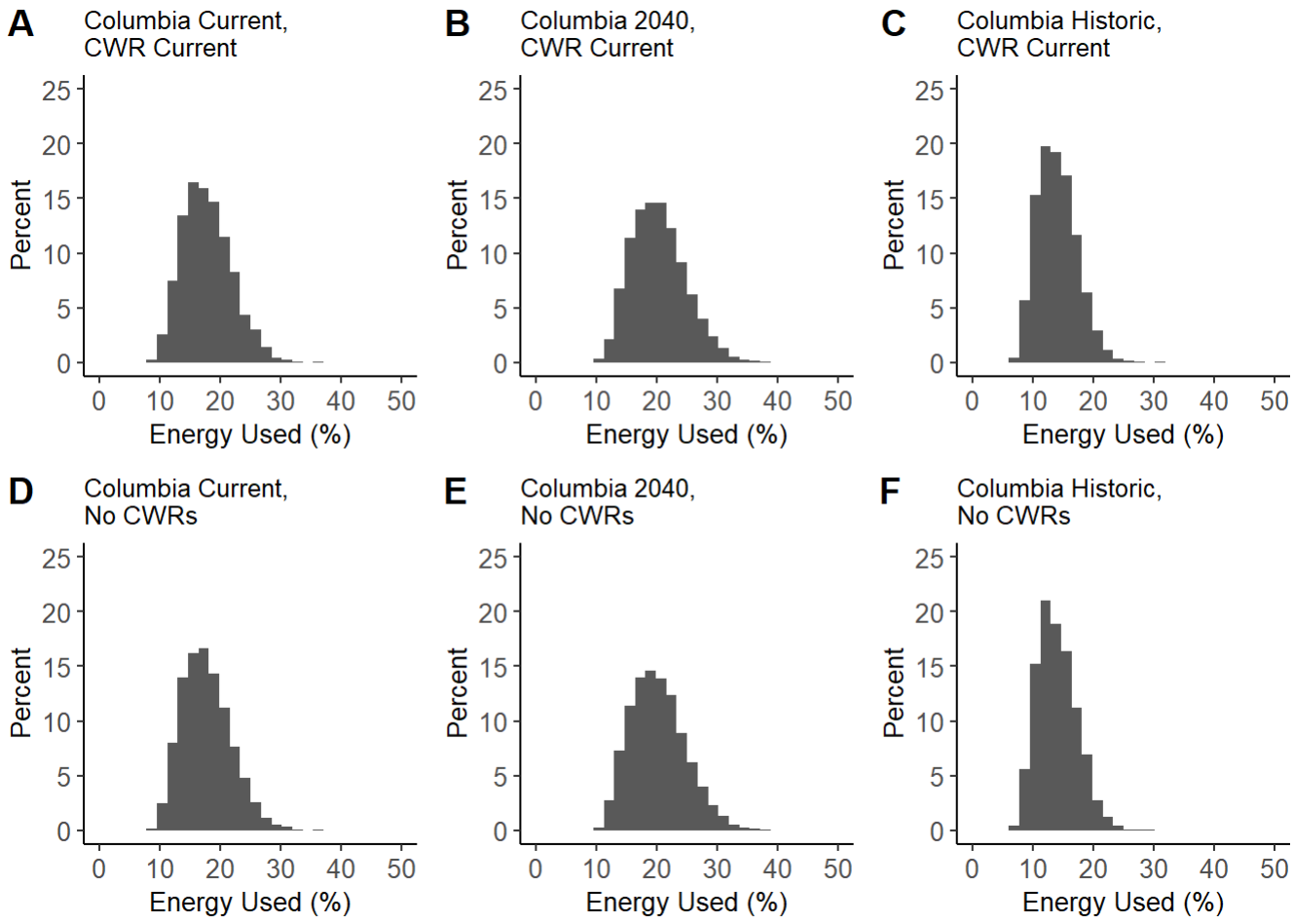


Fig. 1. Histogram of percent energy lost for modeled Snake River Fall Chinook salmon migrating through different modeled thermalscapes.

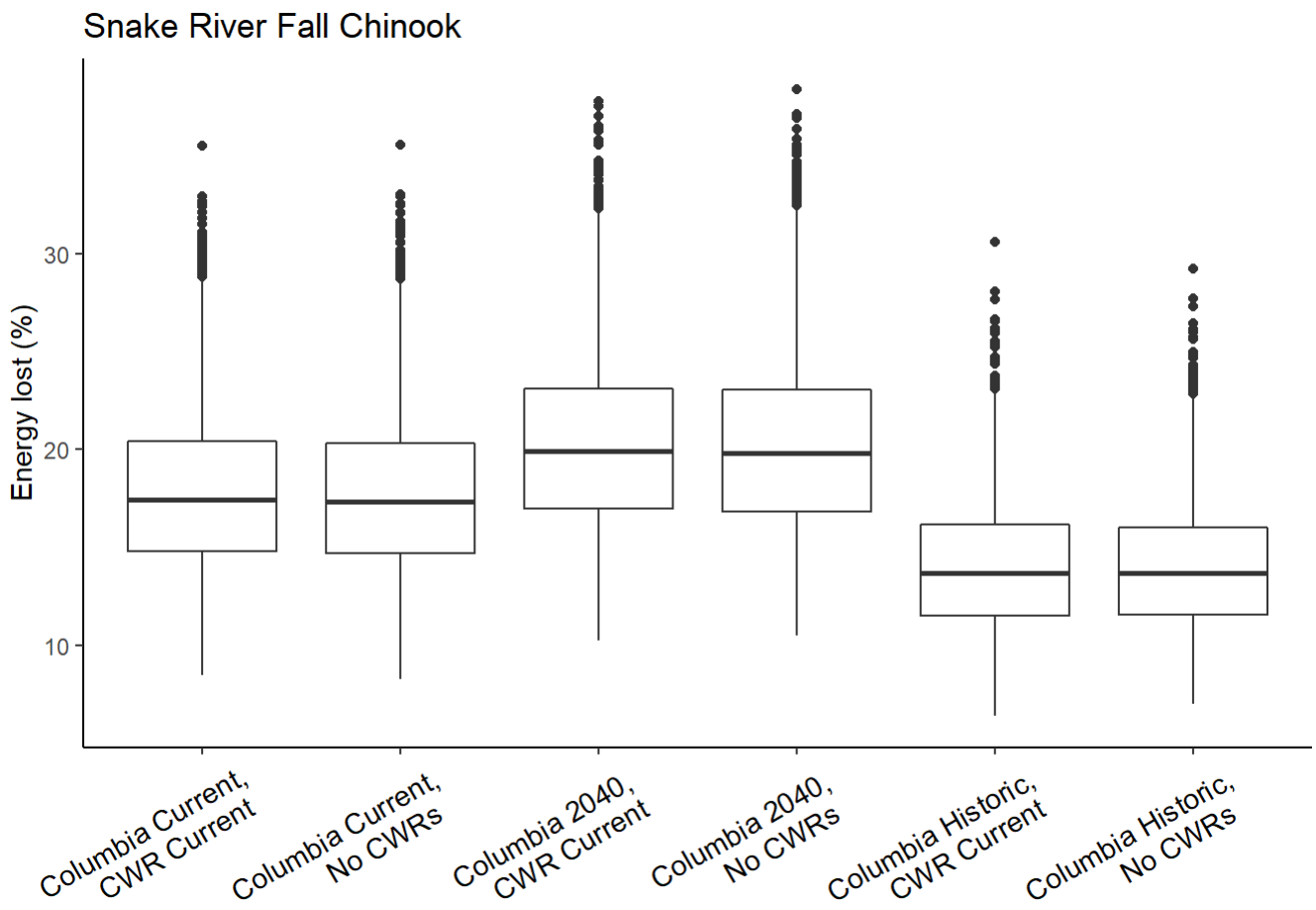


Fig. 2. Boxplot of percent energy lost for modeled Snake River Fall Chinook migrating through different modeled thermalscapes.

Table 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

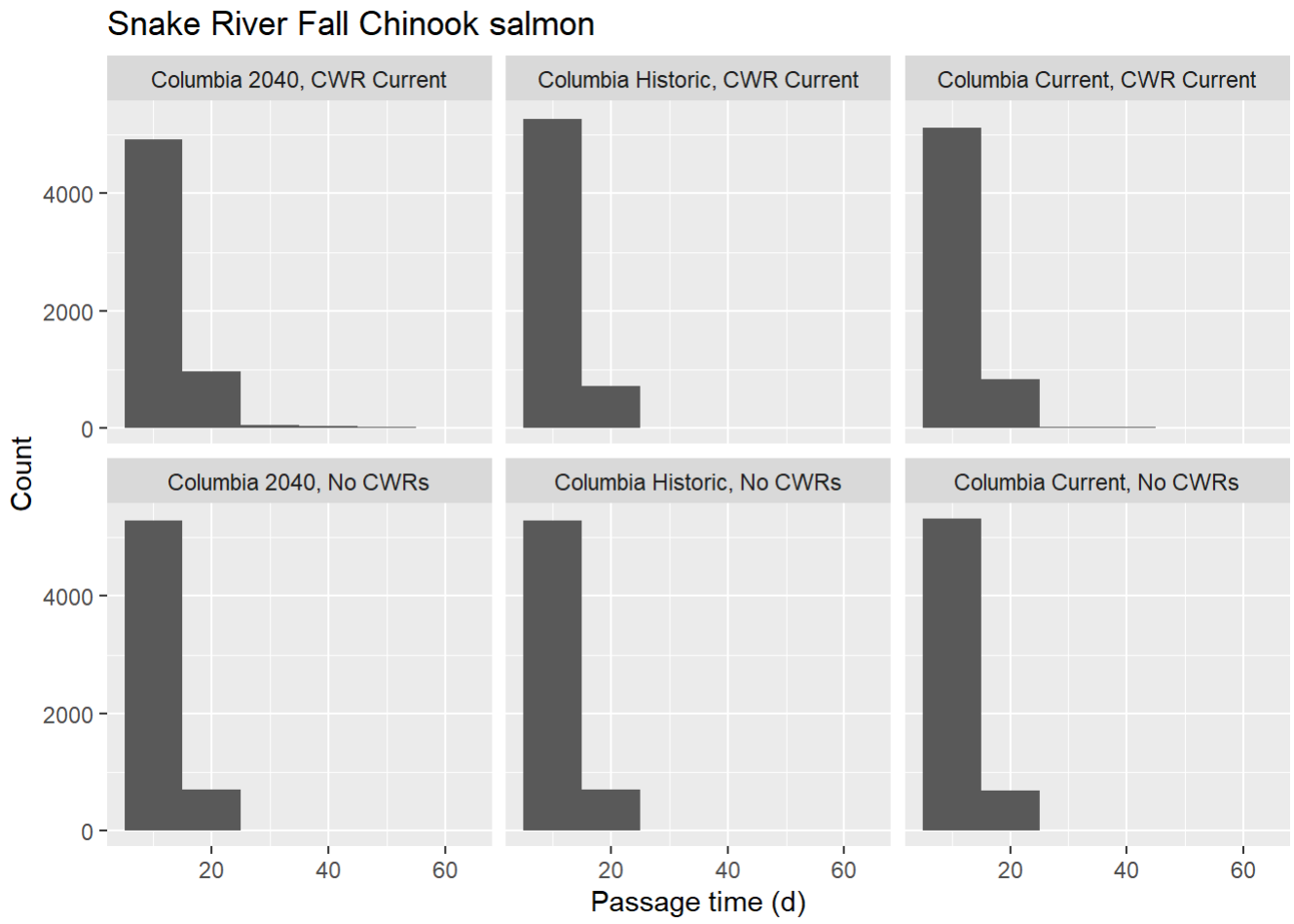
Table 3. Model output for total hours residing in cold water refuges summarized for Snake River Fall Chinook.

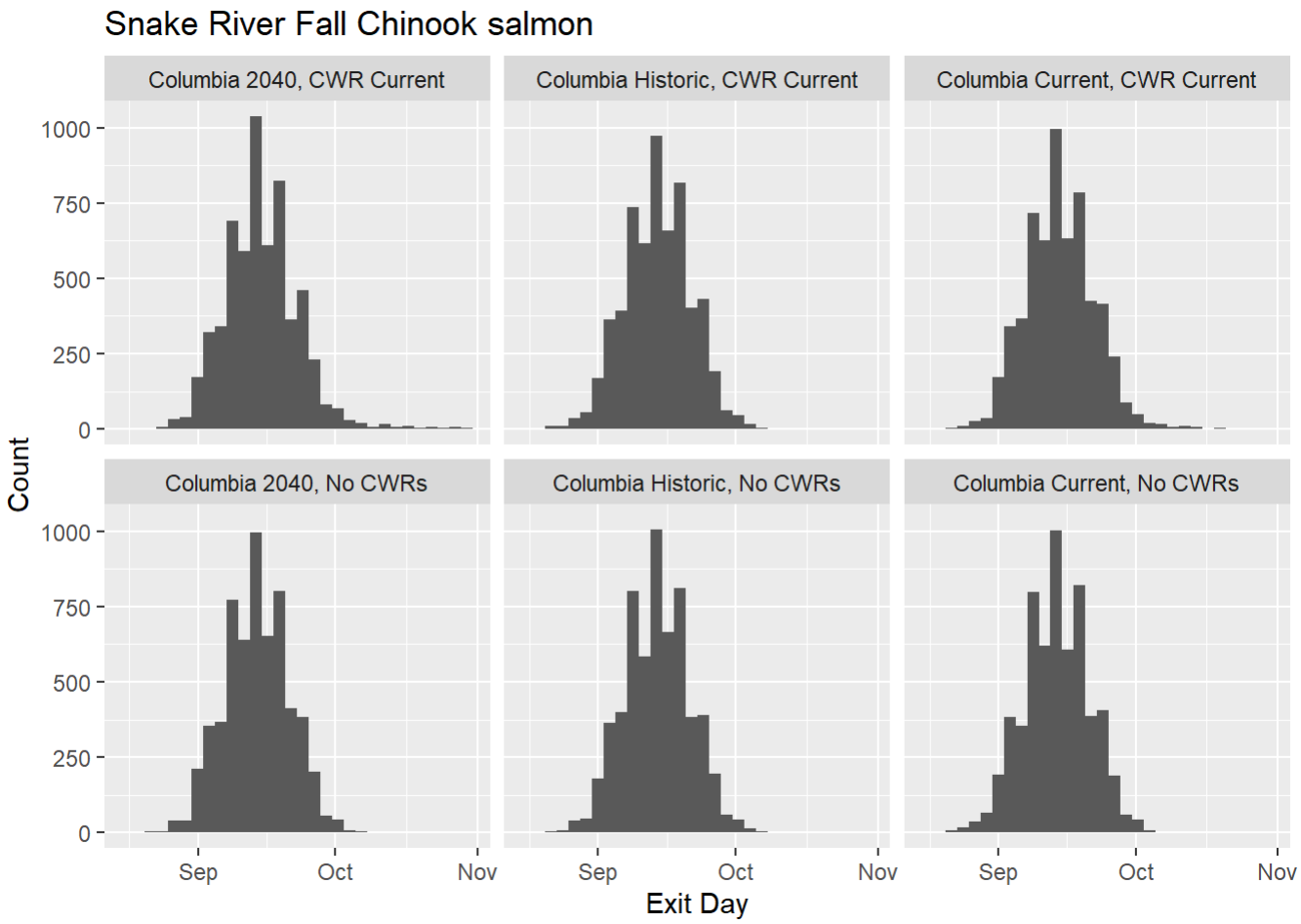
Scenario	Total CWR Residence (h)
Columbia Current,CWR Current	65887
Columbia Current, No CWRs	3
Columbia 2040, Current	126852

Scenario	Total CWR Residence (h)
Columbia 2040, No CWRs	4
Columbia Historic, Current	9068
Columbia Historic, No CWRs	0

Table 4. 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
Columbia Current, No CWRs	0
Columbia 2040, Current	0.2
Columbia 2040, No CWRs	0.3
Columbia Historic, Current	0
Columbia Historic, No CWRs	0




Snake River Fall Chinook salmon
Columbia 2040, CWR Current
Columbia Historic, CWR Current
Columbia Current, CWR Current
Columbia 2040, No CWRs
Columbia Historic, No CWRs
Columbia Current, No CWRs
Count
1000
750
500
250
0
Sep
Oct
Nov
Exit Day

Grande Ronde summer steelhead cumulative DD

MNSnyder

9/4/2019

Grande Ronde summer steelhead Columbia River temperature time series from 2017. 4 scenarios included:

- Columbia River 2017
- Columbia River 2017, no CWRs
- Columbia River 2017 plus 1
- Columbia River 2017 plus 1, no CWRs

Columbia 2017B assigns the John Day Pool temperature from the John Day forebay, which is the warmer part of the pool.

