

Supplementary material

Fluctuating densities of juvenile brown trout (*Salmo trutta*) and Alpine bullhead (*Cottus poecilopus*) over a 25-year period in the Atna River, Norway

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Long term monitoring data from pristine or relatively unimpacted watersheds represents a valuable ecological baseline in the 21st century. Here, we present a 25-year time series of brown trout (*Salmo trutta*) and Alpine bullhead (*Cottus poecilopus*) densities in the boreal-subalpine Atna River in Norway (62 °N) and investigate their relationships with discharge and water temperatures. There was an overall negative trend in densities of Alpine bullhead, a declining trend in densities of age 0 brown trout, and no clear trend for age ≥1+ brown trout across the study sites. There were substantial fluctuations in densities for both species, and the majority of the variance originated from year-to-year variation. For older brown trout, approximately 33 % of the variance could be attributed to site-level factors, i.e. systematic differences in densities between sites. Concurrently, there were changes in some of the discharge and temperature-related metrics. The lowest flow of the year became gradually higher throughout the period whereas mean discharge in spring decreased. The best supported models showed a negative relationship between fish densities and mean annual discharge (Alpine bullhead and older brown trout) and a negative relationship between density and minimum annual discharge for age-0 brown trout. The models explained only modest amounts of overall variance in the dataset (range 0 to 12 %) but did document a potentially limiting effect on fish densities on an annual basis. We discuss the likely mechanisms by which discharge and water temperature can influence the abundance of brown trout and Alpine bullhead in river systems and highlight the value of long-term monitoring as a baseline when investigating broad-scale shifts in abundance.

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SUPPLEMENTARY MATERIAL

Supplementary material 1. Data diagnostics

Supplementary material 2: Nonlinear trend analysis using GAMs

Supplementary material 3: Correlations between densities of each species across sites

Supplementary material 4: Correlations between densities of different species within each site

Supplementary material 5: Variance decomposition

SUPPLEMENTARY MATERIAL 1

Data diagnostics

Check for autocorrelation in density data for all combinations of species / age classes and study sites (Table S.1).

Table S.1. Output from the autocorrelation test with a lag of up to 10 years, i.e. the correlation between densities at year 0 and year 1, year 0 and year 2 etc. The table shows the species and site combinations and their associated Ljung-Box statistics and P values. P values larger than 0.05 indicate no serial autocorrelation. Only Alpine bullhead in site 3 had significant autocorrelation at the $\alpha = 0.05$ -level.

Species	Site	Ljung-Box Statistic	Ljung-Box P-value
Alpine_bullhead	1	4.891	0.898
Brown_trout_0	1	8.974	0.535
Brown_trout_1	1	NA	NA
Alpine_bullhead	2	9.397	0.495
Brown_trout_0	2	7.851	0.643
Brown_trout_1	2	9.159	0.517
Alpine_bullhead	3	23.696	0.008
Brown_trout_0	3	11.122	0.348
Brown_trout_1	3	8.437	0.586
Alpine_bullhead	4	9.501	0.485
Brown_trout_0	4	16.980	0.075
Brown_trout_1	4	10.902	0.365

SUPPLEMENTARY MATERIAL 2

Nonlinear trend analysis using GAMs

Corroboration of monotonic trends using generalized additive models (GAM; figure S.2). Significant nonlinear trends were found for Alpine bullhead in all sites; age-0 brown trout in sites 3 and 4; and for older brown trout at site 3.

