Supplementary Information

Mining strongly reduces local biodiversity across terrestrial and freshwater ecosystems

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Supplementary Figures

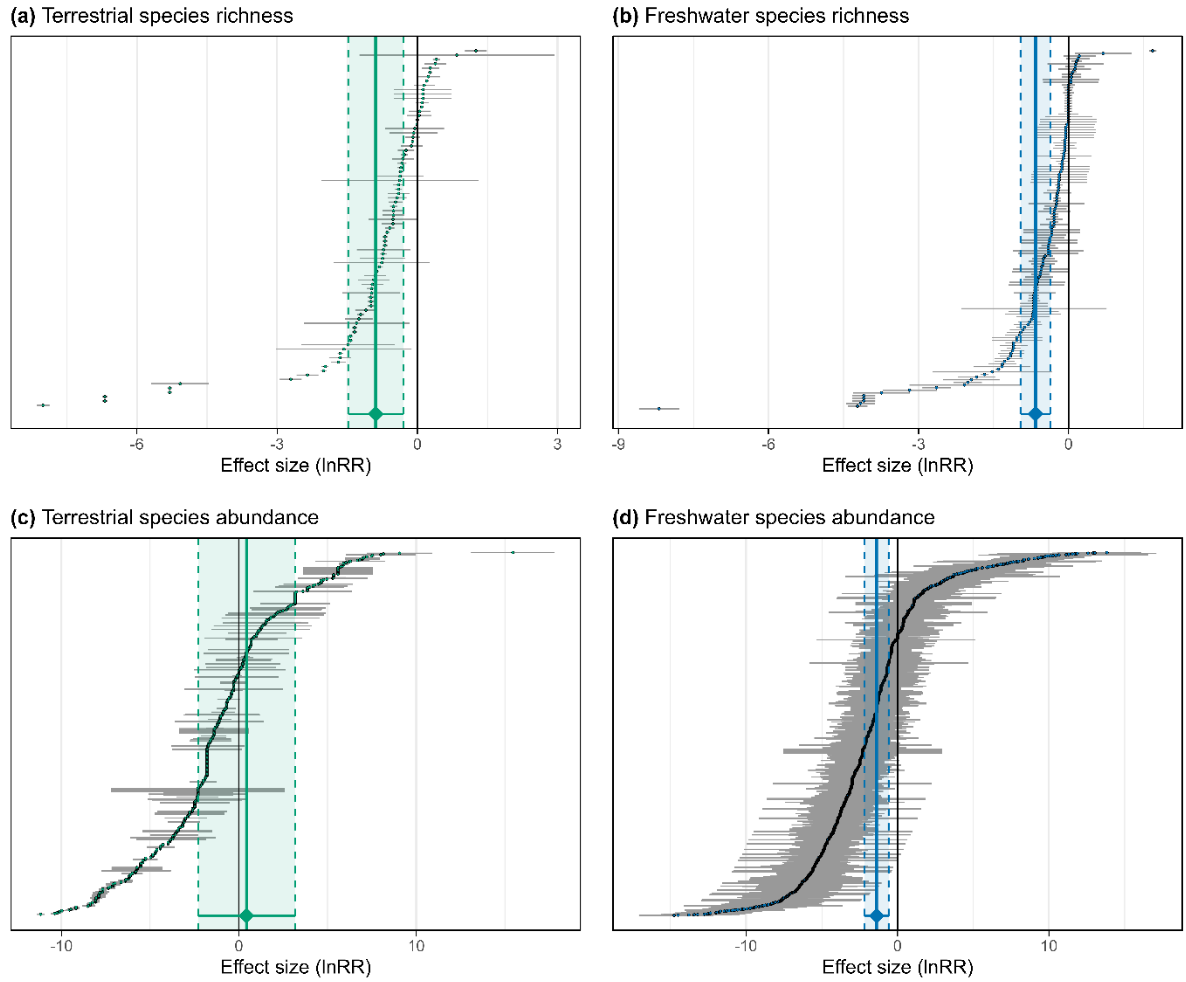

Fig. S1. *Forest plots of species richness and abundance responses to mining in terrestrial (a,c) and freshwater (b,d) ecosystems. Individual effect sizes (log response ratios, lnRRs) are shown as points, with 95% confidence intervals (CIs) in grey. Effect sizes are ordered from lowest to highest within each panel. For some effect sizes, the CIs are narrower than the plotting symbols and are therefore not visible. The solid black vertical line at zero indicates no change in species richness or abundance at mining-affected sites relative to control sites. Negative lnRR values indicate lower species richness or abundance at mining-affected sites relative to control sites, whereas positive values indicate the opposite. Diamonds and solid-coloured vertical lines denote the estimated mean lnRRs from the multilevel random-effects models fitted separately for each response variable and realm; dashed coloured vertical lines and shaded areas indicate the corresponding 95% CIs. One freshwater abundance effect size (lnRR = 5.64, 95% CI = −99.33 to 110.62) was omitted from the plot because its exceptionally wide CI prevented the remaining effect sizes from being displayed legibly.*