DD > 18 °C

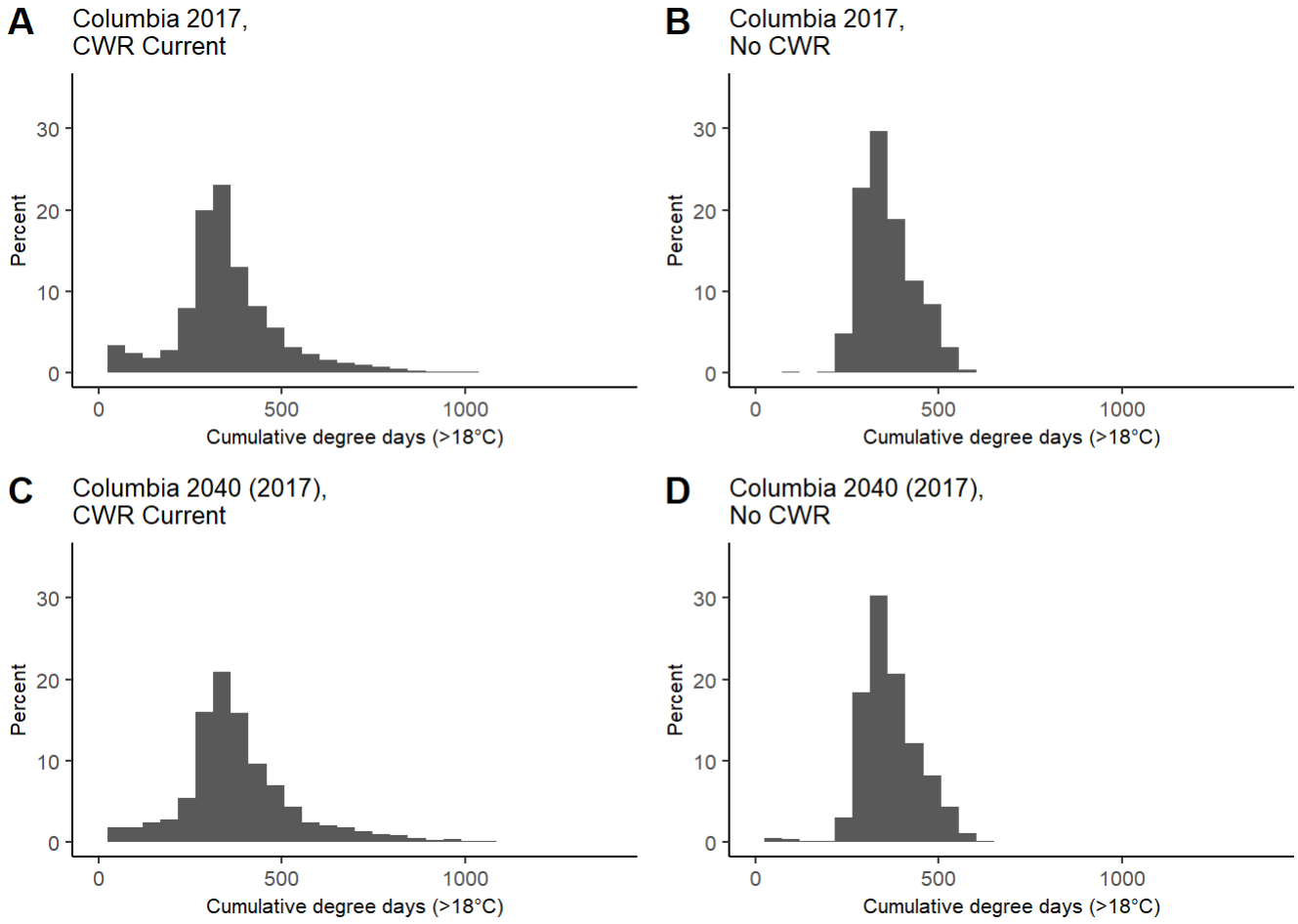


Fig. 1. Histograms of modeled Grande Ronde River summer steelhead accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.

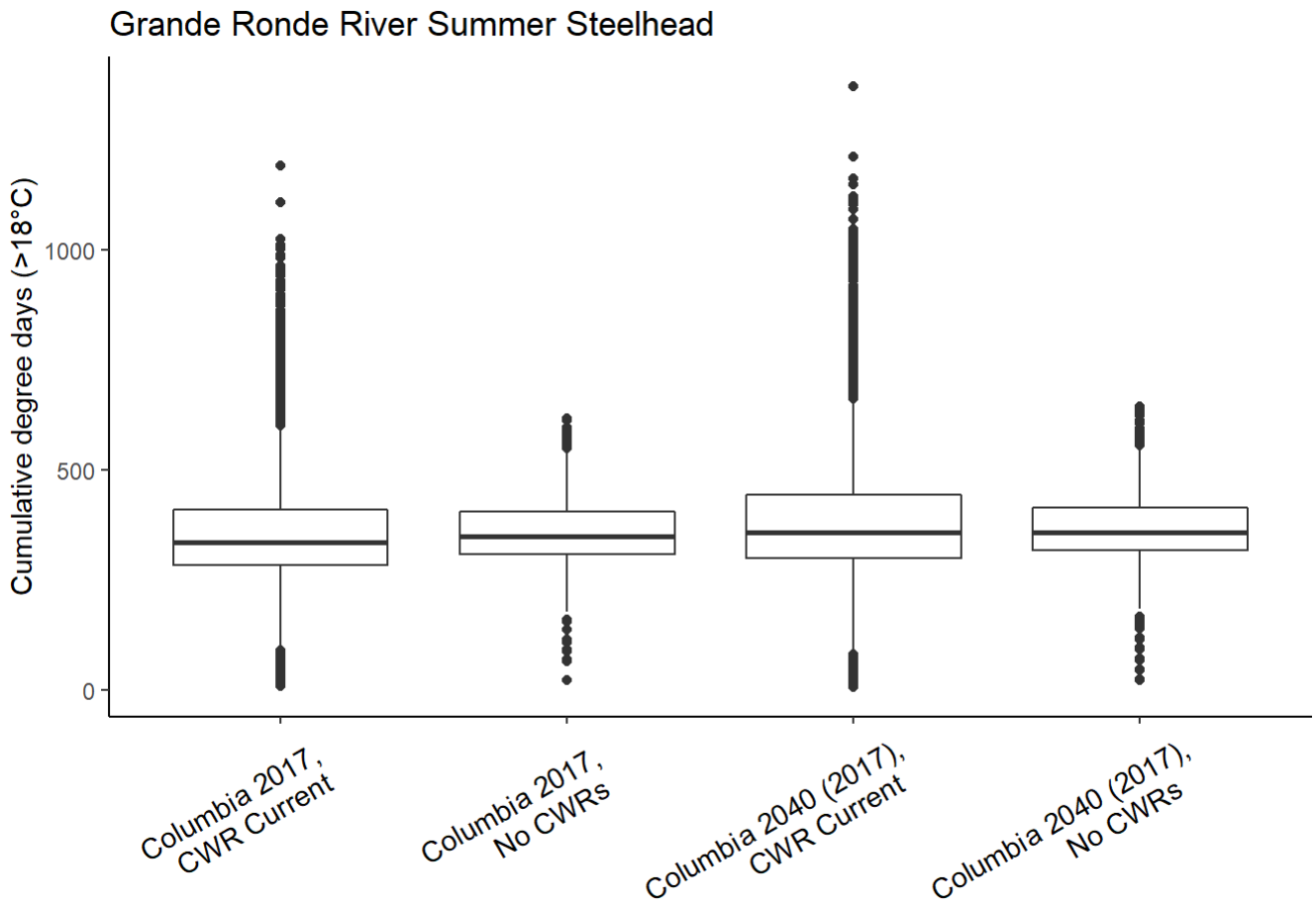


Fig. 2. Boxplots of modeled Grande Ronde River summer steelhead accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.

Table 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	8	283	337	410	1193
Columbia 2017, No CWR	22	309	348	405	619
Columbia 2040 (2017), CWR Current	7	299	357	444	1373
Columbia 2040 (2017), No CWR	22	318	357	414	645

Degree Days > 20°C

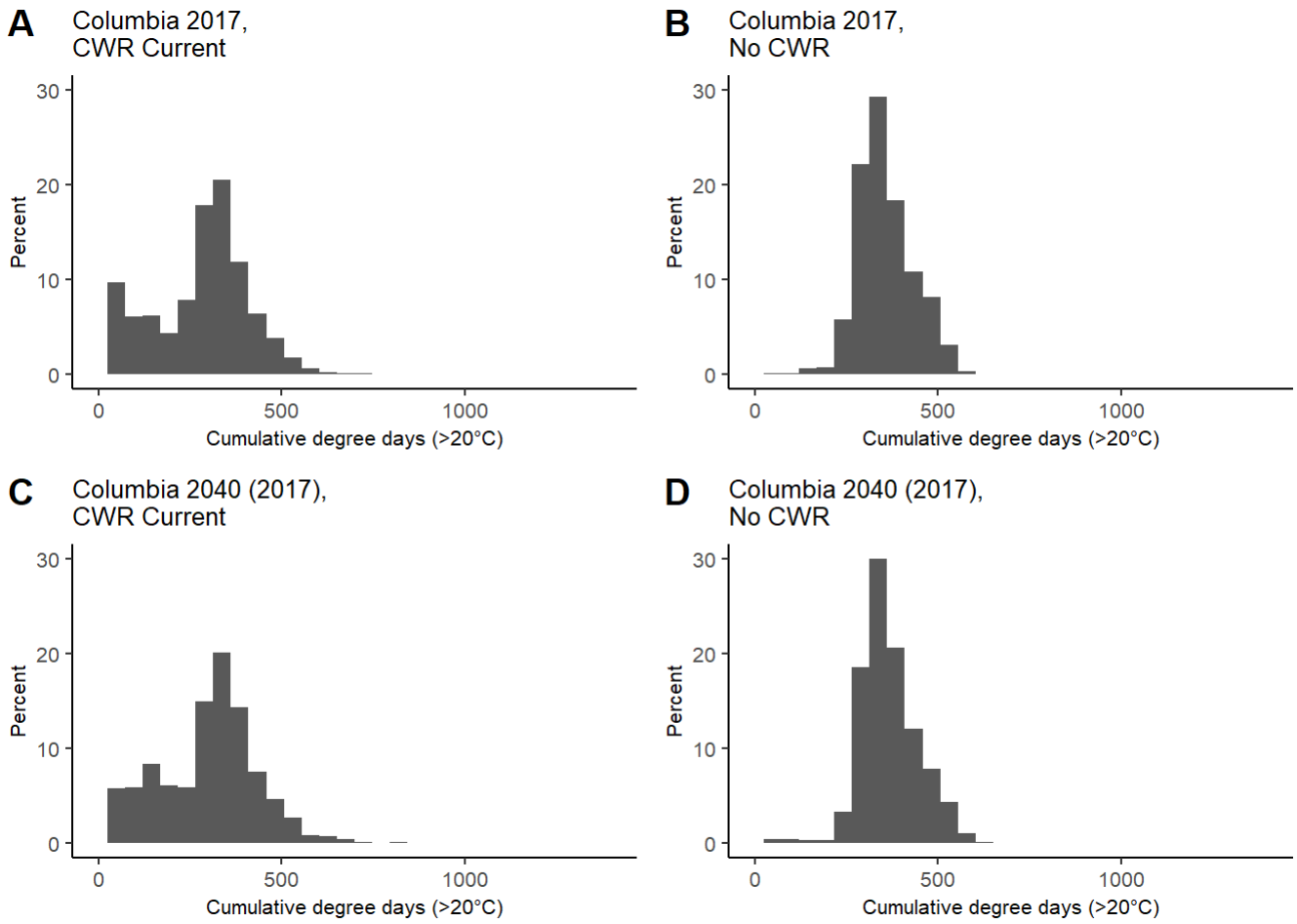


Fig. 1. Histograms of modeled Grande Ronde River summer steelhead accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.

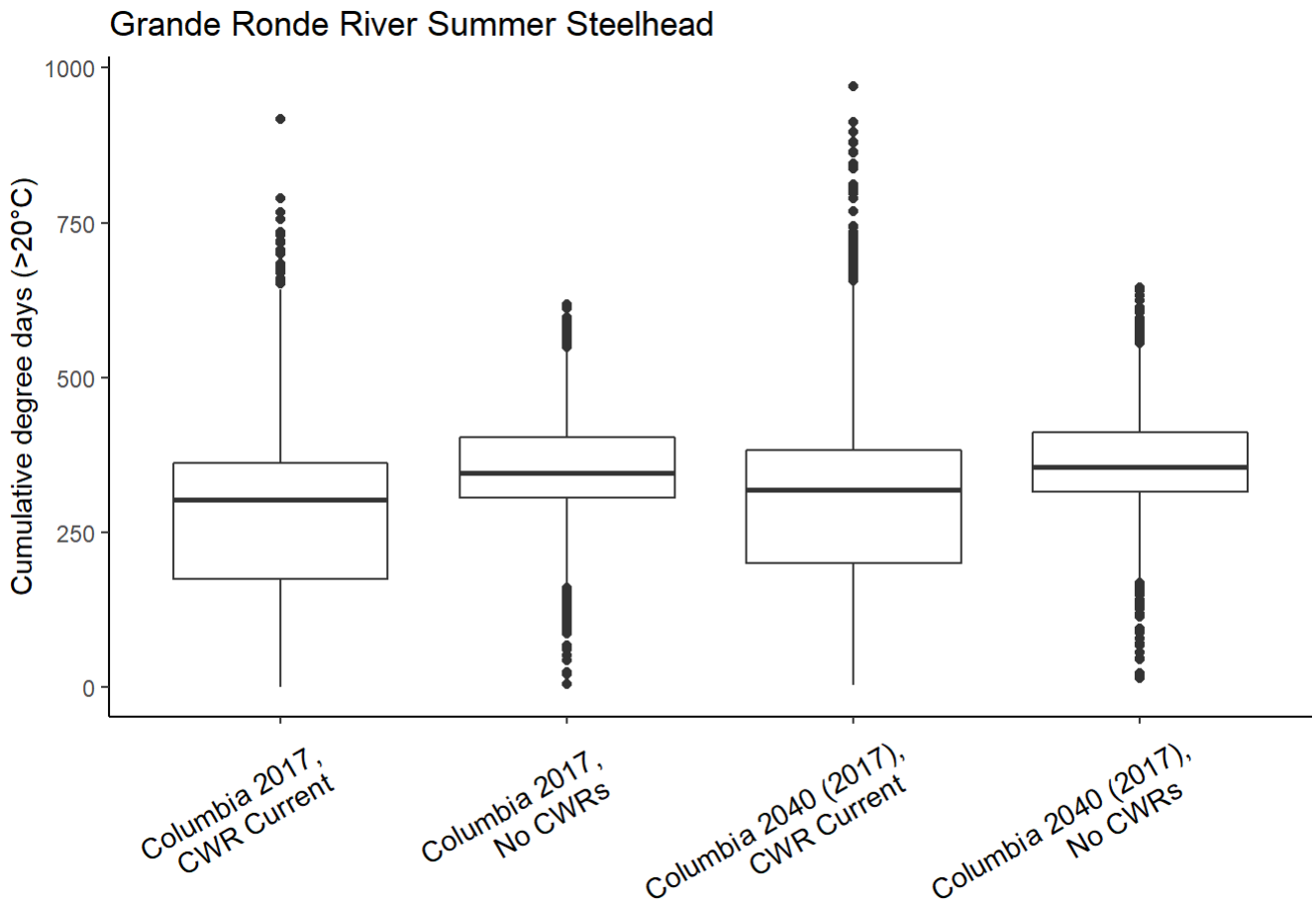


Fig. 2. Boxplots of modeled Grande Ronde River summer steelhead accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.