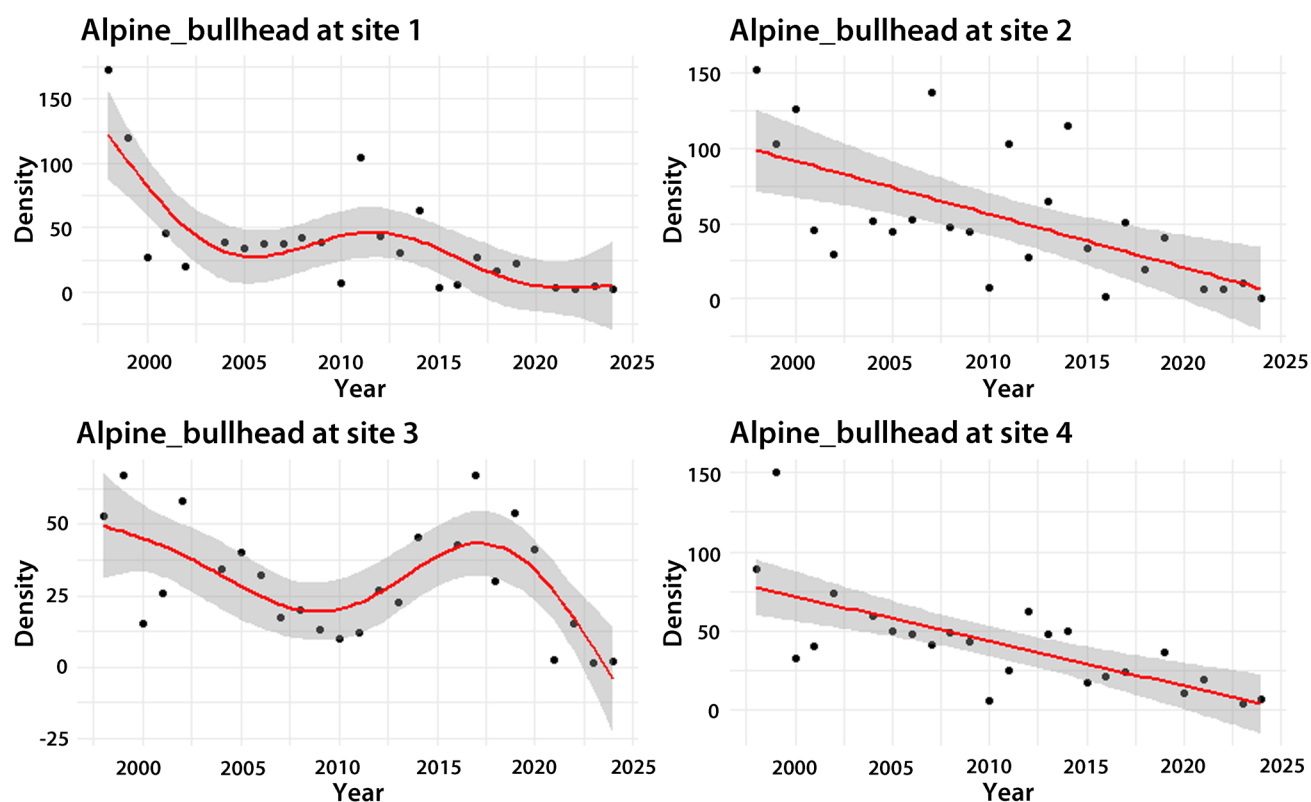


Figure S.2. Splines from the generalized additive models with year as the smooth and up to 5 basis functions ($k = 5$) of the density of each species/age group in each study site from 1998 to 2024. Continued on next page.