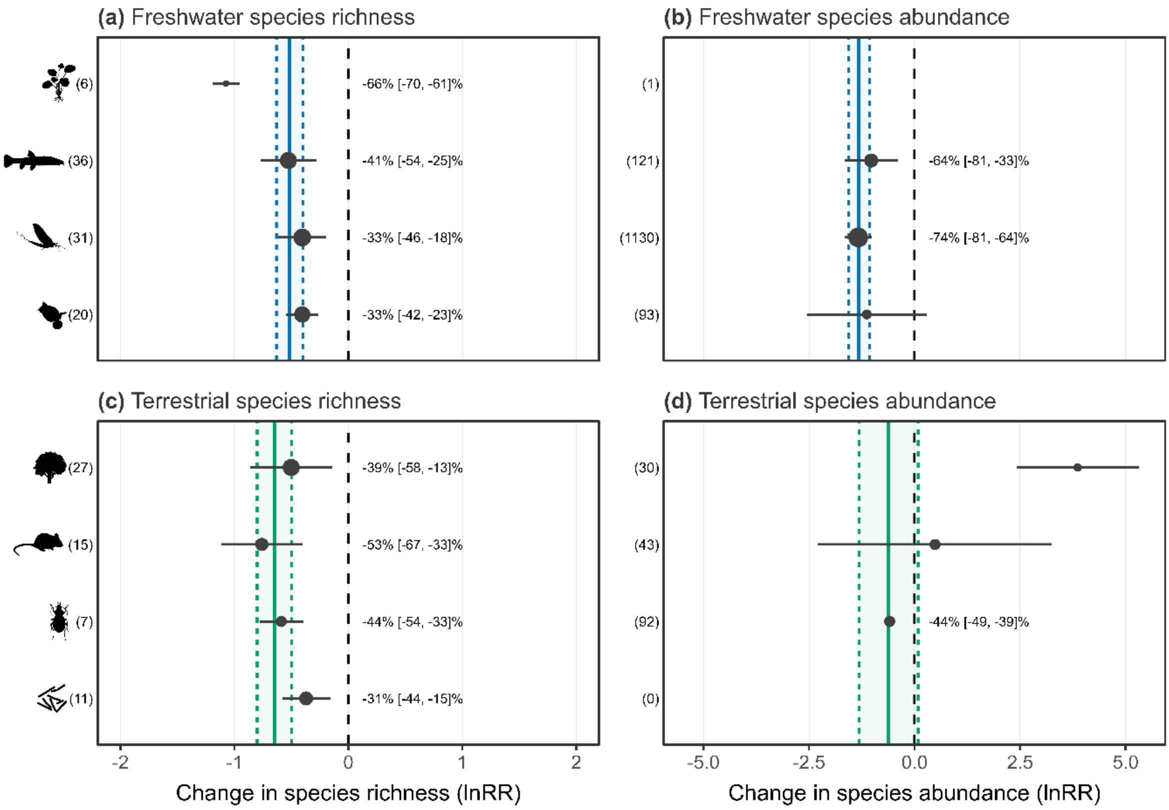

Fig. S2. *Effects of mining on biodiversity across realms and taxonomic groups after excluding statistical outliers. Mean effect sizes (log response ratios, lnRR) and 95% confidence intervals (CIs) from multilevel random-effects meta-analyses are shown for (a) freshwater species richness, (b) freshwater species abundance, (c) terrestrial species richness, and (d) terrestrial species abundance. As a sensitivity check, models were refitted after excluding effect sizes whose 95% CIs did not overlap with the 95% CI of the pooled random-effects estimate. Models were fitted separately for each realm and for each taxonomic group. Circles show the estimated mean lnRR for each taxonomic group, with circle size proportional to number of studies; horizontal lines indicate 95% CIs. Positive lnRR values indicate higher species richness or abundance at mining-affected sites relative to control sites, whereas negative values indicate declines. For taxonomic groups with statistically significant effects based on omnibus tests ($p < 0.05$), mean lnRR values and their 95% CIs are also shown as percentage changes. Coloured vertical lines indicate the overall mean effect size for each realm after outlier exclusion, with dashed coloured lines and shaded areas representing the corresponding 95% CIs (blue: freshwater; green: terrestrial). Numbers in parentheses indicate the number of effect sizes retained in each model. In both realms, silhouettes represent taxonomic groups from top to bottom as plants, vertebrates, invertebrates, and microorganisms and algae, which were accessed from the public domain database PhyloPic using the R package rphylopic 1.5.0* [1].

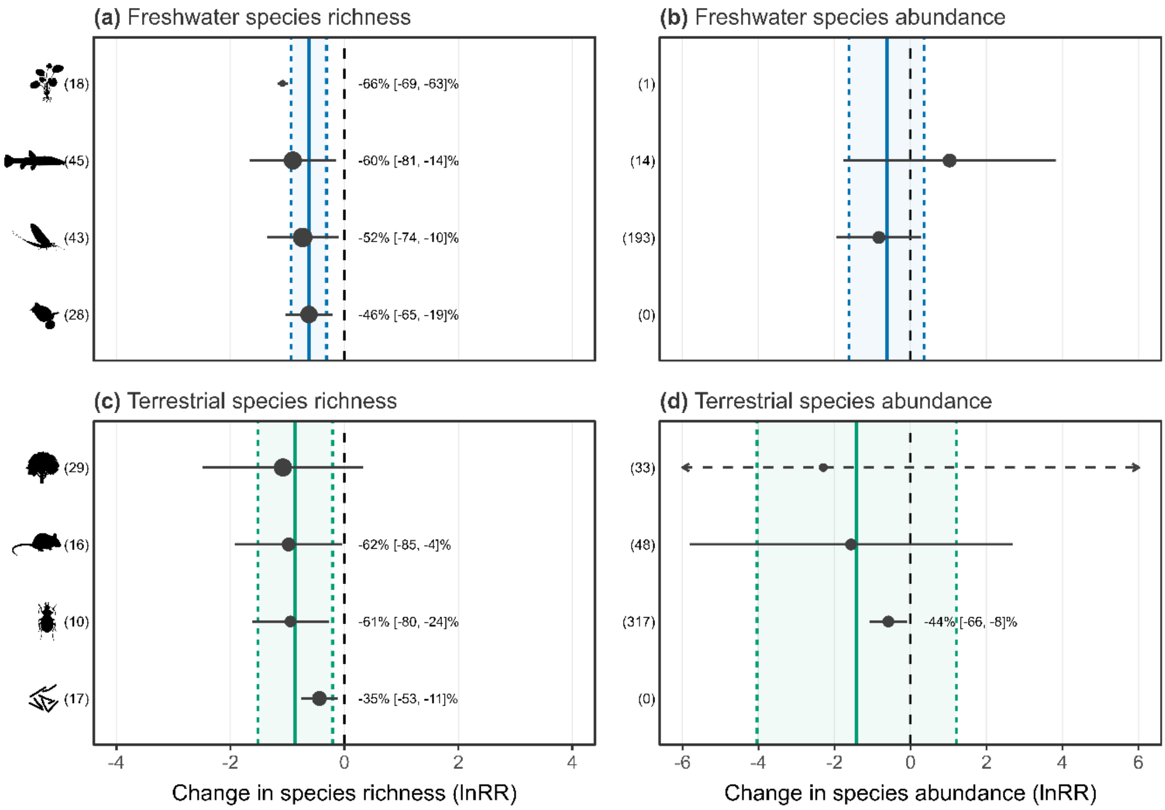

Fig. S3. *Effects of mining on biodiversity across realms and taxonomic groups after applying Geary's rule. Mean effect sizes (log response ratios, lnRR) and 95% confidence intervals (CIs) from multilevel random-effects meta-analyses are shown for (a) freshwater species richness, (b) freshwater species abundance, (c) terrestrial species richness, and (d) terrestrial species abundance. As a sensitivity check, models were refitted using only effect sizes for which both the mining-affected and control groups met Geary's rule. Models were fitted separately for each realm and for each taxonomic group. Circles show the estimated mean lnRR for each taxonomic group, with circle size proportional to number of studies; horizontal lines indicate 95% CIs. For estimates whose 95% CIs extend beyond the displayed axis range, dashed horizontal lines and arrows indicate that the CI continues beyond the plotting limits. Positive lnRR values indicate higher species richness or abundance at mining-affected sites relative to control sites, whereas negative values indicate declines. For taxonomic groups with statistically significant effects based on omnibus tests ($p < 0.05$), mean lnRR values and their 95% CIs are also shown as percentage changes. Coloured vertical lines indicate the overall mean effect size for each realm after applying Geary's rule, with dashed coloured lines and shaded areas representing the corresponding 95% CIs (blue: freshwater; green: terrestrial). Numbers in parentheses indicate the number of effect sizes retained in each model. In both realms, silhouettes represent taxonomic groups from top to bottom as plants, vertebrates, invertebrates, and microorganisms and algae, which were accessed from the public domain database PhyloPic using the R package rphylopic 1.5.0* [1]*.*