Table 1. 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	175	303	362	918
Columbia 2017, No CWR	6	306	346	403	619
Columbia 2040 (2017), CWR Current	4	200	319	382	970
Columbia 2040 (2017), No CWR	15	316	356	412	645

Degree Days > 21°C

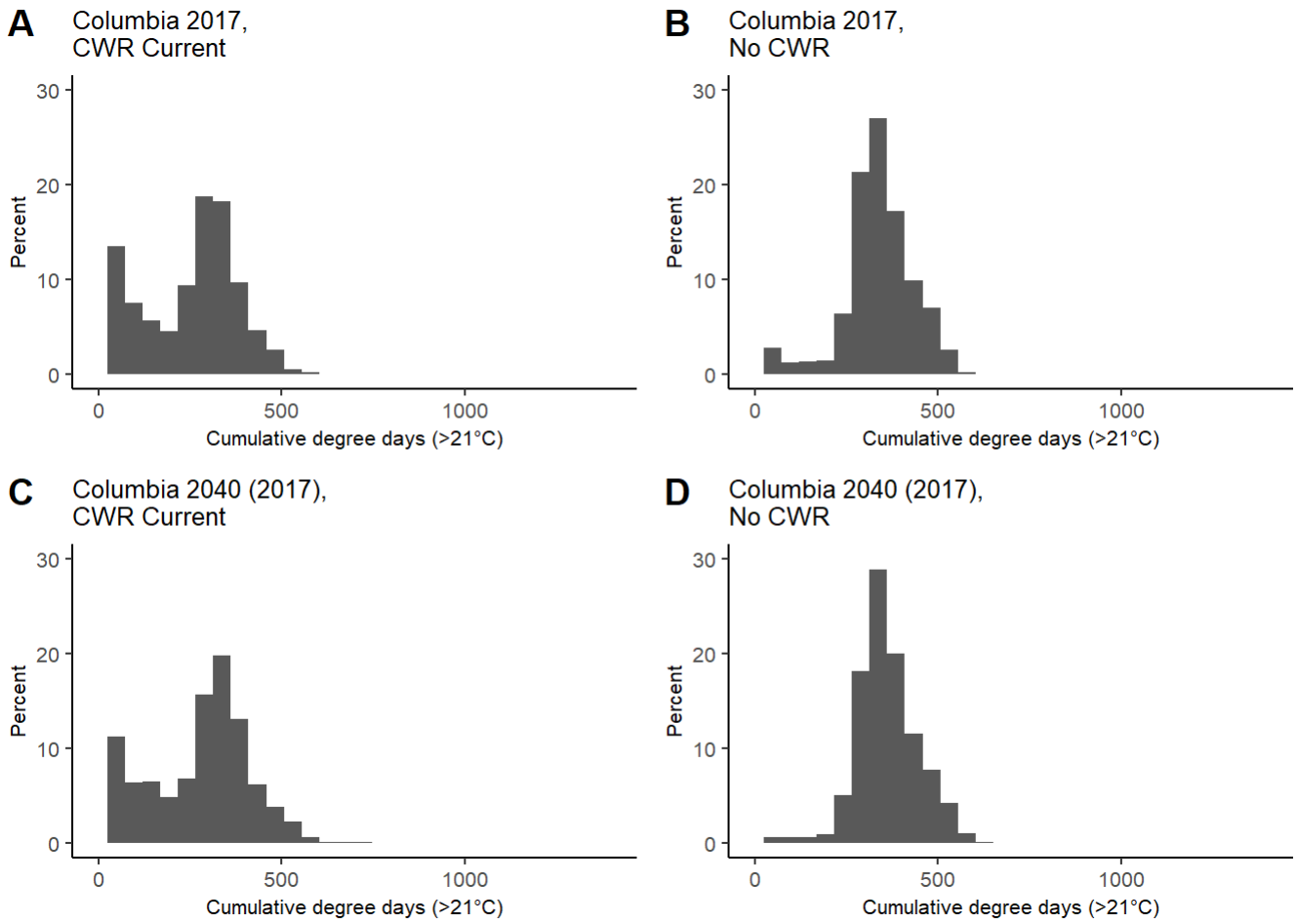


Fig. 1. Histograms of modeled Grande Ronde River summer steelhead accumulated degrees day over 21°C from Bonneville to the Snake River confluence in the Columbia River.

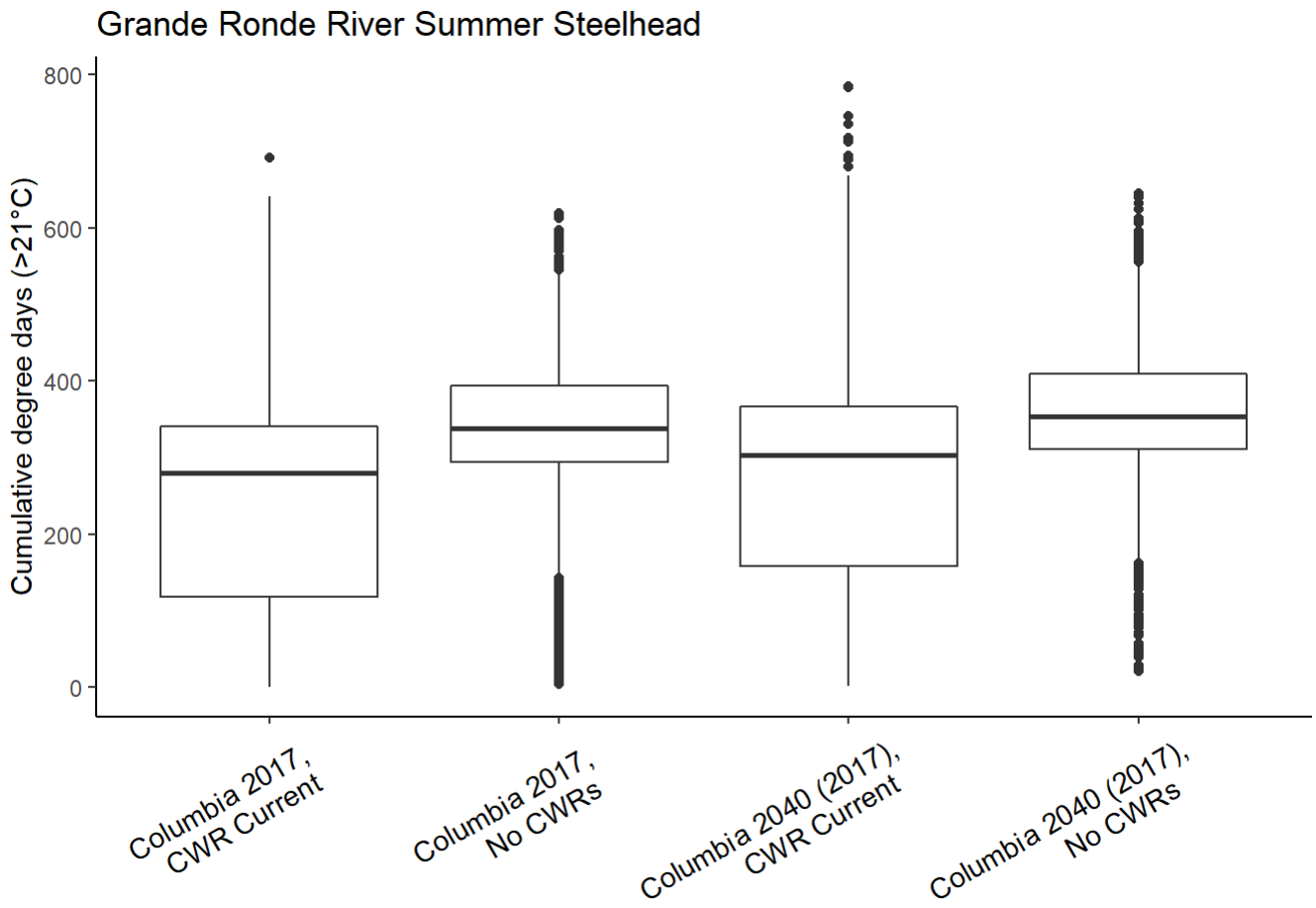


Fig. 2. Boxplots of modeled Grande Ronde River summer steelhead accumulated degrees day over 21°C from Bonneville to the Snake River confluence in the Columbia River.

Table 1. 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	119	280	341	691
Columbia 2017, No CWR	4	294	338	394	619
Columbia 2040 (2017), CWR Current	2	158	303	366	785
Columbia 2040 (2017), No CWR	22	311	353	409	645

Degree Days > 22°C

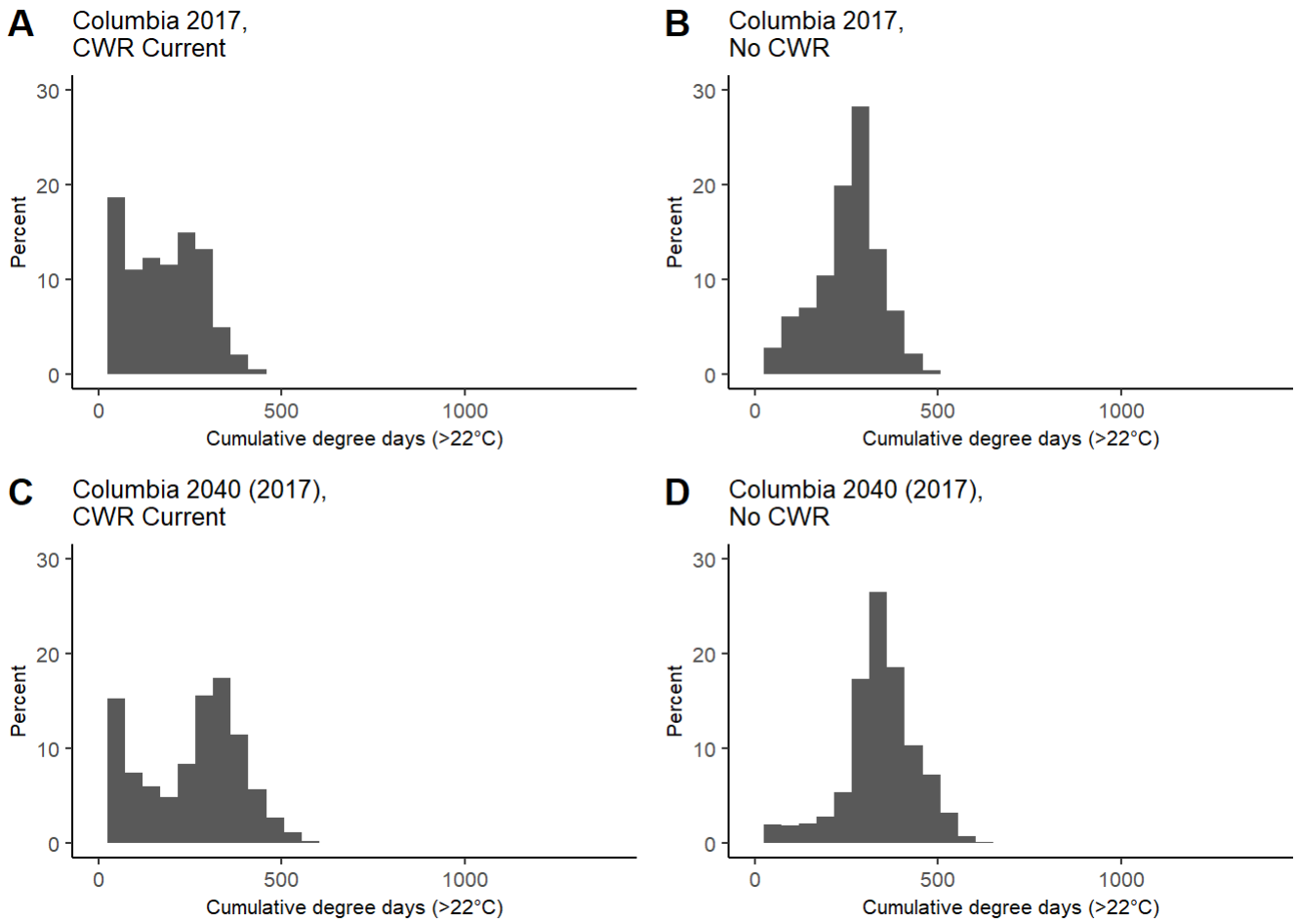


Fig. 1. Histograms of modeled Grande Ronde River summer steelhead accumulated degrees day over 22°C from Bonneville to the Snake River confluence in the Columbia River.