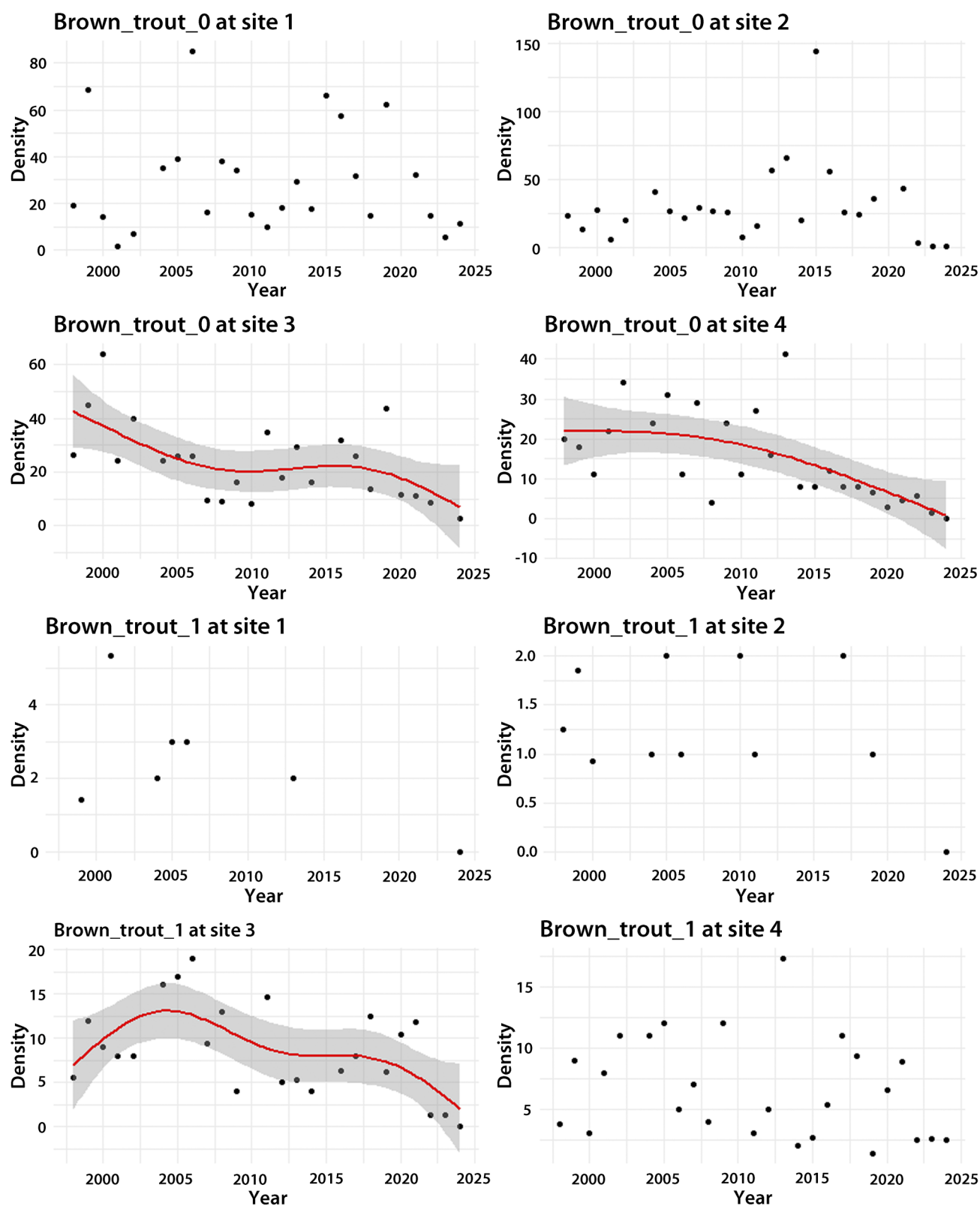


Figure S.2. Continued.

SUPPLEMENTARY MATERIAL 3

Correlations between densities of each species across sites

With the exception of sites 2 and 3, each pair of sites displayed a significant correlation in Alpine bullhead densities (Table S.3). This implies some level of synchronicity in the abundance of Alpine bullhead in the Atna River. Densities of age 0 brown trout correlated in sites 1 and 2, whereas densities of older brown trout correlated in sites 3 and 4.

Table S.3. Correlations for each species and age class across the four study sites for the period 1998 to 2024. A positive connotation (Pearson's correlation coefficient) means that the densities of the same species in a pair of sites are correlated over time, suggesting synchronicity in abundance.