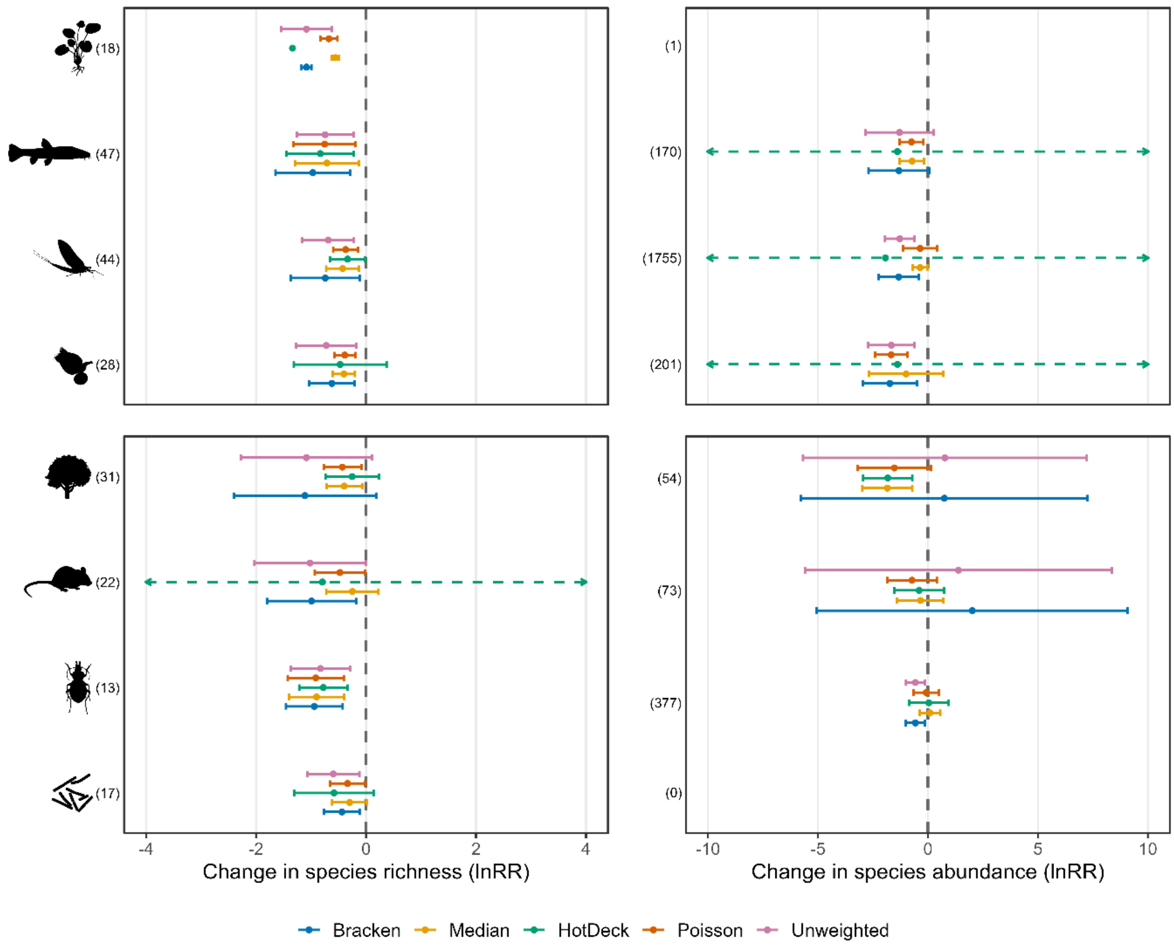

Fig. S4. *Sensitivity of estimated biodiversity responses to alternative standard deviation imputation methods and unweighted models. Mean effect sizes (log response ratios, lnRRs) and 95% confidence intervals (CIs) from multilevel random-effects meta-analyses are shown for species richness (left panels) and abundance (right panels) in freshwater (top panels) and terrestrial (bottom panels) ecosystems. Models were fitted separately for each taxonomic group–realm combination using the Bracken, median, HotDeck and Poisson methods to impute missing standard deviations, as well as without inverse-variance weighting. Points show the estimated mean lnRR for each model, with horizontal bars indicating 95% CIs. Positive lnRR values indicate higher species richness or abundance at mining-affected sites relative to control sites, whereas negative values indicate declines. Numbers in parentheses indicate the number of effect sizes included in each taxonomic group. In both realms, silhouettes represent taxonomic groups from top to bottom as plants, vertebrates, invertebrates, and microorganisms and algae, which were accessed from the public domain database PhyloPic using the R package rphylopic 1.5.0* [1]*. Some HotDeck 95% CIs extended beyond the displayed plotting range and are represented by dashed horizontal lines with arrows at the plot boundaries: terrestrial vertebrate species richness [−9.7, 8.1], freshwater vertebrate abundance [−831.0, 828.2], freshwater invertebrate abundance [−38.9, 35.0], and freshwater microorganisms and algae abundance [−35.5, 32.7].*

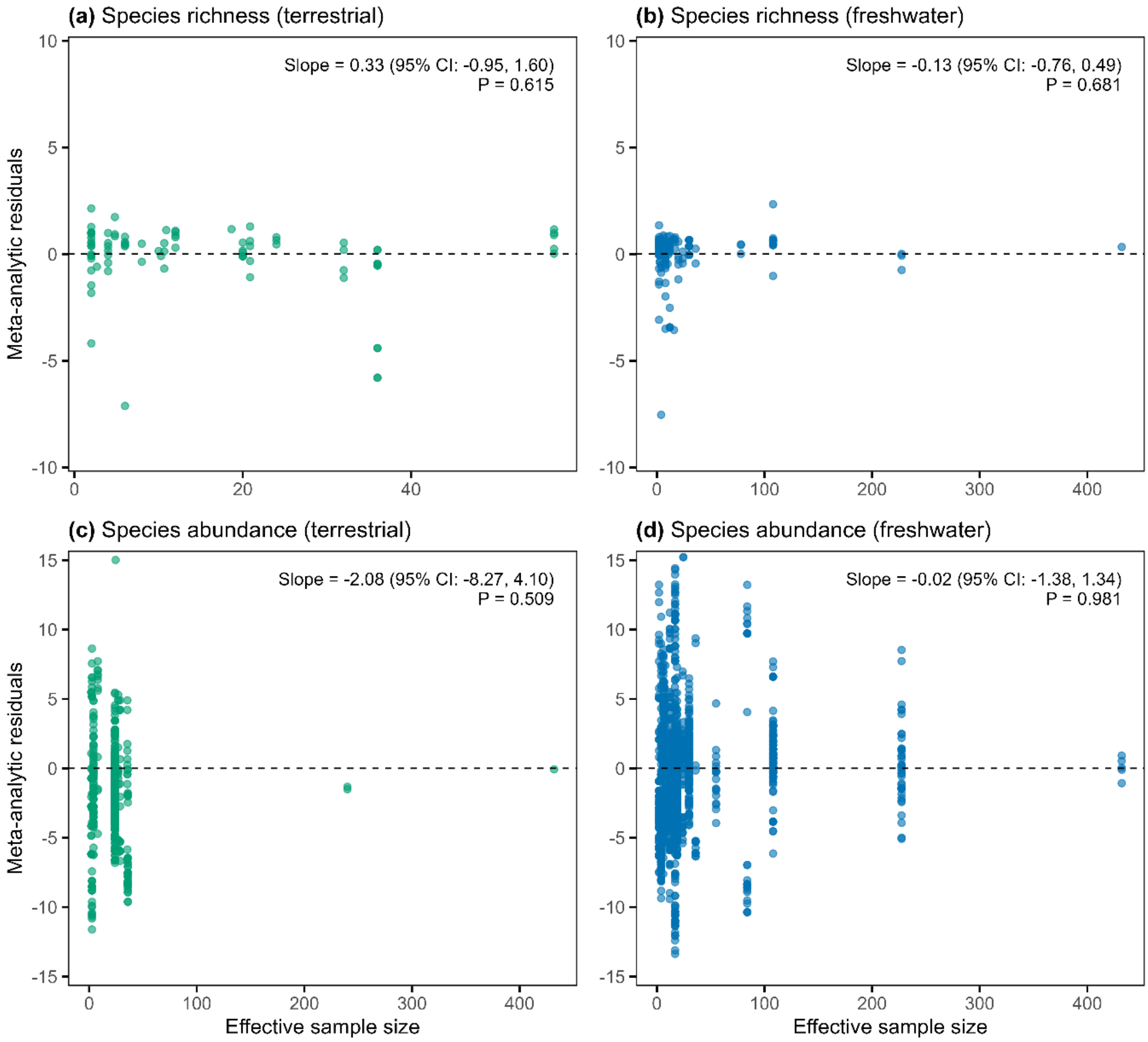

Fig. S5. *Assessment of publication bias in species richness and abundance responses to mining. Funnel plots show meta-analytic residuals against effective sample size for (a) terrestrial species richness, (b) freshwater species richness, (c) terrestrial species abundance and (d) freshwater species abundance. Panel annotations report the slope, 95% confidence interval and P value from the multilevel meta-regression test for funnel asymmetry (small-study effects) following Nakagawa et al.* [2].