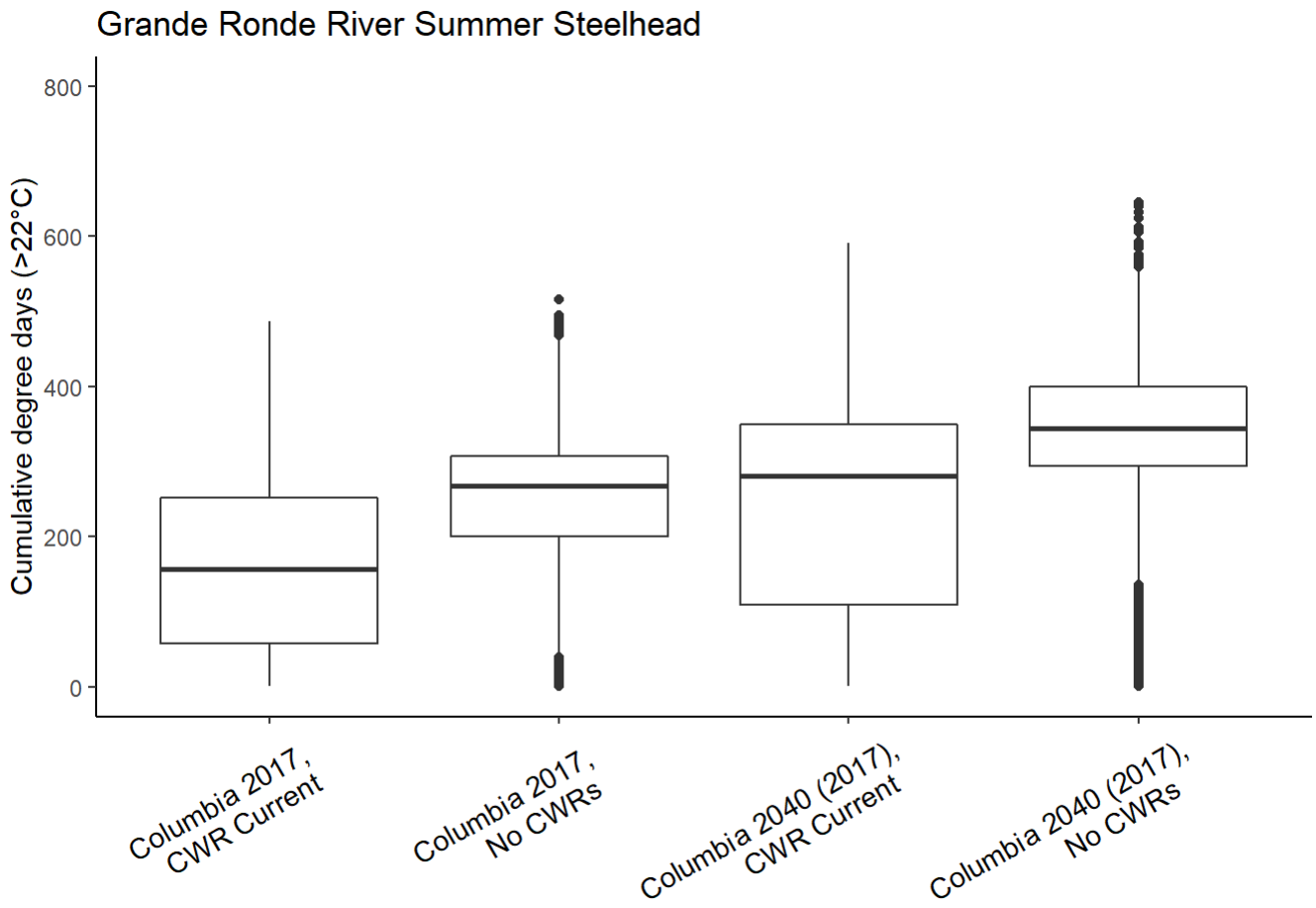


Fig. 2. Boxplots of modeled Grande Ronde River summer steelhead accumulated degrees day over 22°C from Bonneville to the Snake River confluence in the Columbia River.

Table 1. 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	58	157	252	486
Columbia 2017, No CWR	1	201	267	308	516
Columbia 2040 (2017), CWR Current	1	109	280	350	592
Columbia 2040 (2017), No CWR	1	295	345	400	645

Degree Days > 23°C

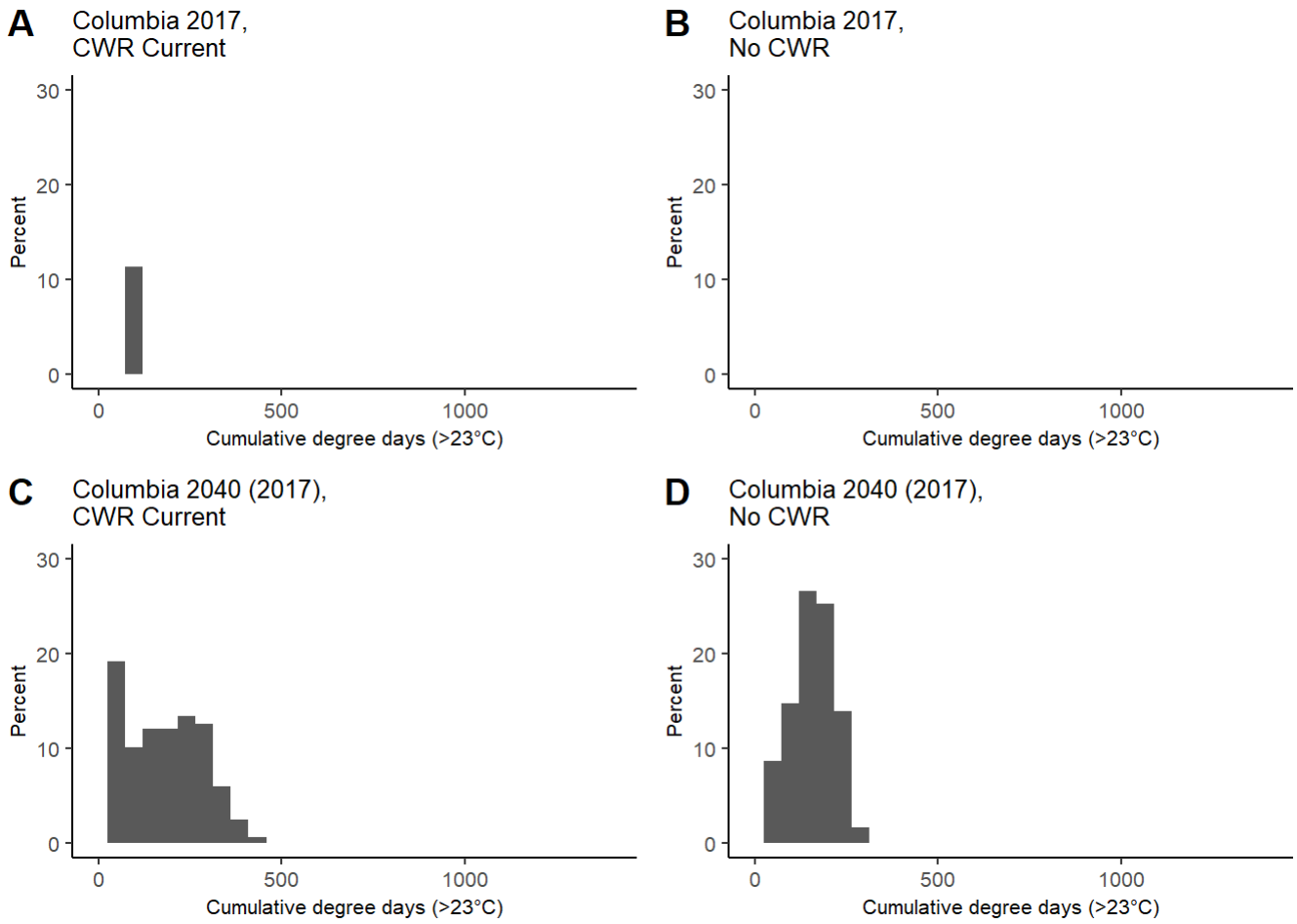


Fig. 1. Histograms of modeled Grande Ronde River summer steelhead accumulated degrees day over 23°C from Bonneville to the Snake River confluence in the Columbia River.

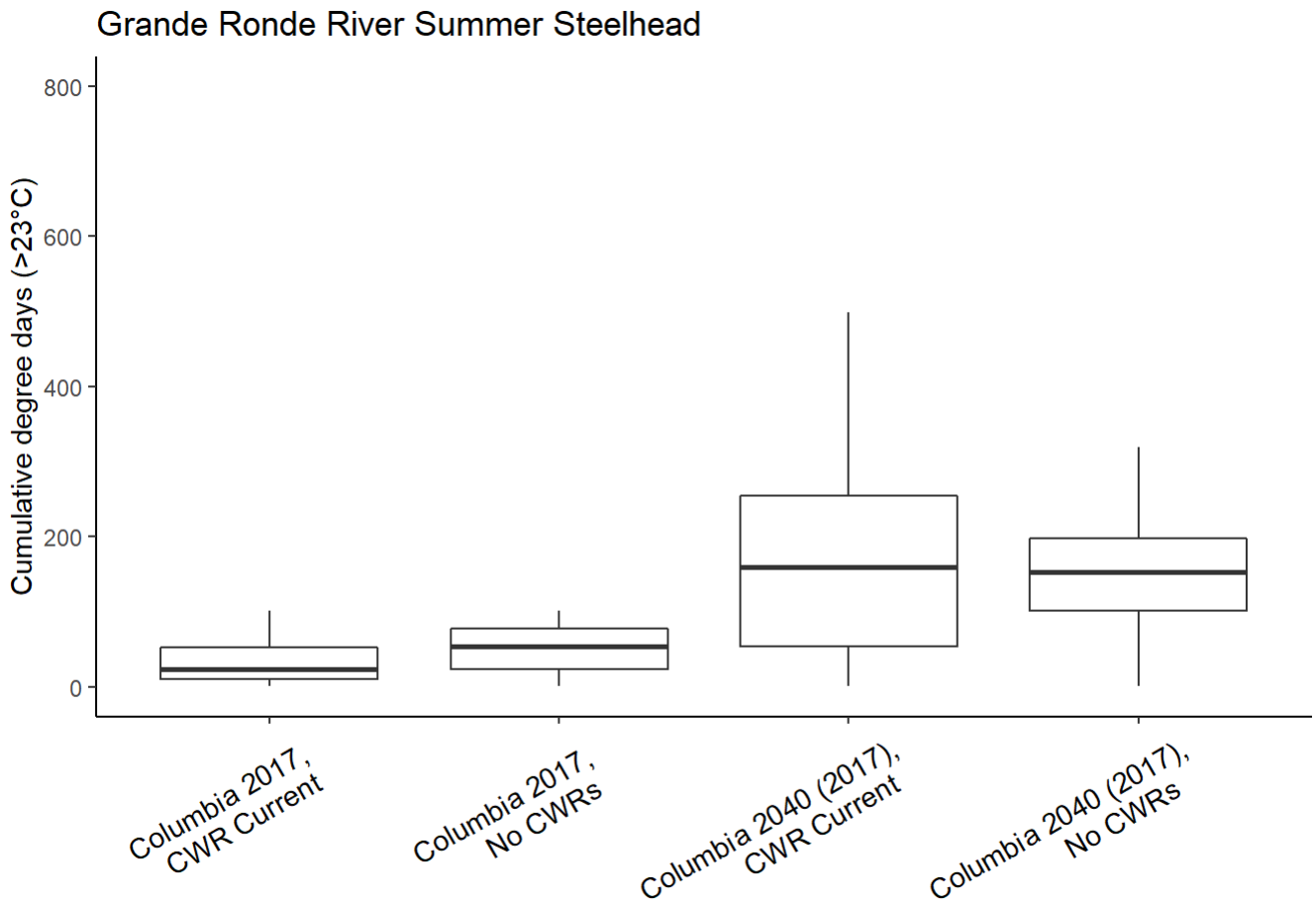


Fig. 2. Boxplots of modeled Grande Ronde River summer steelhead accumulated degrees day over 23°C from Bonneville to the Snake River confluence in the Columbia River.

Table 1. Cumulative degree days (>23°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	10	23	52	101
Columbia 2017, No CWR	1	23	54	78	101
Columbia 2040 (2017), CWR Current	1	54	159	254	500
Columbia 2040 (2017), No CWR	1	101	152	198	320

Grande Ronde summer steelhead summarized fitness outcomes

MNSnyder

9/04/2019

Grande Ronde summer steelhead Columbia River temperature time series from 2017. 4 scenarios included:

- Columbia River 2017
- Columbia River 2017, no CWRs
- Columbia River 2017 plus 1
- Columbia River 2017 plus 1, no CWRs

Columbia 2017A assigns the John Day Pool temperature from the John Day forebay, which is the warmer part of the pool.

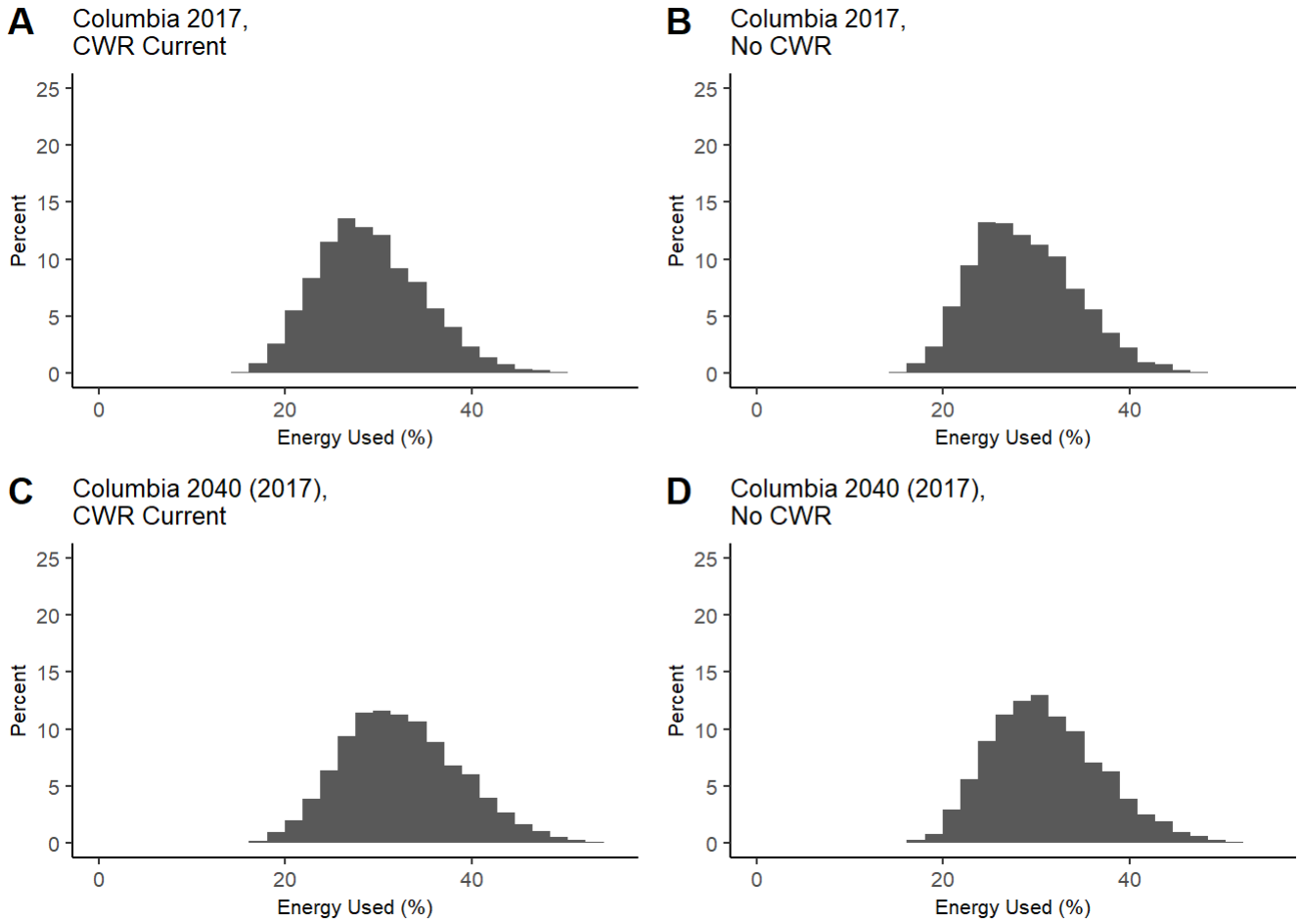


Fig. 1. Histogram of percent energy lost for modeled Grande Ronde summer steelhead migrating through four different modeled thermalscapes.