Species	Site a	Site b	Pearson's correlation coefficient	P-value	N (years)	Lower 95 % CI	Upper 95 % CI
Alpine bullhead	1	2	0.757	< 0.001	25	0.49	1.02
	1	3	0.413	0.045	24	0.03	0.79
	1	4	0.695	0.000	23	0.39	1.00
	2	3	0.285	0.177	24	-0.12	0.69
	2	4	0.489	0.018	23	0.12	0.86
	3	4	0.594	0.003	23	0.25	0.94
Brown trout 0+	1	2	0.455	0.022	25	0.09	0.82
	1	3	0.257	0.237	23	-0.16	0.67
	1	4	-0.117	0.579	25	-0.52	0.29
	2	3	0.185	0.398	23	-0.24	0.61
	2	4	0.087	0.679	25	-0.32	0.49
	3	4	0.308	0.143	24	-0.09	0.71
Brown trout ≥ 1	1	2	0.649	0.236	5	-0.21	1.51
	1	3	0.369	0.416	7	-0.45	1.18
	1	4	0.165	0.723	7	-0.70	1.03
	2	3	0.426	0.219	10	-0.20	1.05
	2	4	0.721	0.019	10	0.24	1.20
	3	4	0.271	0.200	24	-0.13	0.67

SUPPLEMENTARY MATERIAL 4

Correlations between densities of different species within each site

Pairs of species in each site were assessed for synchronicity. Alpine bullhead and age 0 brown trout displayed positive significant correlation in sites 3 and 4, and age 0 brown trout and older brown trout correlated significantly in site 4 (Table S.4; Figure S.1)