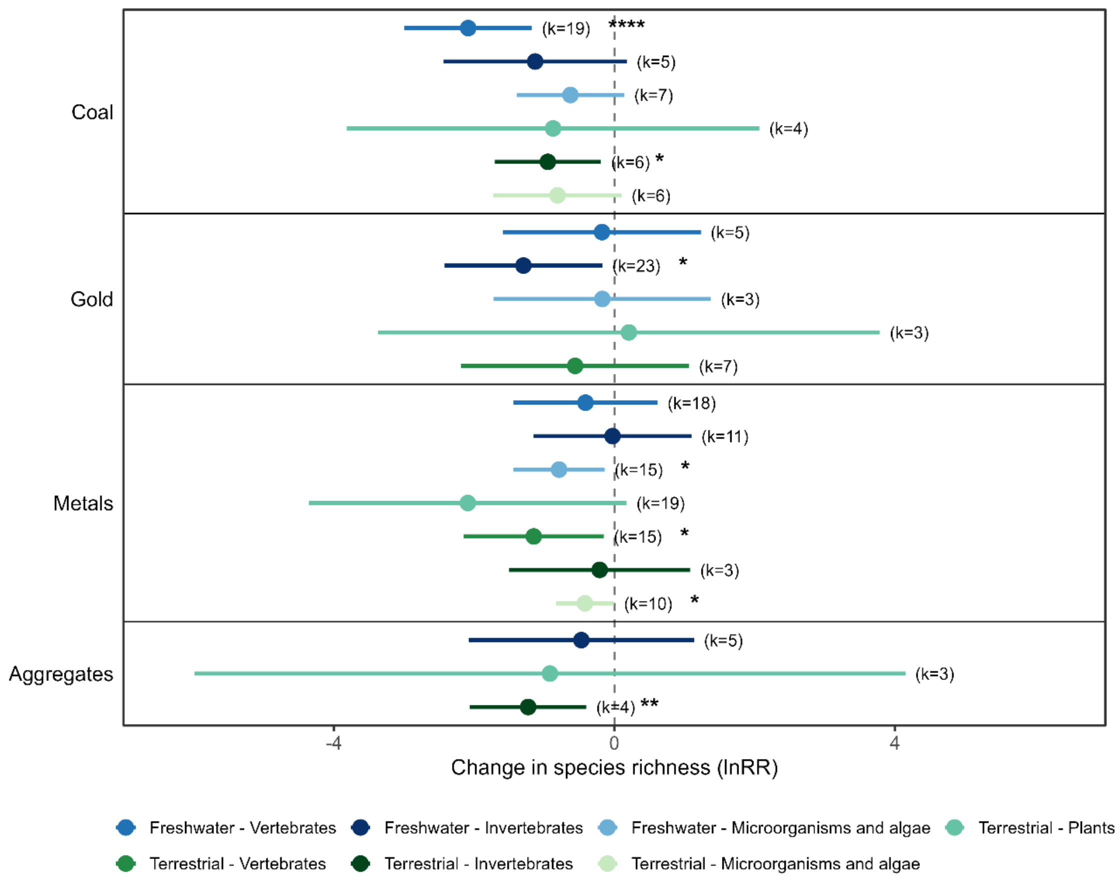

Fig. S6. *Variation in mining impacts on species richness across commodity groups. Effects on species richness were estimated using mixed-effects meta-regression models in which commodity group was included as a categorical fixed effect. Models were fitted separately for each taxonomic group within freshwater and terrestrial ecosystems. Points show the estimated mean log response ratio (lnRR) for each commodity group, comparing mining-affected sites with control sites, and horizontal bars indicate 95% confidence intervals. Positive lnRR values indicate greater species richness at mining-affected sites than at control sites, whereas negative values indicate declines. Numbers in parentheses indicate the number of effect sizes included in each model (k). Asterisks denote statistical significance: $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***), and $p < 0.0001$ (****).*

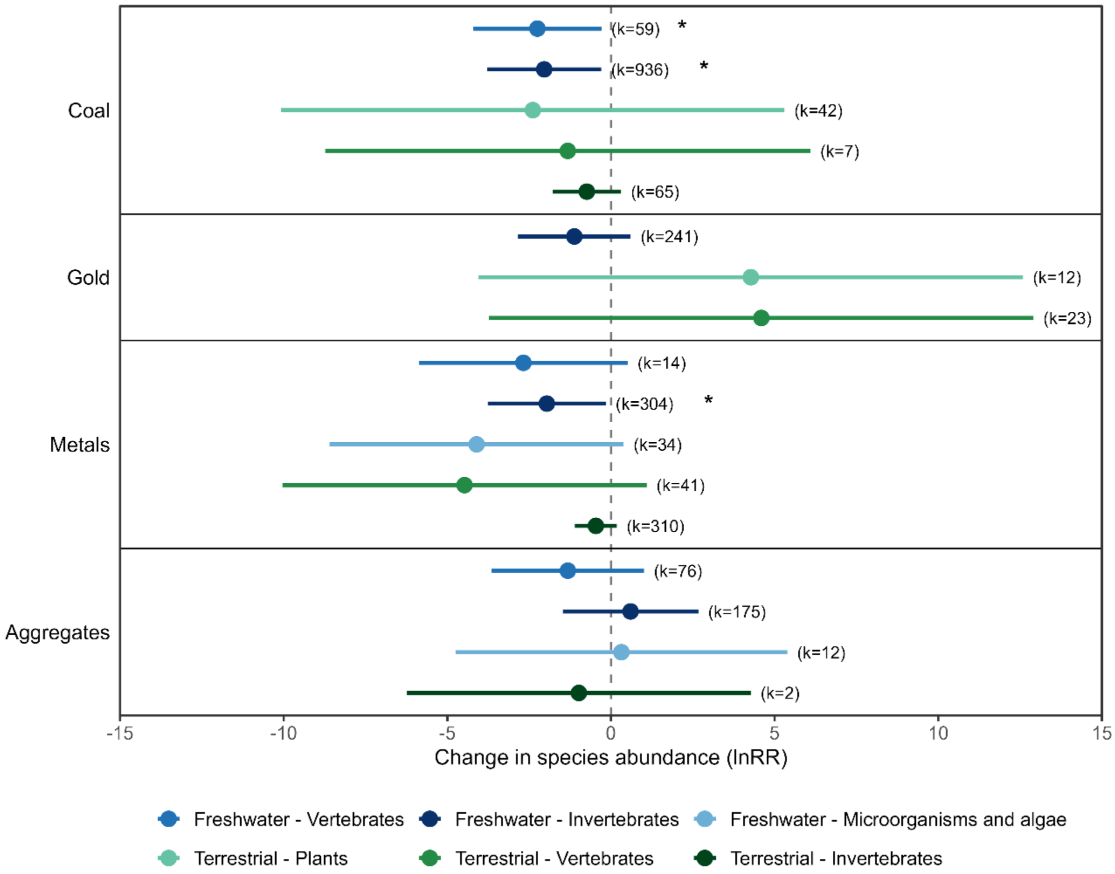

Fig. S7. *Variation in mining impacts on species abundance across commodity groups. Effects on species abundance were estimated using mixed-effects meta-regression models in which commodity group was included as a categorical fixed effect. Models were fitted separately for each taxonomic group within freshwater and terrestrial ecosystems. Points show the estimated mean log response ratio (lnRR) for each commodity group, comparing mining-affected sites with control sites, and horizontal bars indicate 95% confidence intervals. Positive lnRR values indicate greater species abundance at mining-affected sites than at control sites, whereas negative values indicate declines. Numbers in parentheses indicate the number of effect sizes included in each model (k). Asterisks denote statistical significance: p < 0.05 (*), p < 0.01 (**), and p < 0.001 (***).*