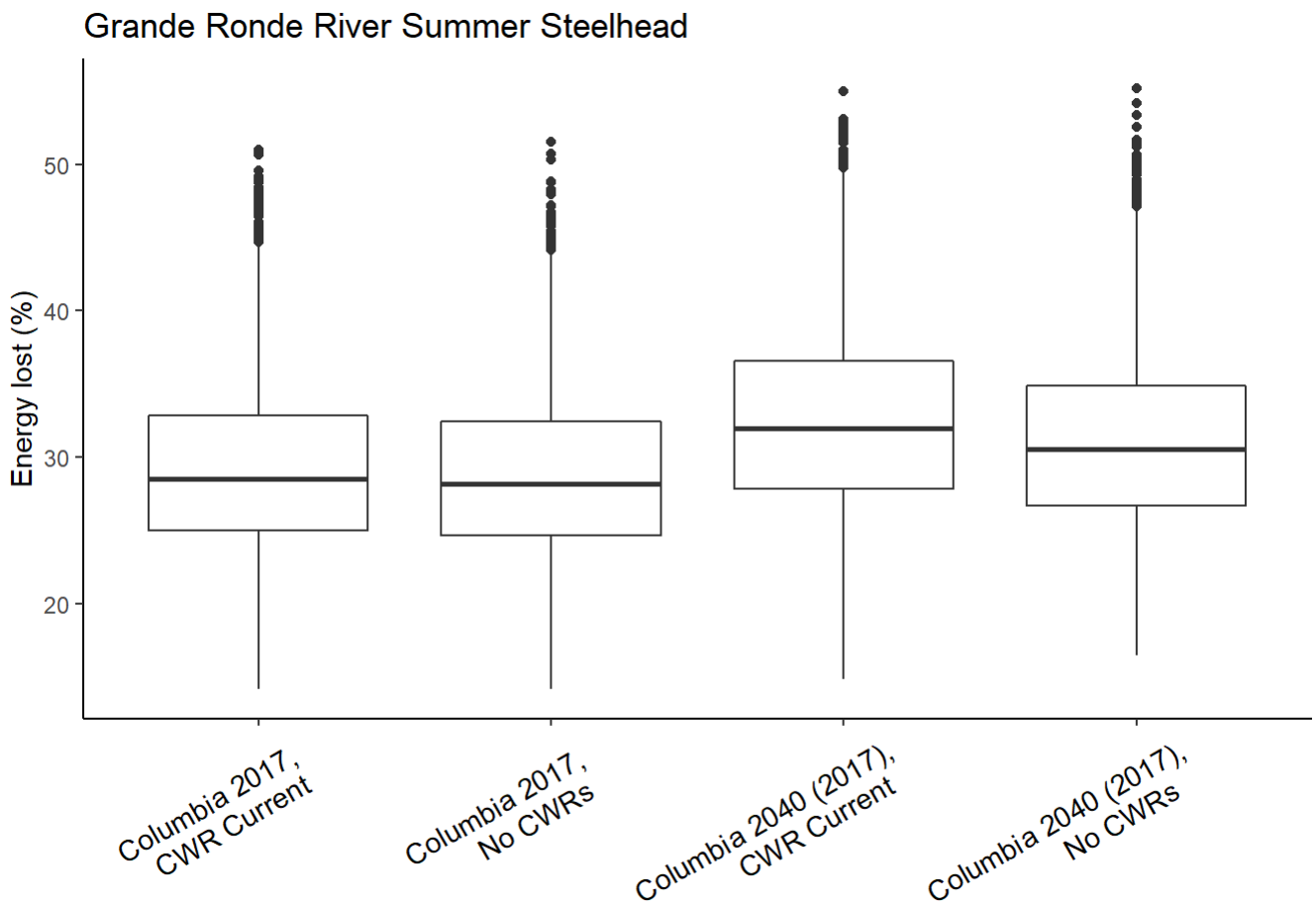


Fig. 2. Boxplot of percent energy lost for modeled Grande Ronde summer steelhead migrating through four different modeled thermalscapes.

Table 1. Percent energy used across different HexSim thermalscapes summarized for Grande Ronde River Summer Steelhead.

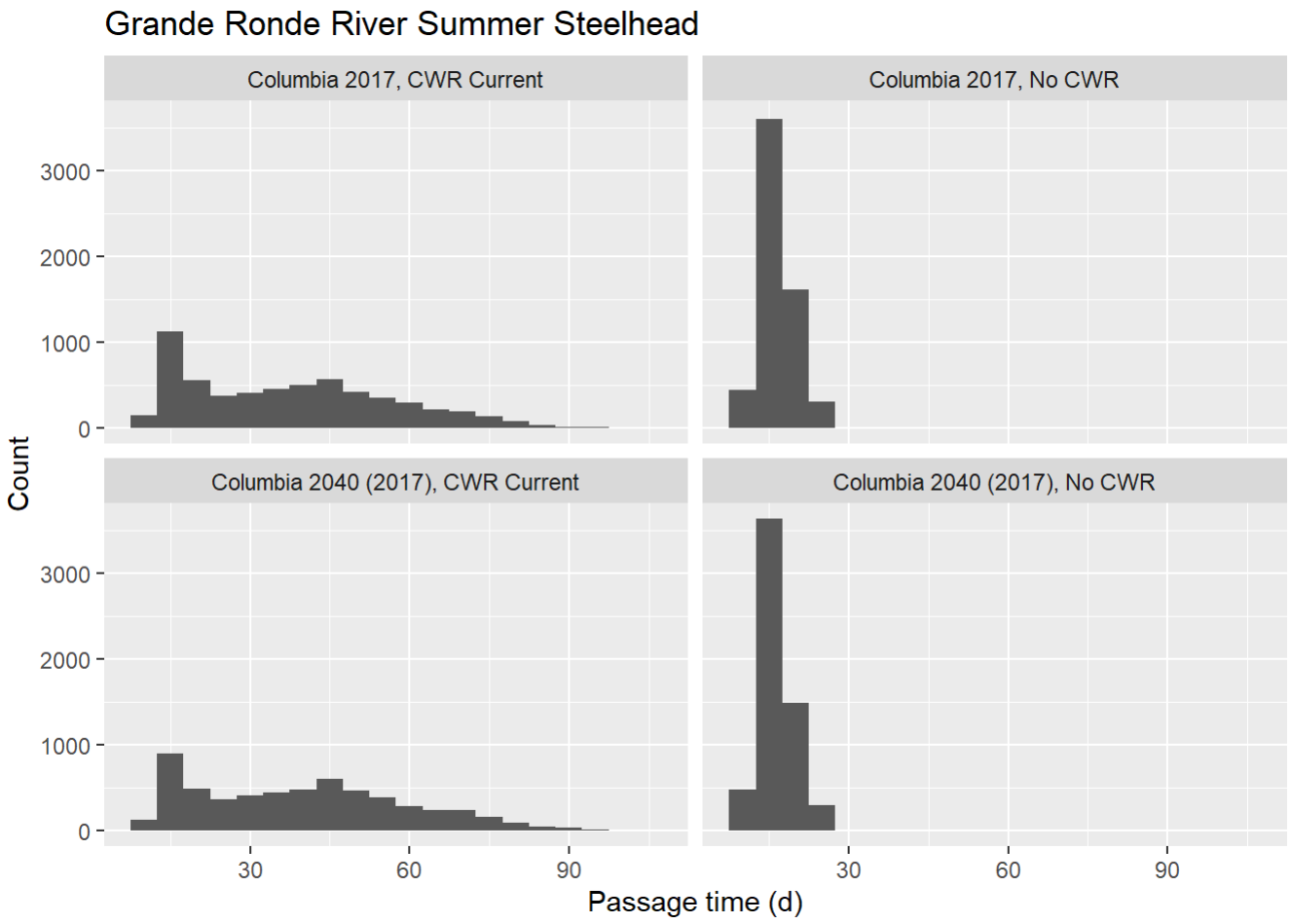
Scenario	Minimum	25% quantile	Median	75% quantile	Maximum
Columbia 2017, CWR Current	14	25	29	33	51
Columbia 2017, No CWR	14	25	28	32	52
Columbia 2017, CWR Current	15	28	32	37	55
Columbia 2017, No CWR	16	27	31	35	55

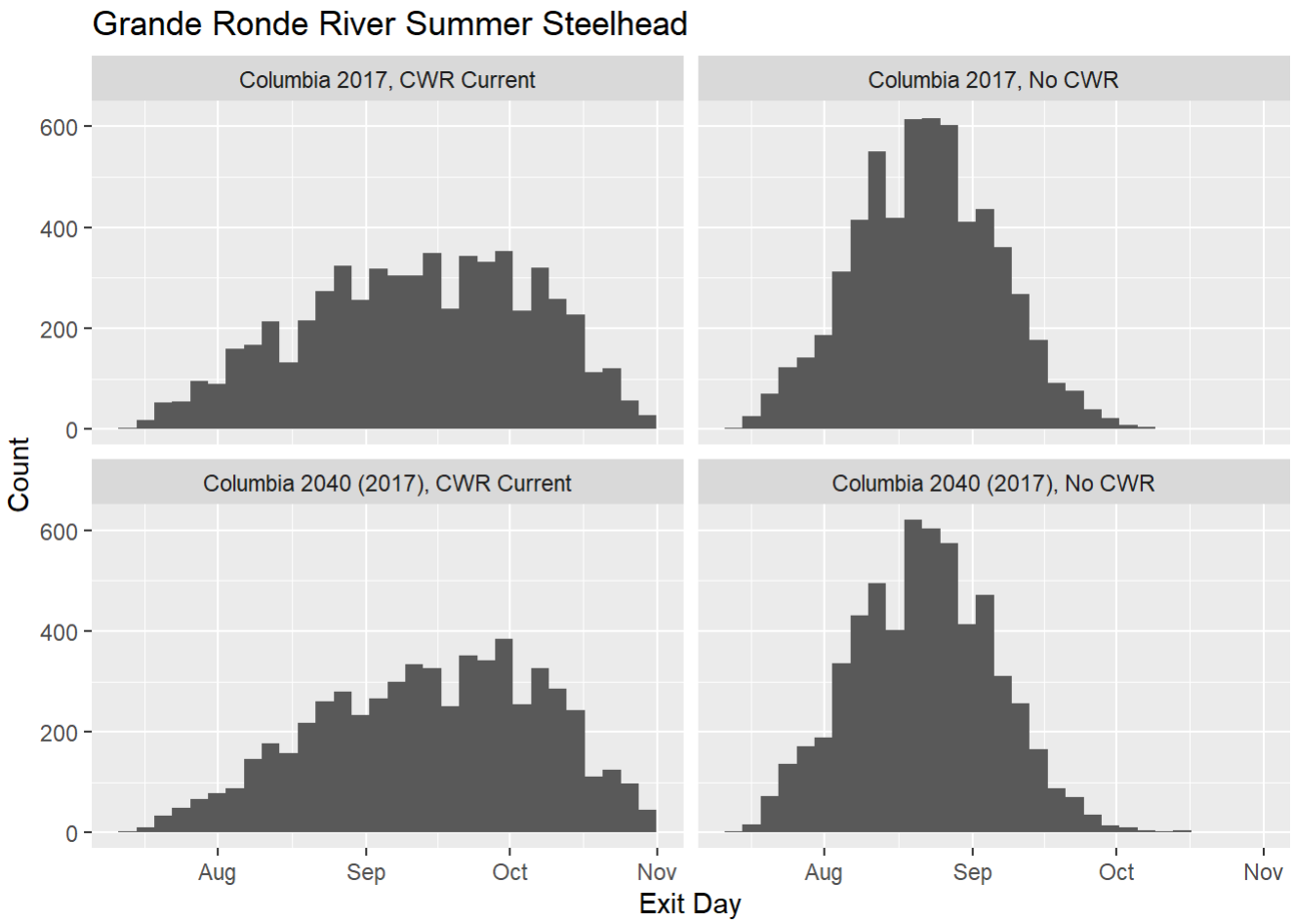
Table 3. Model output for total hours residing n cold water refuges summarized for Grande Ronde River Summer Steelhead.

Scenario	Total CWR Residence (h)
Columbia 2017,CWR Current	3061505
Columbia 2017, No CWRs	16
Columbia 2040 (2017), Current	3410964
Columbia 2040 (2017), No CWRs	17

Table 4. 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	0.95
Columbia 2017, No CWRs	1.5
Columbia 2040 (2017), Current	5.2
Columbia 2040 (2017), No CWRs	5.25




Grande Ronde River Summer Steelhead
Columbia 2017, CWR Current
Columbia 2017, No CWR
Columbia 2040 (2017), CWR Current
Columbia 2040 (2017), No CWR
Count
600
400
200
0
Aug
Sep
Oct
Nov
Exit Day

Snake River fall chinook cumulative DD

MNSnyder

9/5/2019

Snake River fall chinook Columbia River temperature time series from 2017. 4 scenarios included:

- Columbia River 2017
- Columbia River 2017, no CWRs
- Columbia River 2017 plus 1
- Columbia River 2017 plus 1, no CWRs

Columbia 2017B assigns the John Day Pool temperature from the John Day forebay, which is the warmer section of the pool.

DD > 18 °C

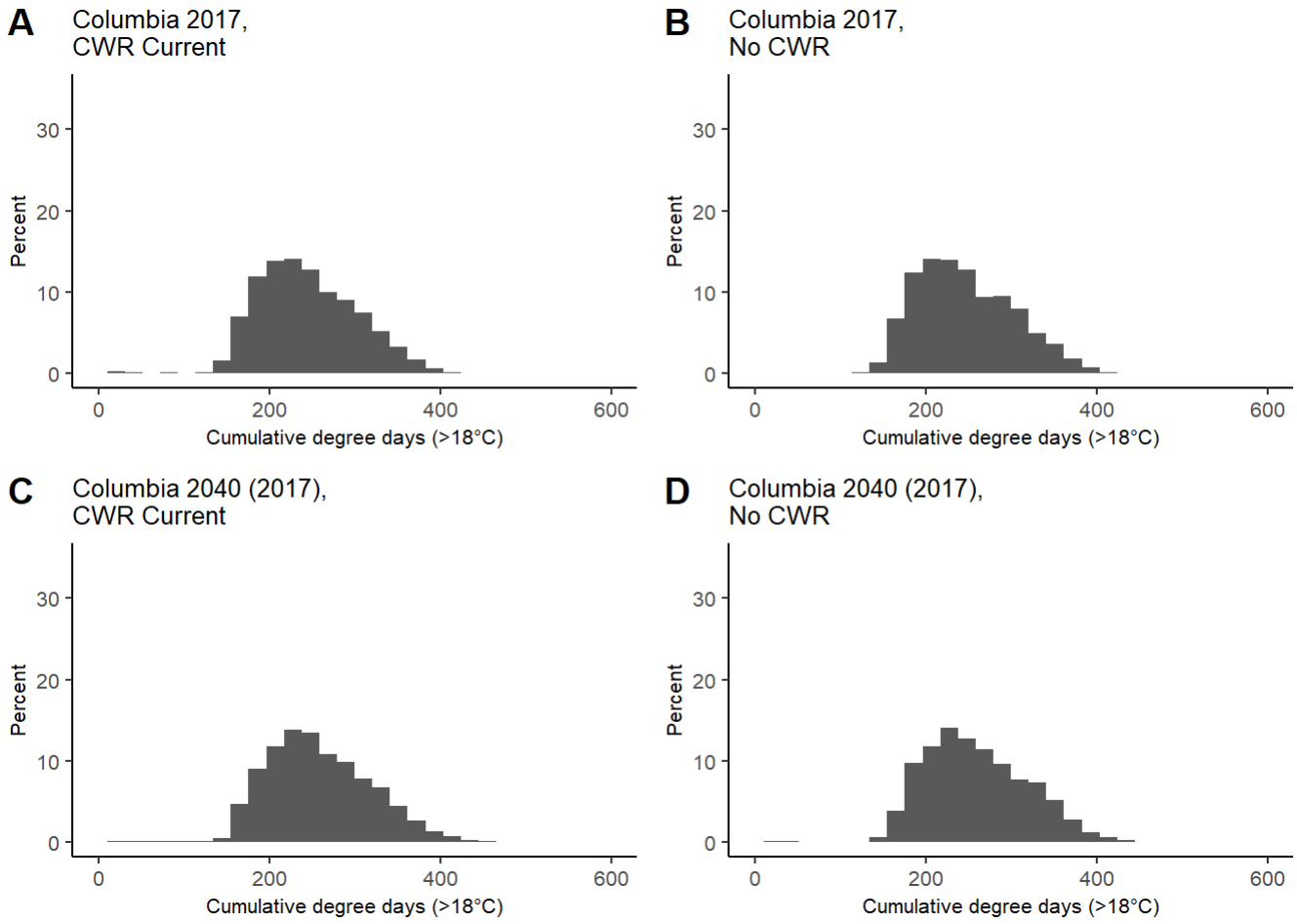


Fig. 1. Histograms of modeled Snake River fall chinook accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.