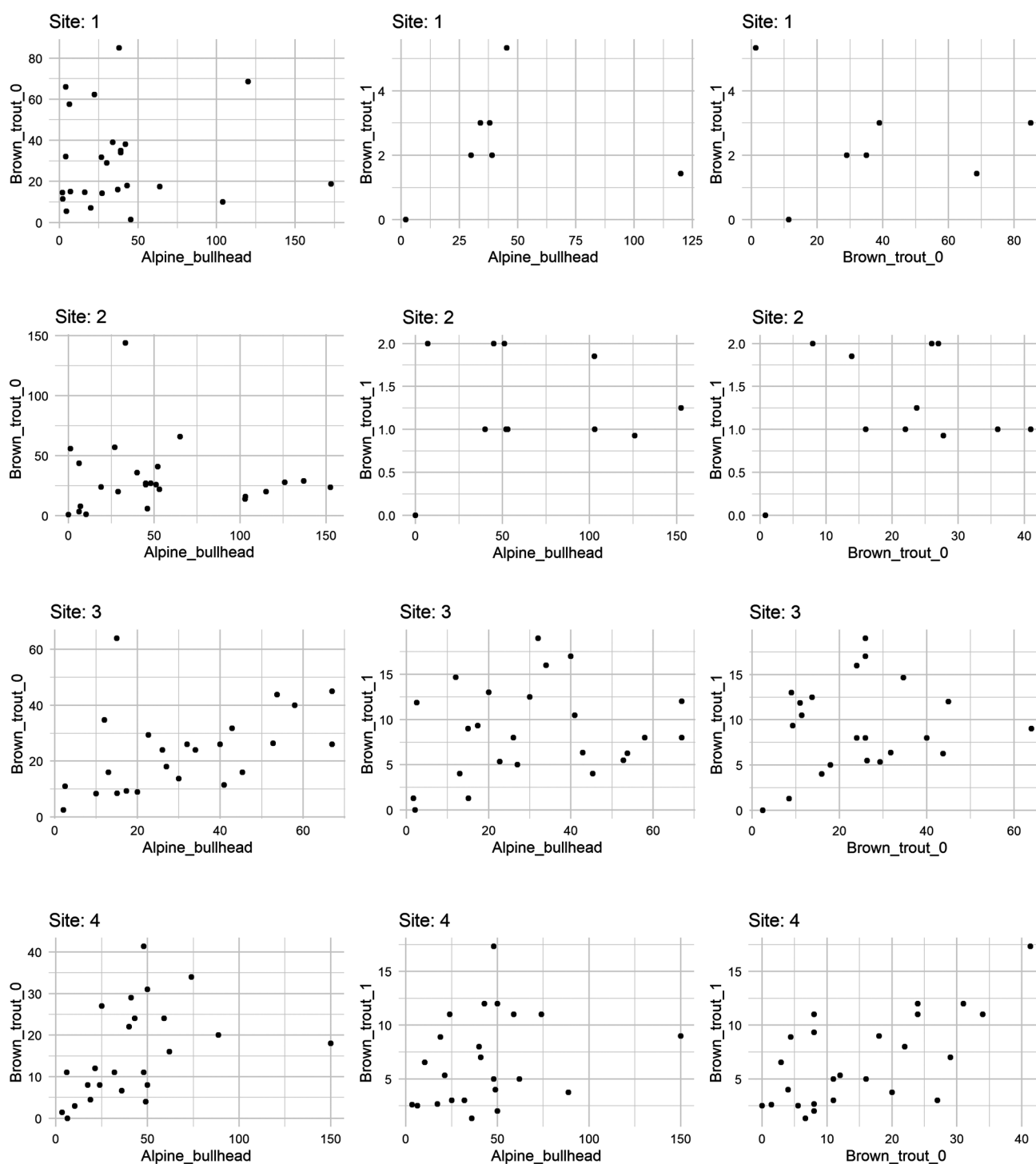


Figure S.4. Correlations between pairs of species in each site from 1998 through 2024.

Table S4. Correlations for each species and age class in each of the four study sites for the period 1998 to 2024. A positive connotation (Pearson's correlation coefficient) means that the densities of a pair of species in a site are correlated over time, suggesting synchronicity in abundance.

Site	Species 1	Species 2	Pearson's correlation coefficient	P-value	N (years)	Lower 95 % CI	Upper 95 % CI
1	Alpine_bullhead	Brown_trout_0	0.023	0.913	25	-0.39	0.43
1	Alpine_bullhead	Brown_trout_1	0.080	0.864	7	-0.79	0.95
1	Brown_trout_0	Brown_trout_1	-0.136	0.772	7	-1.00	0.73
2	Alpine_bullhead	Brown_trout_0	-0.059	0.779	25	-0.47	0.35
2	Alpine_bullhead	Brown_trout_1	0.059	0.864	11	-0.59	0.71
2	Brown_trout_0	Brown_trout_1	0.124	0.716	11	-0.52	0.77
3	Alpine_bullhead	Brown_trout_0	0.442	0.031	24	0.07	0.82
3	Alpine_bullhead	Brown_trout_1	0.185	0.387	24	-0.23	0.60
3	Brown_trout_0	Brown_trout_1	0.189	0.389	23	-0.23	0.61
4	Alpine_bullhead	Brown_trout_0	0.427	0.038	24	0.05	0.80
4	Alpine_bullhead	Brown_trout_1	0.266	0.221	23	-0.15	0.68
4	Brown_trout_0	Brown_trout_1	0.658	0.000	25	0.35	0.97

SUPPLEMENTARY MATERIAL 5

Variance decomposition

Given as site-specific deviation from the grand mean intercept (Table S.5 and Figure S.5).

Table S.5. Estimates of the site-specific deviation from the grand mean intercept from the one-way ANOVA with site as a random effect. Visualization shown in Figure S.5 below.