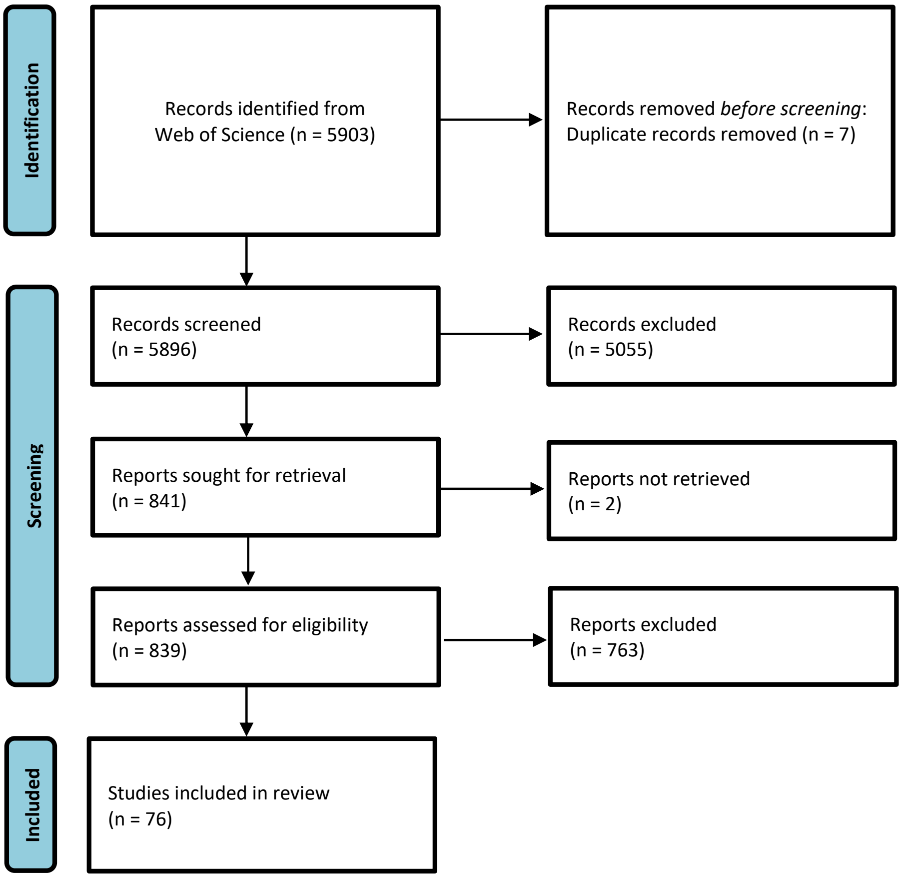

Fig. S8. *PRISMA flow diagram of the literature search, screening and study selection process.*

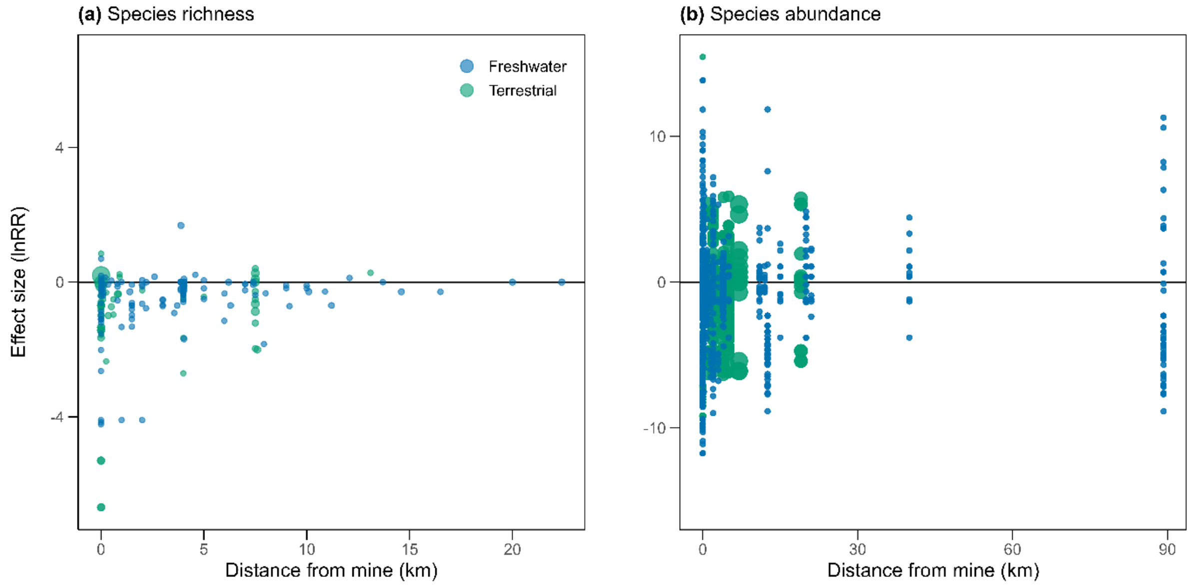

Fig. S9. *Species richness and abundance effect sizes across distances from mines. Individual log response ratios (lnRRs) for (a) species richness and (b) species abundance are plotted against the distance between the mining-affected sampling site and the associated mine. Point size is proportional to inverse sampling variance, with larger points representing more precise effect sizes. The horizontal black line indicates no change relative to control sites (lnRR = 0). Negative lnRR values indicate lower species richness or abundance at mining-affected sites, whereas positive values indicate higher values. Only effect sizes with available distance data are shown. The figure provides a descriptive representation of the data and does not show fitted meta-regression results.*

Supplementary Tables

Table S1. *Effects of mining on species richness across realms and taxonomic groups. Results are based on multilevel random-effects meta-analytic models fitted with inverse-variance weighting, using the Bracken (1992) method for imputation of missing standard deviations. Effect sizes are reported as log response ratios (lnRR) with 95% confidence intervals (CIs), where negative values indicate lower richness in mined sites relative to controls. Percentage change represents the back-transformed lnRR. N = number of effect sizes; N_studies = number of studies; N_mines = number of mines; N_sites = number of disturbed sites. The significance of the models was evaluated using omnibus tests (reported p-value).* Q_E *= Cochran's Q statistic;* Q_E*_p = associated p-value;* I^2 *(%) = proportion of total variance attributable to heterogeneity.*

Realm	Taxonomic group	N	N_studies	N_mines	N_sites	lnRR (95% CI)	% change (95% CI)	p-value	Q_E	Q_E_p	I^2(%)
Freshwater	All taxa	137	33	40	98	-0.66 (-0.96, -0.36)	-48.3 (-61.8, -30.0)	<0.001	16140	<0.001	93.1
	Invertebrates	44	13	14	31	-0.74 (-1.36, -0.12)	-52.4 (-74.4, -11.3)	0.019	8178	<0.001	97.8
	Plants	18	1	1	3	-1.08 (-1.17, -0.99)	-66.2 (-69.0, -63.0)	<0.001	1165	<0.001	0.0
	Vertebrates	47	13	16	45	-0.97 (-1.65, -0.29)	-62.1 (-80.7, -25.4)	0.005	1449	<0.001	95.9
	Microorganisms & algae	28	10	13	24	-0.62 (-1.04, -0.21)	-46.3 (-64.5, -18.7)	0.003	5091	<0.001	80.9
Terrestrial	All taxa	83	28	35	60	-0.89 (-1.48, -0.30)	-59.0 (-77.3, -26.1)	0.003	196934	<0.001	97.7
	Invertebrates	13	5	8	13	-0.94 (-1.46, -0.42)	-61.0 (-76.7, -34.6)	<0.001	1784	<0.001	0.0
	Plants	31	12	15	22	-1.11 (-2.41, 0.18)	-67.1 (-91.0, 20.1)	0.092	17861	<0.001	99.4
	Vertebrates	22	7	8	13	-0.99 (-1.80, -0.18)	-62.9 (-83.5, -16.6)	0.016	113758	<0.001	93.2
	Microorganisms & algae	17	7	7	17	-0.44 (-0.76, -0.12)	-35.5 (-53.3, -10.9)	0.008	3708	<0.001	93.1

Table S2. *Effects of mining on species abundance across realms and taxonomic groups. See Table S1 for definitions of terms and metrics.*