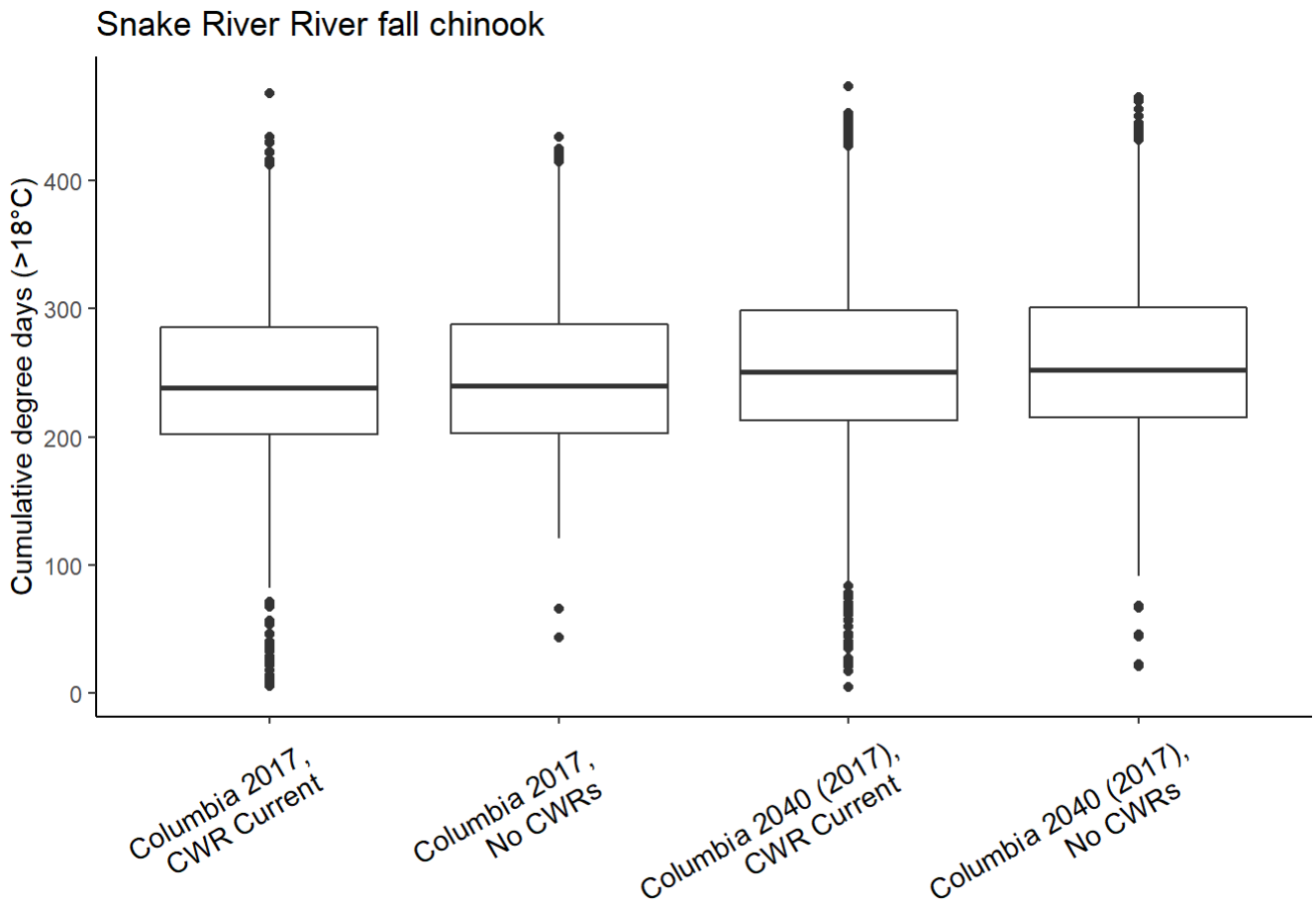


Fig. 2. Boxplots of modeled Snake River fall chinook accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.

Table 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	5	202	239	285	468
Columbia 2017, No CWR	43	203	240	288	434
Columbia 2040 (2017), CWR Current	5	213	251	299	474
Columbia 2040 (2017), No CWR	21	215	252	301	465

Degree Days > 20°C

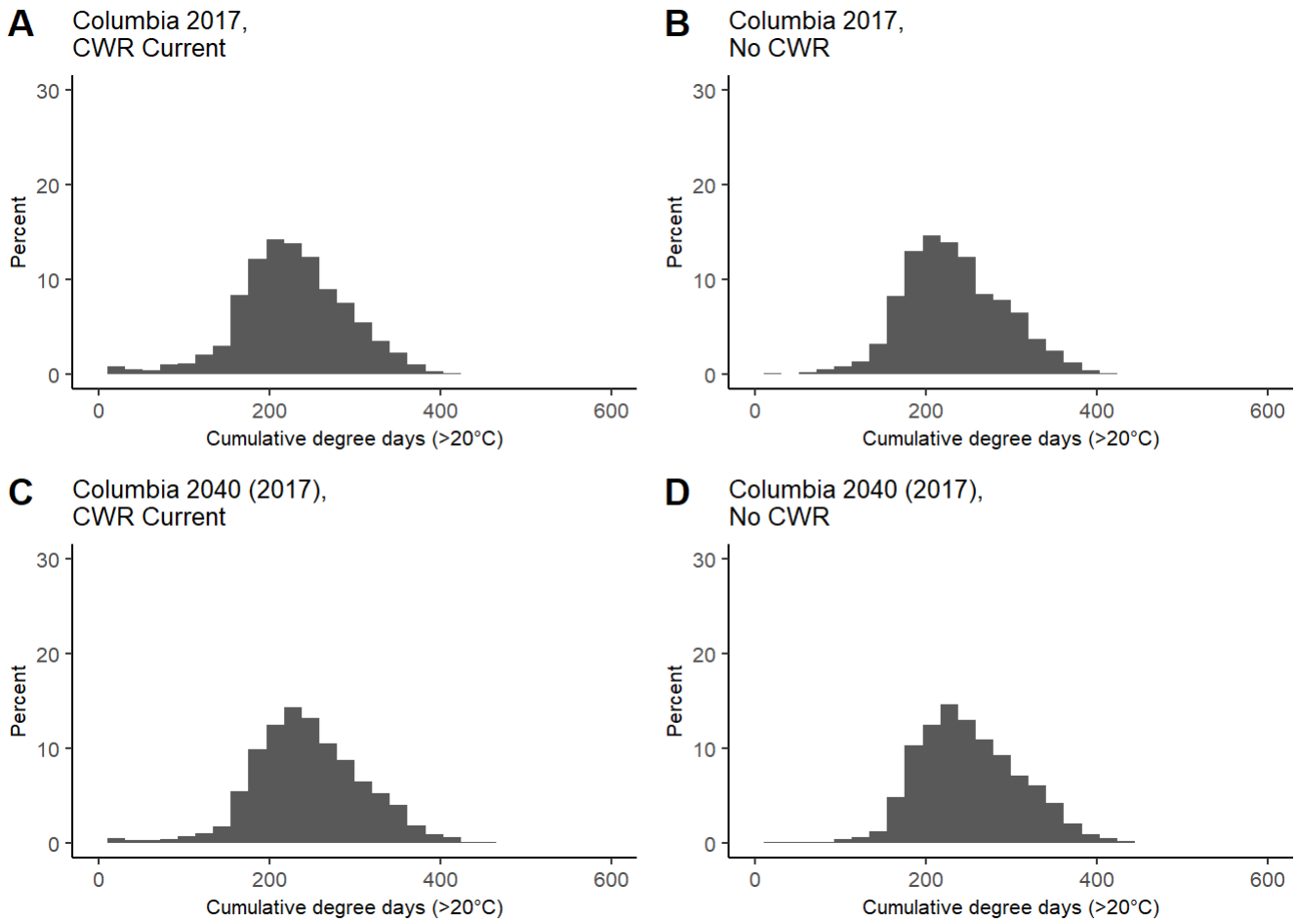


Fig. 1. Histograms of modeled Snake River fall chinook accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.

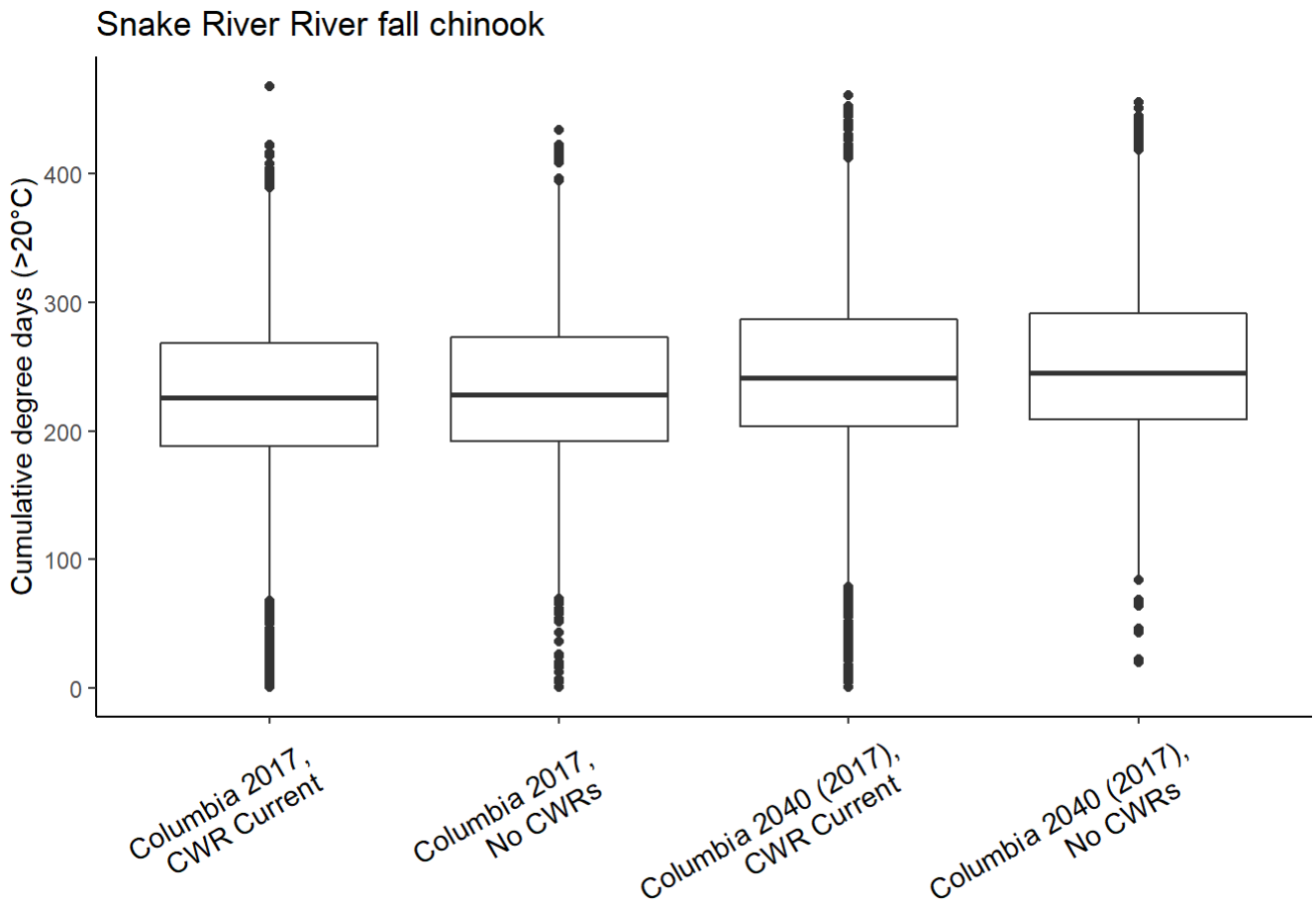


Fig. 2. Boxplots of modeled Snake River fall chinook accumulated degrees day over 18°C from Bonneville to the Snake River confluence in the Columbia River.

Table 1. 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	188	226	268	468
Columbia 2017, No CWR	1	192	228	273	434
Columbia 2040 (2017), CWR Current	1	204	242	287	462
Columbia 2040 (2017), No CWR	20	209	245	292	456

Degree Days > 21°C

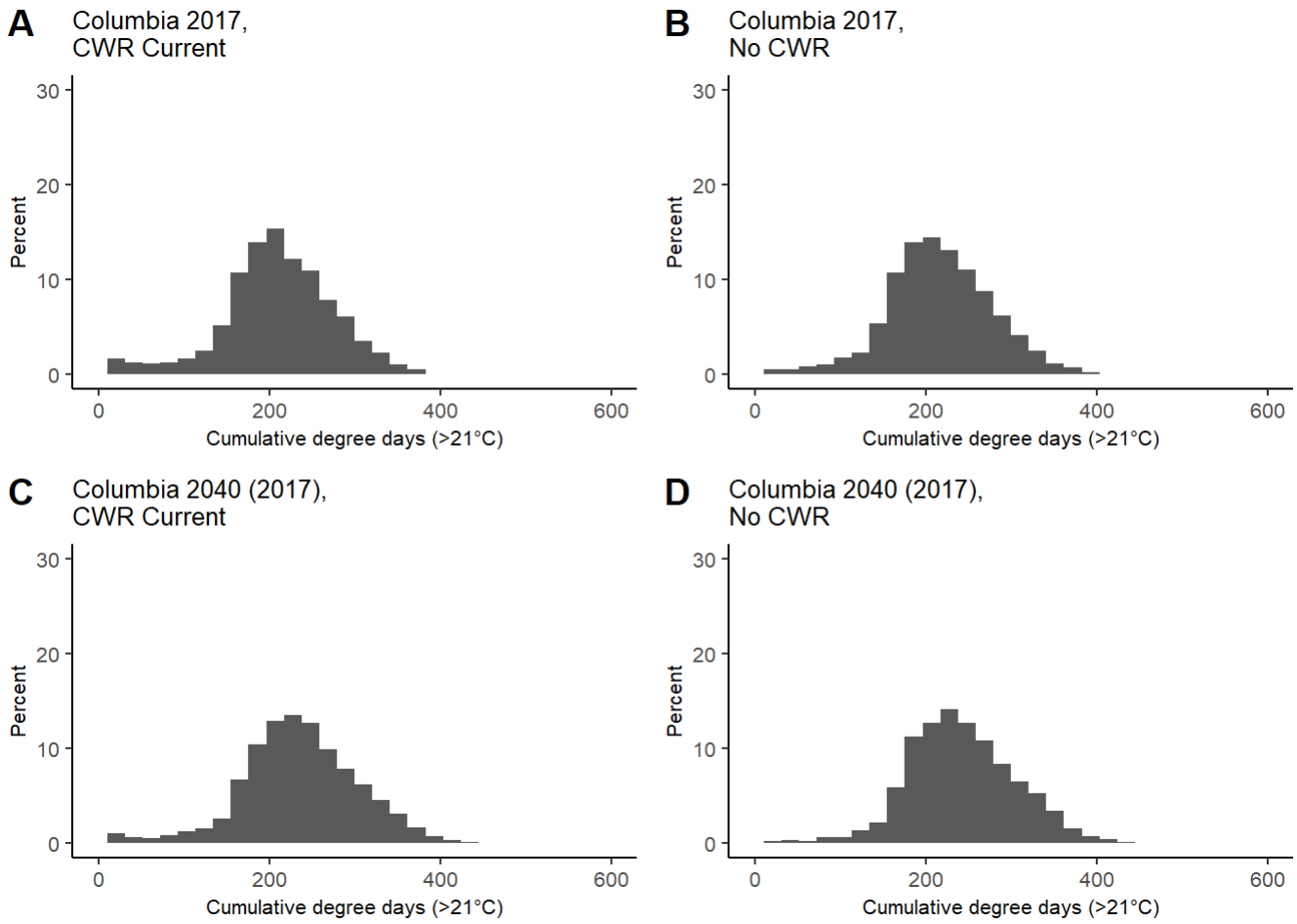


Fig. 1. Histograms of modeled Snake River fall chinook accumulated degrees day over 21°C from Bonneville to the Snake River confluence in the Columbia River.