Species	Site	Grand mean intercept	Site-specific deviation from grand mean intercept	Site-level intercept (site mean)
Alpine bullhead	1	40.63	-1.18	39.45
	2	40.63	5.43	46.05
	3	40.63	-4.76	35.87
	4	40.63	0.51	41.14
Brown trout 0+	1	24.67	3.42	28.09
	2	24.67	4.06	28.73
	3	24.67	-0.76	23.90
	4	24.67	-6.72	17.95
Brown trout ≥ 1	1	4.88	-2.05	2.83
	2	4.88	-3.17	1.70
	3	4.88	3.56	8.44
	4	4.88	1.66	6.53

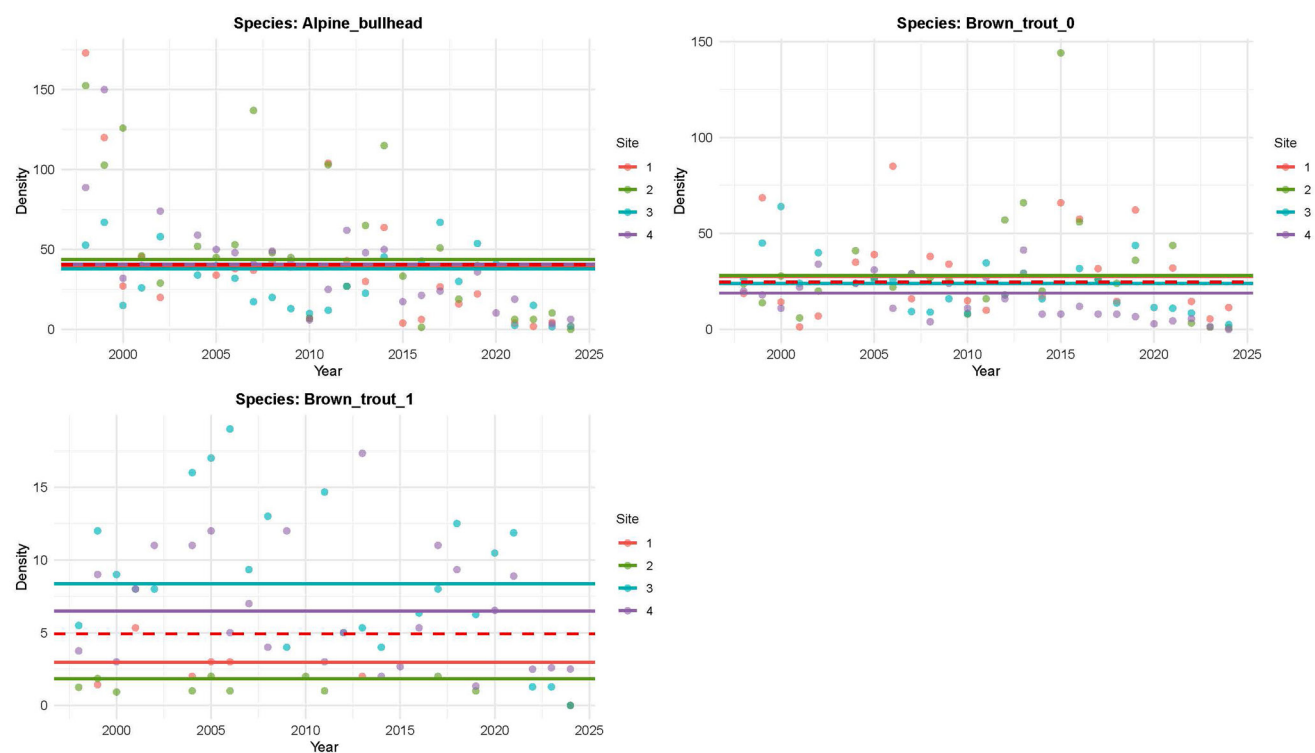


Figure S.5. Densities (no. per 100m²) of Alpine bullhead and the two age classes of brown trout across all sites from 1998 to 2024. Red dashed lines show the grand mean density for each species or age class, whereas solid lines show site-level means. Estimates for each site-level mean are given in Table S.5 above. Note different scales on the y-axes.