Realm	Taxonomic group	N	N_studies	N_mines	N_sites	lnRR (95% CI)	% change (95% CI)	p-value	Q_E	Q_E_p	I^2(%)
Freshwater	All taxa	2127	24	24	55	-1.38 (-2.18, -0.59)	-74.9 (-88.7, -44.5)	0.001	48968	<0.001	40.3
	Invertebrates	1755	16	16	44	-1.33 (-2.24, -0.42)	-73.6 (-89.4, -34.3)	0.004	38039	<0.001	63.2
	Plants	1	1	1	1	-	-	-	-	-	-
	Vertebrates	170	7	7	11	-1.32 (-2.70, 0.05)	-73.4 (-93.3, 5.4)	0.059	3568	<0.001	53.4
	Microorganisms & algae	201	3	3	5	-1.73 (-2.97, -0.50)	-82.4 (-94.8, -39.5)	0.006	7234	<0.001	0.6
Terrestrial	All taxa	504	11	13	24	0.43 (-2.30, 3.17)	54.3 (-90.0, 2270.4)	0.756	21432764	<0.001	98.4
	Invertebrates	377	4	5	10	-0.57 (-1.00, -0.14)	-43.5 (-63.4, -13.0)	0.010	1181556	<0.001	0.0
	Plants	54	2	2	2	0.75 (-5.77, 7.26)	111.2 (-99.7, 142548.3)	0.822	239172	<0.001	94.7
	Vertebrates	73	5	6	12	2.01 (-5.05, 9.08)	647.4 (-99.4, 874691.6)	0.577	2854041		98.9
	Microorganisms & algae	0	0	0	0	-	-	-	-	-	-

Table S3. *Comparison of species richness responses to mining between freshwater and terrestrial ecosystems. Results are from a mixed-effects meta-regression in which realm was included as a categorical fixed effect. ΔlnRR represents the estimated difference in mean log response ratio between freshwater and terrestrial ecosystems (freshwater − terrestrial). Positive values indicate a higher, or less negative, response in freshwater ecosystems. N = number of effect sizes; SE = standard error; z = test statistic;* Q_m *= omnibus moderator test statistic;* Q_m*_p = corresponding p-value.*

Comparison	N	ΔlnRR	SE	z	Q_M	Q_M_p
Freshwater **vs.** Terrestrial	220	0.177	0.286	0.620	0.385	0.535

Table S4. *Differences in species richness responses to mining among taxonomic groups within freshwater and terrestrial ecosystems. Results are from mixed-effects meta-regression models in which taxonomic group was included as a categorical fixed effect, fitted separately for each realm. ΔlnRR represents the estimated difference in mean log response ratio between the first and second taxonomic groups listed in each comparison. Negative values indicate a lower, or more negative, response in the first group. Pairwise p-values are shown before and after adjustment for multiple comparisons using the Holm method. The omnibus Q_M test evaluates whether mean lnRR differs among taxonomic groups within each realm. See Table S3 for the remaining metric definitions.*

Realm	Comparison	ΔlnRR	SE	z	p (pairwise)	p (Holm)	N	Q_M	Q_M_p
Freshwater	Invertebrates **vs.** Microorganisms & algae	-0.001	0.115	-0.011	0.991	1	137	49.4	<0.001
	Invertebrates **vs.** Plants	0.846	1.095	0.772	0.440	1			
	Invertebrates **vs.** Vertebrates	1.224	0.186	6.594	<0.001	<0.001			
	Microorganisms & algae **vs.** Plants	0.847	1.096	0.773	0.439	1			
	Microorganisms & algae **vs.** Vertebrates	1.225	0.182	6.724	<0.001	<0.001			
	Plants **vs.** Vertebrates	0.378	1.099	0.344	0.731	1			
Terrestrial	Invertebrates **vs.** Microorganisms & algae	0.069	0.819	0.085	0.933	1	83	205.5	<0.001
	Invertebrates **vs.** Plants	-0.255	0.818	-0.311	0.756	1			
	Invertebrates **vs.** Vertebrates	0.403	0.824	0.489	0.625	1			
	Microorganisms & algae **vs.** Plants	-0.324	0.024	-13.594	<0.001	<0.001			
	Microorganisms & algae **vs.** Vertebrates	0.334	0.146	2.294	0.022	0.088			
	Plants **vs.** Vertebrates	0.658	0.144	4.579	<0.001	<0.001			

Table S5. *Comparison of species abundance responses to mining between freshwater and terrestrial ecosystems. Results are from a mixed-effects meta-regression in which realm was included as a categorical fixed effect. ΔlnRR represents the estimated difference in mean log response ratio between freshwater and terrestrial ecosystems (freshwater − terrestrial). Positive values indicate a higher, or less negative, response in freshwater ecosystems. See Table S3 for the remaining metric definitions.*

Comparison	N	ΔlnRR	SE	z	Q_M	Q_M_p
Freshwater **vs.** Terrestrial	2631	-2.310	2.266	-1.02	0.959	0.327

Table S6. *Differences in species abundance responses to mining among taxonomic groups within freshwater and terrestrial ecosystems. Results are from mixed-effects meta-regression models in which taxonomic group was included as a categorical fixed effect, with models fitted separately for each realm. The omnibus* Q_M *test evaluates whether mean lnRR differs among taxonomic groups within each realm. Because neither omnibus test was statistically significant, pairwise comparisons among taxonomic groups were not conducted. See Table S3 for the remaining metric definitions.*

Realm	N	Q_M	Q_M_p
Freshwater	2127	0.024	0.999
Terrestrial	504	0.270	0.874

Table S7. *Effects of mining on species richness across realms and taxonomic groups after exclusion of outliers. Outliers were identified following Harrer et al. [3]. See Table S1 for definitions of terms and metrics.*

Realm	Taxonomic group	N	N_studies	N_mines	N_sites	lnRR (95% CI)	% change (95% CI)	p-value	Q_E	Q_E_p	I^2(%)
Freshwater	All taxa	84	29	34	68	-0.52 (-0.63, -0.40)	-40.3 (-46.8, -33.0)	<0.001	612	<0.001	44.4
	Invertebrates	31	12	13	26	-0.40 (-0.62, -0.19)	-33.3 (-46.0, -17.5)	<0.001	1792	<0.001	0.0
	Plants	6	1	1	2	-1.07 (-1.19, -0.95)	-65.8 (-69.7, -61.4)	<0.001	9	0.102	0.0
	Vertebrates	36	11	14	35	-0.53 (-0.77, -0.28)	-40.9 (-53.8, -24.5)	<0.001	331	<0.001	54.8
	Microorganisms & algae	20	10	12	17	-0.40 (-0.55, -0.26)	-33.3 (-42.1, -23.1)	<0.001	191	<0.001	40.6
Terrestrial	All taxa	55	21	26	45	-0.65 (-0.80, -0.50)	-47.8 (-55.1, -39.3)	<0.001	3524	<0.001	54.8
	Invertebrates	7	4	6	7	-0.59 (-0.78, -0.40)	-44.5 (-54.2, -32.7)	<0.001	9	0.150	7.0
	Plants	27	11	14	21	-0.50 (-0.86, -0.14)	-39.5 (-57.9, -13.0)	0.007	4094	<0.001	90.9
	Vertebrates	15	6	6	10	-0.76 (-1.11, -0.40)	-53.2 (-67.2, -33.2)	<0.001	1040	<0.001	40.5
	Microorganisms & algae	11	7	7	11	-0.37 (-0.58, -0.16)	-31.0 (-44.1, -14.8)	0.001	786	<0.001	83.7

Table S8. *Effects of mining on species abundance across realms and taxonomic groups after exclusion of outliers. Outliers were identified following Harrer et al.* [3]. *See Table S1 for definitions of terms and metrics.*

Realm	Taxonomic group	N	N_studies	N_mines	N_sites	lnRR (95% CI)	% change (95% CI)	p-value	Q_E	Q_E_p	I^2(%)
Freshwater	All taxa	1302	23	23	54	-1.32 (-1.56, -1.07)	-73.2 (-79.0, -65.6)	<0.001	2706	<0.001	6.3
	Invertebrates	1130	15	15	43	-1.33 (-1.66, -1.01)	-73.7 (-80.9, -63.7)	<0.001	2529	<0.001	10.3
	Plants	1	1	1	1	-	-	-	-	-	-
	Vertebrates	121	7	7	11	-1.03 (-1.65, -0.40)	-64.2 (-80.9, -32.9)	0.001	464	<0.001	21.9
	Microorganisms & algae	93	3	3	5	-1.13 (-2.55, 0.29)	-67.7 (-92.2, 34.1)	0.120	230	<0.001	1.9
Terrestrial	All taxa	308	10	12	23	-0.61 (-1.31, 0.09)	-45.9 (-73.1, 8.9)	0.085	271169	<0.001	0.0
	Invertebrates	92	4	5	10	-0.59 (-0.68, -0.50)	-44.5 (-49.1, -39.4)	<0.001	2193	<0.001	0.0
	Plants	30	2	2	2	3.87 (2.42, 5.31)	4672.5 (1027.1, 20109.0)	<0.001	39033	<0.001	0.0
	Vertebrates	43	4	5	11	0.49 (-2.29, 3.26)	62.5 (-89.8, 2496.6)	0.731	2412828	<0.001	69.3
	Microorganisms & algae	0	0	0	0	-	-	-	-	-	-