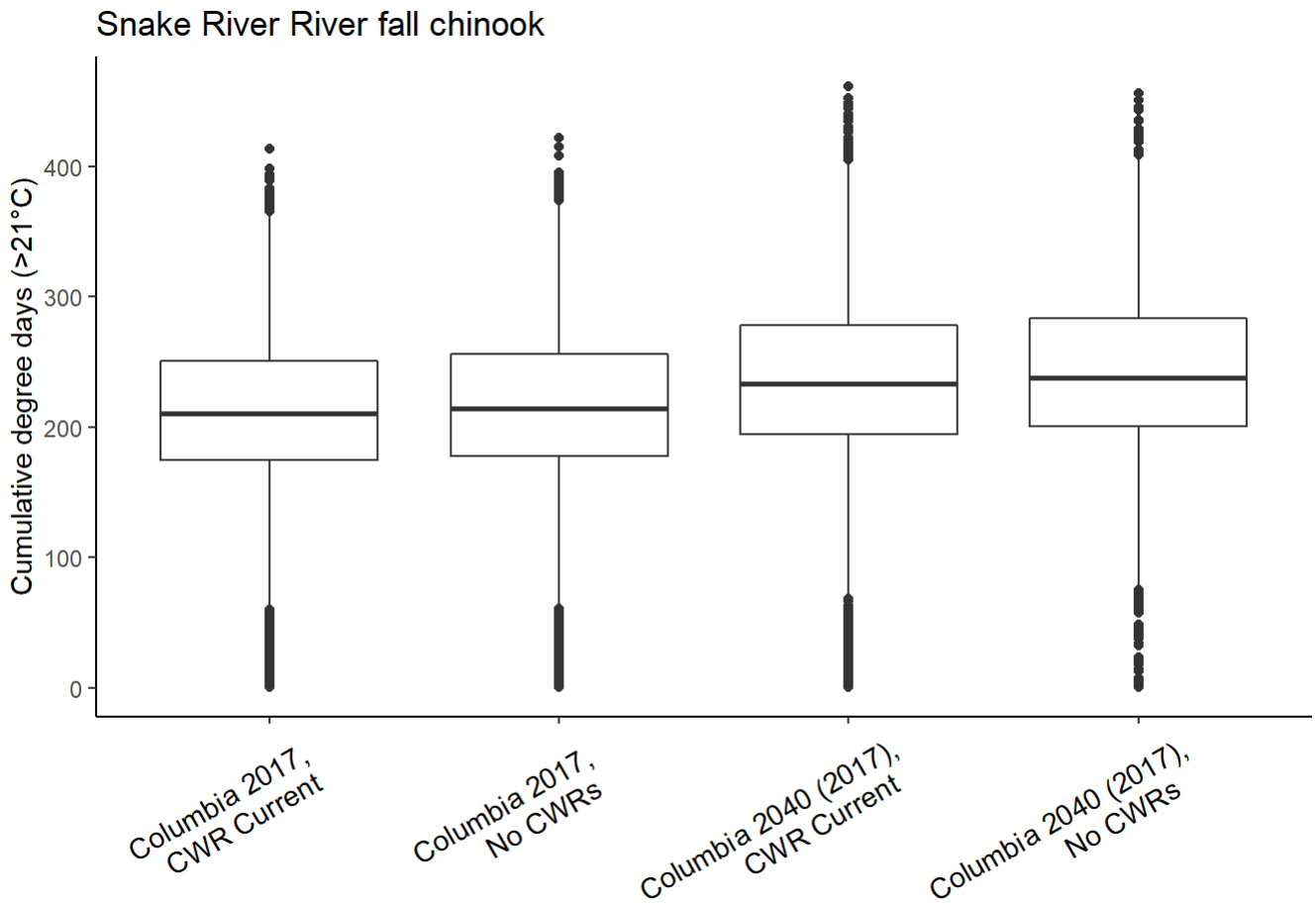


Fig. 2. Boxplots of modeled Snake River fall chinook accumulated degrees day over 21°C from Bonneville to the Snake River confluence in the Columbia River.

Table 1. 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	175	210	251	413
Columbia 2017, No CWR	1	178	215	256	422
Columbia 2040 (2017), CWR Current	1	195	233	279	462
Columbia 2040 (2017), No CWR	1	200	238	284	456

Degree Days > 22°C

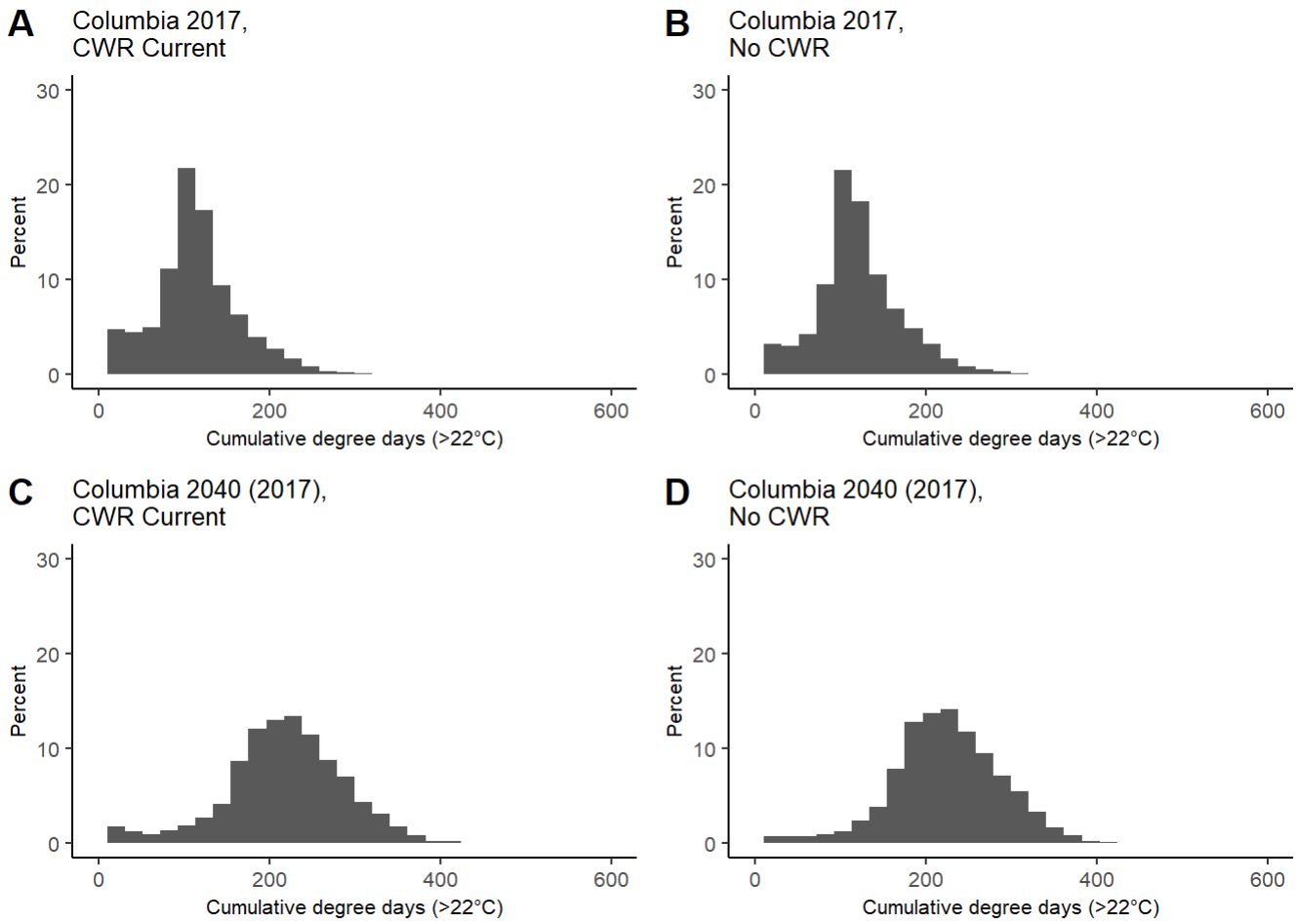


Fig. 1. Histograms of modeled Snake River fall chinook accumulated degrees day over 22°C from Bonneville to the Snake River confluence in the Columbia River.

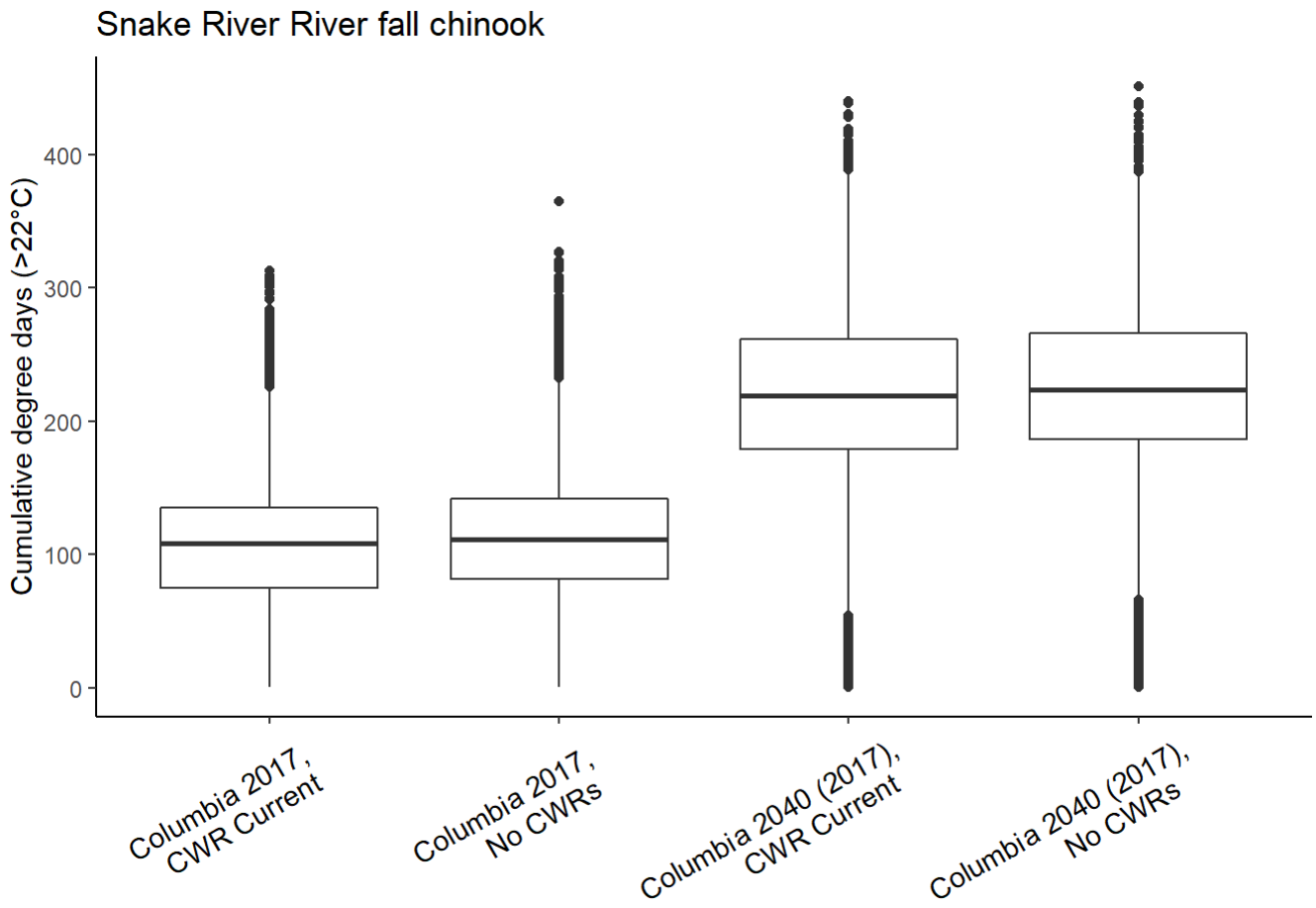


Fig. 2. Boxplots of modeled Snake River fall chinook accumulated degrees day over 22°C from Bonneville to the Snake River confluence in the Columbia River.

Table 1. 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	75	109	135	313
Columbia 2017, No CWR	1	82	111	142	365
Columbia 2040 (2017), CWR Current	1	179	219	262	440
Columbia 2040 (2017), No CWR	1	186	224	266	451

Snake River fall Chinook summarized fitness outcomes

MNSnyder

9/05/2019

Snake River fall Chinook Columbia River temperature time series from 2017. 4 scenarios included:

- Columbia River 2017
- Columbia River 2017, no CWRs
- Columbia River 2017 plus 1
- Columbia River 2017 plus 1, no CWRs

Columbia 2017B assigns the John Day Pool temperature from the John Day forebay, which is the warmer section of the pool.

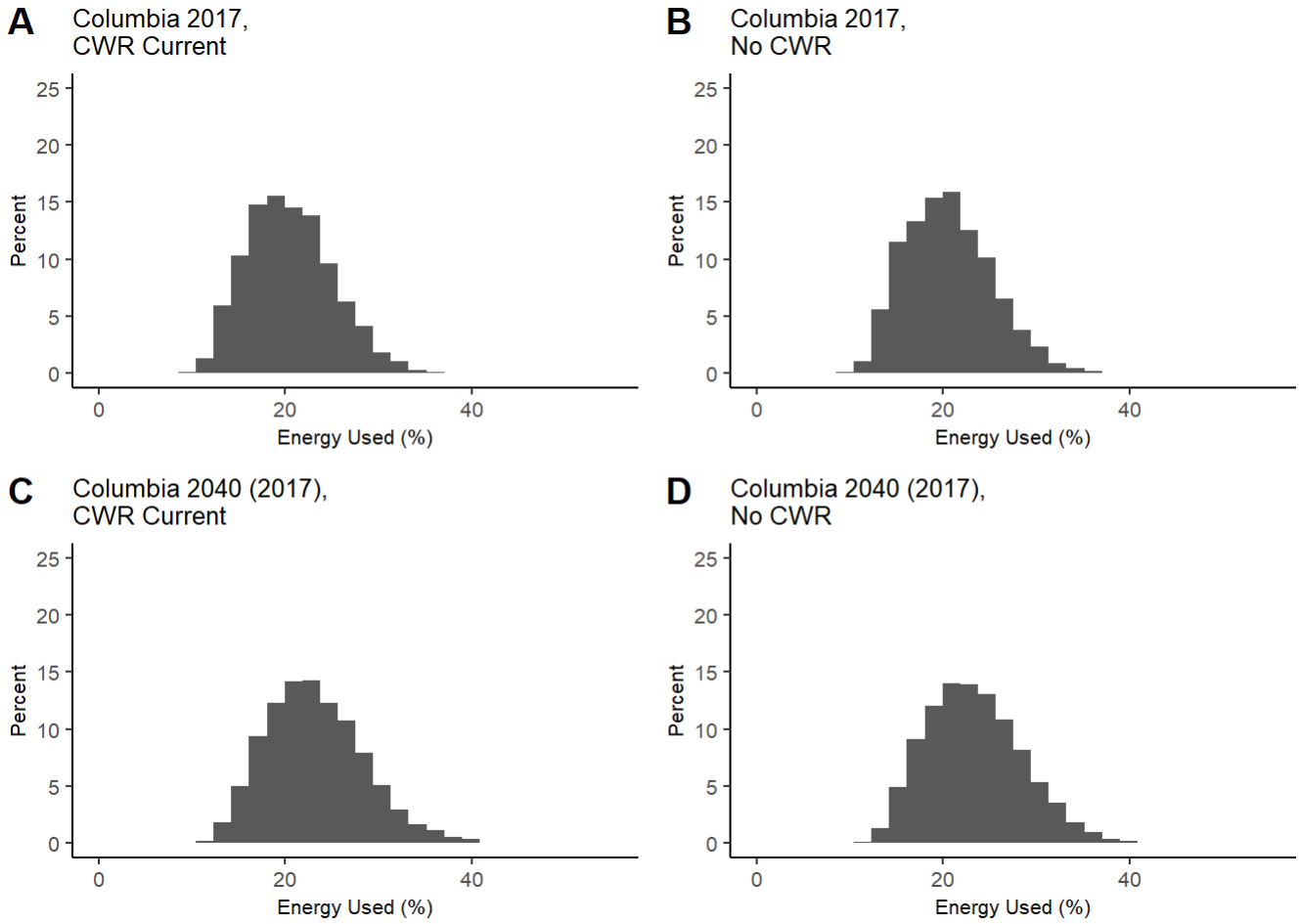


Fig. 1. Histogram of percent energy lost for modeled Snake River fall Chinook migrating through four different modeled thermalscapes.

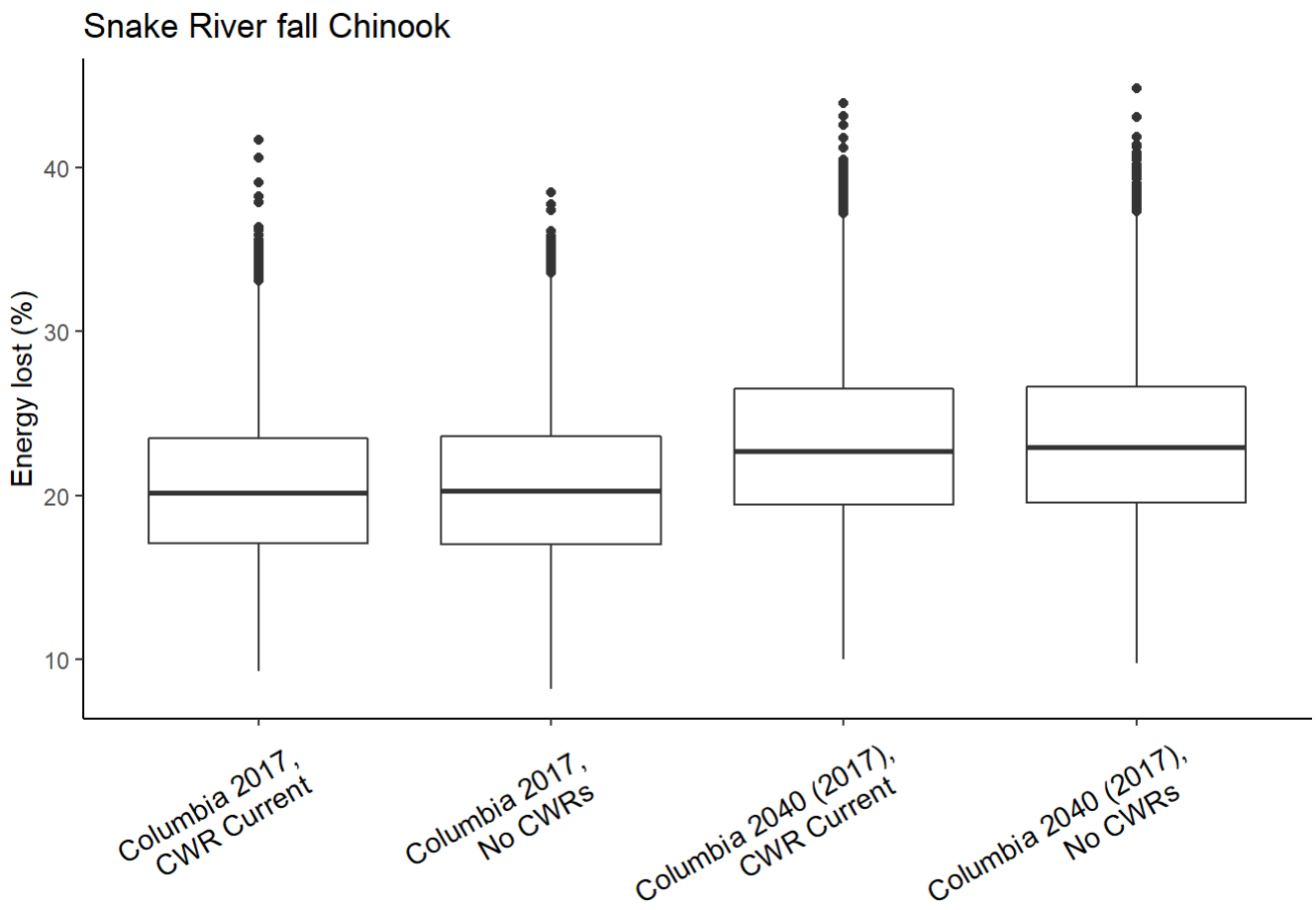


Fig. 2. Boxplot of percent energy lost for modeled Snake River fall Chinook migrating through four different modeled thermalscapes.

Table 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	9.3	17.1	20.2	23.5	41.7
Columbia 2017, No CWR	8.2	17.1	20.3	23.6	38.5
Columbia 2017, CWR Current	10.0	19.4	22.7	26.5	43.9
Columbia 2017, No CWR	9.8	19.5	22.9	26.7	44.8

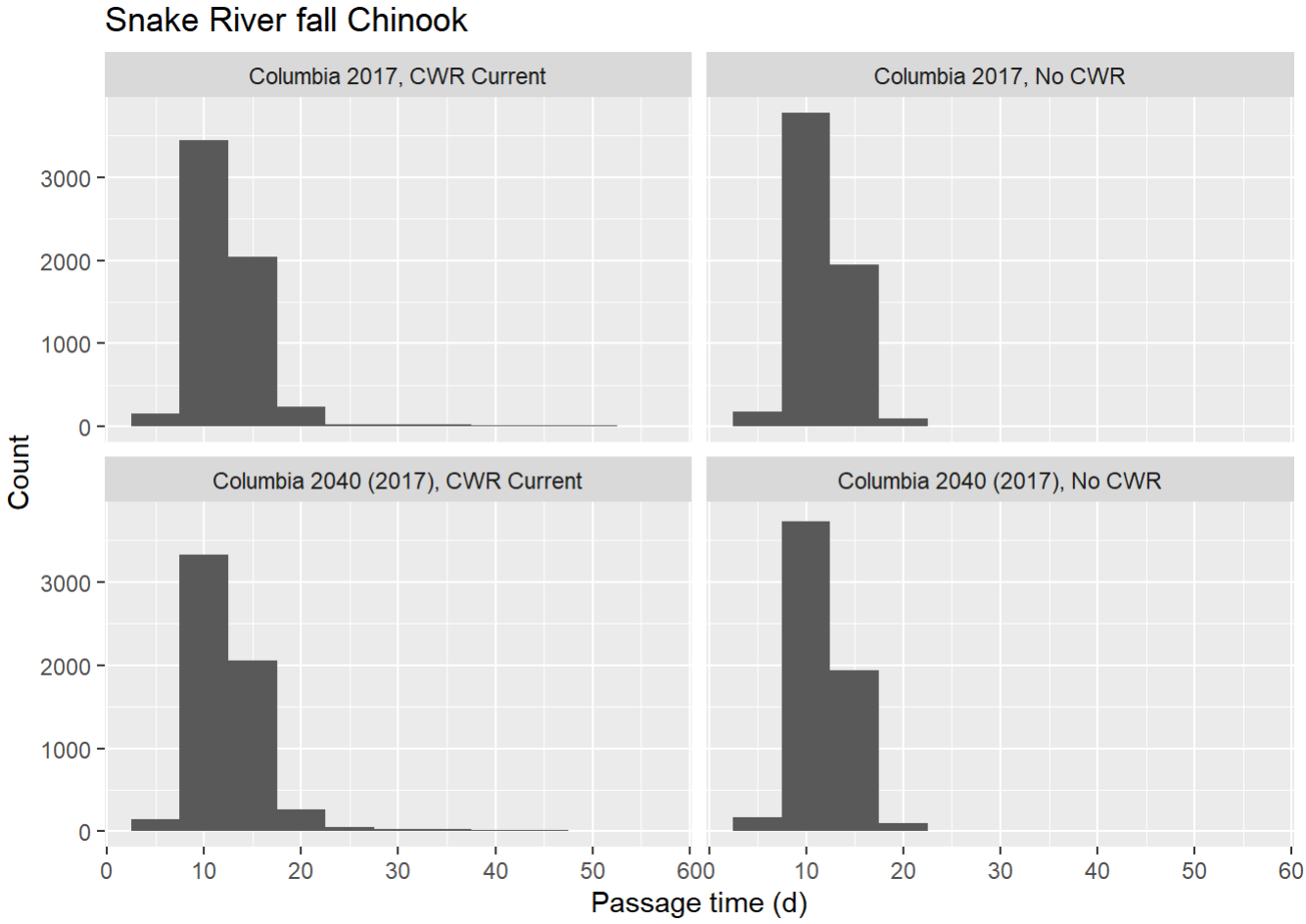
Table 3. Model output for total hours residing n cold water refuges summarized for Snake River fall Chinook.

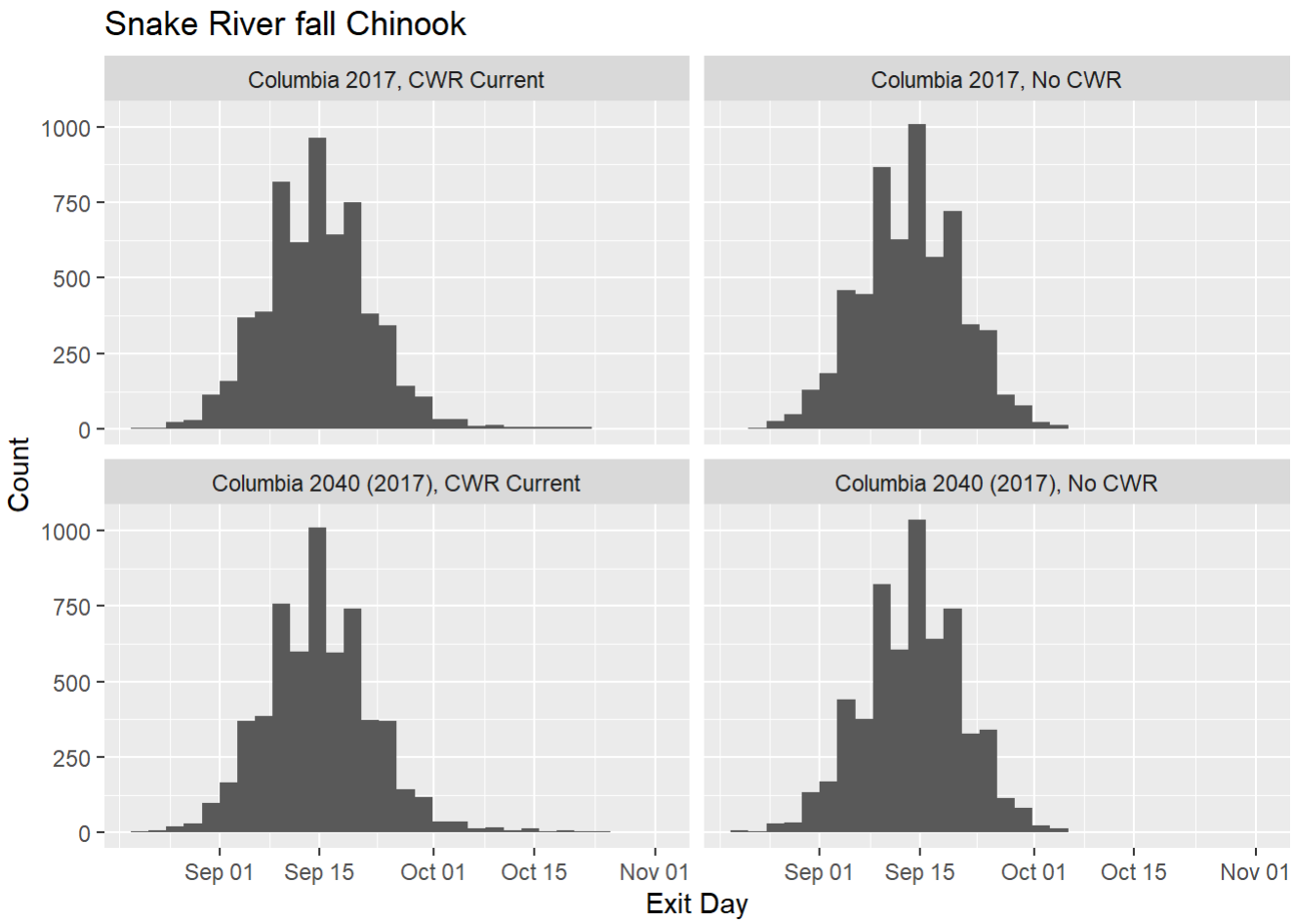
Scenario	Total CWR Residence (h)
Columbia 2017,CWR Current	125134
Columbia 2017, No CWRs	2
Columbia 2040 (2017), Current	151218
Columbia 2040 (2017), No CWRs	4

Table 4. Model output for percent of individuals dying from acute temperature stress summarized for Snake River

fall Chinook.

Scenario	Total mortality
Columbia 2017,CWR Current	0.45
Columbia 2017, No CWRs	0.15
Columbia 2040 (2017), Current	2.95
Columbia 2040 (2017), No CWRs	3.05




Snake River fall Chinook
Columbia 2017, CWR Current
Columbia 2017, No CWR
Columbia 2040 (2017), CWR Current
Columbia 2040 (2017), No CWR
Count
1000
750
500
250
0
Sep 01
Sep 15
Oct 01
Oct 15
Nov 01
Exit Day