Table S9. *Effects of mining on species richness across realms and taxonomic groups after applying Geary's rule to exclude small sample means* [4]. *See Table S1 for definitions of terms and metrics.*

Realm	Taxonomic group	N	N_studies	N_mines	N_sites	lnRR (95% CI)	% change (95% CI)	p-value	Q_E	Q_E_p	I^2(%)
Freshwater	All taxa	134	31	38	95	-0.62 (-0.93, -0.31)	-46.4 (-60.7, -26.9)	<0.001	16125	<0.001	94.5
	Invertebrates	43	13	14	30	-0.73 (-1.36, -0.11)	-51.9 (-74.3, -10.0)	0.022	8172	<0.001	98.4
	Plants	18	1	1	3	-1.08 (-1.17, -0.99)	-66.2 (-69.0, -63.0)	<0.001	1165	<0.001	0.0
	Vertebrates	45	11	14	43	-0.90 (-1.66, -0.15)	-59.5 (-81.1, -13.5)	0.020	1438	<0.001	97.2
	Microorganisms & algae	28	10	13	24	-0.62 (-1.04, -0.21)	-46.3 (-64.5, -18.7)	0.003	5091	<0.001	80.9
Terrestrial	All taxa	72	25	30	50	-0.86 (-1.52, -0.21)	-57.8 (-78.1, -18.6)	0.010	193069	<0.001	99.5
	Invertebrates	10	4	5	10	-0.95 (-1.62, -0.27)	-61.2 (-80.2, -24.0)	0.006	1783	<0.001	0.0
	Plants	29	11	14	20	-1.08 (-2.49, 0.33)	-66.0 (-91.7, 39.5)	0.134	17856	<0.001	99.8
	Vertebrates	16	6	7	8	-0.98 (-1.92, -0.04)	-62.4 (-85.3, -3.7)	0.042	109851	<0.001	99.0
	Microorganisms & algae	17	7	7	17	-0.44 (-0.76, -0.12)	-35.5 (-53.3, -10.9)	0.008	3708	<0.001	93.1

Table S10. *Effects of mining on species abundance across realms and taxonomic groups after applying Geary's rule to exclude small sample means* [4]. *See Table S1 for definitions of terms and metrics.*

Realm	Taxonomic group	N	N_studies	N_mines	N_sites	lnRR (95% CI)	% change (95% CI)	p-value	Q_E	Q_E_p	I^2(%)
Freshwater	All taxa	208	12	12	13	-0.63 (-1.62, 0.37)	-46.6 (-80.2, 44.1)	0.216	26807	<0.001	67.8
	Invertebrates	193	5	5	6	-0.83 (-1.94, 0.28)	-56.5 (-85.7, 32.0)	0.142	25631	<0.001	78.0
	Plants	1	1	1	1	-	-	-	-	-	-
	Vertebrates	14	6	6	6	1.03 (-1.77, 3.83)	180.0 (-82.9, 4494.5)	0.471	1170	<0.001	98.4
	Microorganisms & algae	0	0	0	0	-	-	-	-	-	-
Terrestrial	All taxa	398	10	12	21	-1.42 (-4.04, 1.21)	-75.7 (-98.2, 235.8)	0.291	1482554	<0.001	100.0
	Invertebrates	317	4	5	10	-0.58 (-1.08, -0.08)	-44.1 (-66.2, -7.7)	0.023	1180616	<0.001	19.1
	Plants	33	2	2	2	-2.30 (-15.15, 10.56)	-89.9 (-100.0, 3856447.9)	0.726	237653	<0.001	100.0
	Vertebrates	48	4	5	9	-1.57 (-5.82, 2.69)	-79.1 (-99.7, 1372.0)	0.471	62202	<0.001	99.8
	Microorganisms & algae	0	0	0	0	-	-	-	-	-	-

Table S11. *Variation in species richness responses to mining among commodity groups across realms and taxonomic groups. Results are from mixed-effects meta-regression models in which commodity group was included as a categorical fixed effect. Separate models were fitted for each realm and for each taxonomic group–realm combination. The omnibus tests assessed whether mean lnRR differed among commodity groups within each model. Models were additionally fitted without an intercept to estimate the mean log response ratio (lnRR) and 95% confidence interval (CI) for each commodity group, with percentage changes back-transformed from lnRR. N = number of effect sizes; Q_M = omnibus test; Q_{M}_p = associated p-value; Q_E = Cochran's Q statistic for residual heterogeneity; Q_E_p = associated p-value.*

Realm	Taxonomic group	Commodity group	N	lnRR (95% CI)	% change (95% CI)	p-value	Q_M	Q_M_p	Q_E	Q_E_p
Freshwater	All taxa	Aggregates	5	-0.48 (-1.78, 0.82)	-38.0 (-83.1, 127.0)	0.470	2.73	0.436	15276	<0.001
		Coal	31	-1.10 (-1.74, -0.47)	-66.9 (-82.5, -37.4)	0.001				
		Gold	31	-0.83 (-1.52, -0.14)	-56.3 (-78.0, -12.9)	0.019				
		Metals	62	-0.45 (-0.95, 0.05)	-36.4 (-61.5, 5.0)	0.077				
	Invertebrates	Aggregates	5	-0.47 (-2.08, 1.14)	-37.6 (-87.5, 211.2)	0.565	2.93	0.402	6470	<0.001
		Coal	5	-1.13 (-2.44, 0.18)	-67.7 (-91.3, 19.2)	0.090				
		Gold	23	-1.30 (-2.42, -0.17)	-72.7 (-91.1, -16.0)	0.024				
		Metals	11	-0.03 (-1.15, 1.10)	-2.7 (-68.4, 200.0)	0.962				
	Vertebrates	Aggregates	0	-	-	-	7.87	0.020	1168	<0.001
		Coal	19	-2.09 (-3.00, -1.18)	-87.6 (-95.0, -69.2)	<0.001				
		Gold	5	-0.18 (-1.59, 1.23)	-16.3 (-79.6, 242.8)	0.805				
		Metals	18	-0.41 (-1.44, 0.62)	-33.8 (-76.4, 85.1)	0.431				
	Microorganisms & algae	Aggregates	0	-	-	-	0.54	0.765	4616	<0.001
		Coal	7	-0.63 (-1.40, 0.14)	-46.6 (-75.2, 15.1)	0.109				
		Gold	3	-0.17 (-1.72, 1.38)	-15.9 (-82.1, 296.1)	0.827				
		Metals	15	-0.79 (-1.44, -0.14)	-54.6 (-76.3, -13.0)	0.017				
Terrestrial	All taxa	Aggregates	8	-0.91 (-2.54, 0.71)	-59.8 (-92.1, 104.2)	0.272	1.23	0.745	196112	<0.001
		Coal	16	-0.84 (-2.17, 0.49)	-56.8 (-88.6, 63.7)	0.217				
		Gold	10	-0.17 (-1.81, 1.46)	-15.8 (-83.6, 332.2)	0.837				
		Metals	47	-1.22 (-2.11, -0.32)	-70.3 (-87.9, -27.2)	0.008				
	Invertebrates	Aggregates	4	-1.23 (-2.06, -0.40)	-70.8 (-87.3, -33.1)	0.004	1.70	0.428	1561	<0.001
		Coal	6	-0.95 (-1.71, -0.19)	-61.3 (-81.9, -17.4)	0.014				
		Gold	0	-	-	-				
		Metals	3	-0.21 (-1.50, 1.08)	-19.0 (-77.8, 194.7)	0.749				
	Plants	Aggregates	3	-0.92 (-5.99, 4.15)	-60.2 (-99.7, 6240.6)	0.722	1.24	0.744	17729	<0.001
		Coal	4	-0.87 (-3.82, 2.07)	-58.3 (-97.8, 689.7)	0.560				
		Gold	3	0.21 (-3.37, 3.78)	22.9 (-96.6, 4301.7)	0.910				
		Metals	19	-2.09 (-4.35, 0.17)	-87.6 (-98.7, 18.8)	0.070				
	Vertebrates	Aggregates	0	-	-	-	0.37	0.545	113636	<0.001
		Coal	0	-	-	-				
		Gold	7	-0.56 (-2.19, 1.07)	-42.9 (-88.8, 190.1)	0.499				
		Metals	15	-1.15 (-2.15, -0.15)	-68.4 (-88.3, -14.1)	0.024				
	Microorganisms & algae	Aggregates	1	-	-	-	1.07	0.587	3145	<0.001
		Coal	6	-0.81 (-1.73, 0.11)	-55.6 (-82.3, 11.1)	0.083				
		Gold	0	-	-	-				
		Metals	10	-0.42 (-0.84, -0.01)	-34.4 (-56.7, -0.6)	0.047				

Table S12. *Pairwise comparisons of species richness responses to mining among commodity groups. Comparisons were derived from the mixed-effects meta-regression model in which commodity group was included as a categorical fixed effect. Pairwise comparisons were conducted only for models in which the omnibus test indicated differences among commodity groups (freshwater vertebrates in this case). ΔlnRR represents the estimated difference in mean log response ratio between the first and second commodity groups listed in each comparison. Negative values indicate a lower, or more negative, response for the first commodity group. Pairwise p-values are shown before and after adjustment for multiple comparisons using the Holm method. SE = standard error; z = test statistic.*

	Comparison	**ΔlnRR**	**SE**	**z**	**p (pairwise)**	**p (Holm)**
Freshwater vertebrates	Coal **vs.** Gold	-1.908	0.856	-2.229	0.026	0.052
	Coal **vs.** Metals	-1.673	0.701	-2.388	0.017	0.051
	Gold **vs.** Metals	0.235	0.890	0.264	0.792	0.792

***Table S13**. Variation in species abundance responses to mining among commodity groups across realms and taxonomic groups. See Table S11 for definitions of terms and metrics.*

Realm	Taxonomic group	Commodity group	N	lnRR (95% CI)	% change (95% CI)	p-value	Q_M	Q_M_p	Q_E	Q_E_p
Freshwater	All taxa	Aggregates	263	0.11 (-1.52, 1.74)	11.9 (-78.1, 470.6)	0.893	5.19	0.159	39294	<0.001
		Coal	995	-2.05 (-3.40, -0.69)	-87.1 (-96.7, -50.0)	0.003				
		Gold	241	-1.13 (-2.71, 0.45)	-67.6 (-93.3, 57.1)	0.162				
		Metals	353	-2.05 (-3.51, -0.58)	-87.1 (-97.0, -44.0)	0.006				
	Invertebrates	Aggregates	175	0.60 (-1.47, 2.67)	82.1 (-77.1, 1345.3)	0.571	4.54	0.209	35800	<0.001
		Coal	936	-2.04 (-3.78, -0.30)	-87.0 (-97.7, -25.8)	0.022				
		Gold	241	-1.12 (-2.84, 0.60)	-67.3 (-94.2, 82.5)	0.202				
		Metals	304	-1.96 (-3.76, -0.15)	-85.9 (-97.7, -14.3)	0.033				
	Vertebrates	Aggregates	76	-1.32 (-3.65, 1.01)	-73.2 (-97.4, 174.5)	0.267	0.60	0.741	2868	<0.001
		Coal	59	-2.25 (-4.21, -0.29)	-89.4 (-98.5, -25.3)	0.024				
		Gold	0	-	-	-				
		Metals	14	-2.68 (-5.87, 0.51)	-93.1 (-99.7, 67.2)	0.100				
	Microorganisms & algae	Aggregates	12	0.32 (-4.75, 5.39)	37.5 (-99.1, 21776.5)	0.902	1.64	0.201	295	<0.001
		Coal	0	-	-	-				
		Gold	0	-	-	-				
		Metals	34	-4.11 (-8.60, 0.39)	-98.4 (-100.0, 47.8)	0.073				
Terrestrial	All taxa	Aggregates	2	-0.98 (-10.12, 8.15)	-62.5 (-100.0, 347842.1)	0.833	127 0.71	<0.001	2048372	<0.001
		Coal	114	-0.93 (-2.91, 1.04)	-60.7 (-94.5, 182.5)	0.354				
		Gold	35	4.37 (0.55, 8.20)	7839.2 (72.7, 364832.4)	0.025				
		Metals	351	-2.66 (-4.63, -0.69)	-93.0 (-99.0, -49.6)	0.008				
	Invertebrates	Aggregates	2	-0.98 (-6.23, 4.27)	-62.5 (-99.8, 7055.0)	0.714	0.22	0.895	1181413	<0.001
		Coal	65	-0.74 (-1.79, 0.31)	-52.2 (-83.2, 36.2)	0.167				
		Gold	0	-	-	-				
		Metals	310	-0.46 (-1.10, 0.18)	-37.0 (-66.8, 19.6)	0.158				
	Plants	Aggregates	0	-	-	-	1.29	0.255	59395	<0.001
		Coal	42	-2.39 (-10.08, 5.30)	-90.8 (-100.0, 19989.4)	0.543				
		Gold	12	4.27 (-4.04, 12.59)	7080.0 (-98.2, 29381933.8)	0.314				
		Metals	0	-	-	-				
	Vertebrates	Aggregates	0	-	-	-	3.41	0.181	79839	<0.001
		Coal	7	-1.32 (-8.73, 6.09)	-73.3 (-100.0, 44111.8)	0.727				
		Gold	23	4.59 (-3.72, 12.91)	9797.5 (-97.6, 40529291.4)	0.279				
		Metals	41	-4.47 (-10.04, 1.09)	-98.9 (-100.0, 197.7)	0.115				

Table S14. *Pairwise comparisons of species abundance responses to mining among commodity groups. Comparisons were conducted only for models in which the omnibus test indicated differences among commodity groups (terrestrial taxa in this case). See Table S12 for definitions of terms and metrics.*

	Comparison	**ΔlnRR**	**SE**	**z**	**p (pairwise)**	**p (Holm)**
Terrestrial taxa	Aggregates **vs.** Coal	-0.048	4.768	-0.01	0.992	1
	Aggregates **vs.** Gold	-5.356	5.054	-1.06	0.289	0.867
	Aggregates **vs.** Metals	1.676	4.768	0.352	0.725	1
	Coal **vs.** Gold	-5.308	2.197	-2.416	0.016	0.064
	Coal **vs.** Metals	1.724	0.049	35.53	<0.001	<0.001
	Gold **vs.** Metals	7.032	2.197	3.201	0.001	0.005

***Table S15**. Variation in freshwater insect abundance responses to mining among biological trait levels. Results are from separate mixed-effects meta-regression models in which each trait was included as a categorical fixed effect. The omnibus tests assessed whether mean lnRR differed among the levels of each trait. Models were additionally fitted without an intercept to estimate the mean log response ratio (lnRR) and 95% confidence interval (CI) for each trait level, with percentage changes back-transformed from lnRR. Q_M = omnibus test for differences among trait levels; Q_M_p = associated p-value. Q_E = Cochran's Q statistic for residual heterogeneity; Q_E_p = associated p-value. The definitions of trait abbreviations and levels are provided in Table S17.*

Trait abbreviation	Trait level	N	lnRR (95% CI)	% change (95% CI)	p-value	Q_M	Q_M_p	Q_E	Q_E_p
Disp	1	785	-2.00 (-3.41, -0.59)	-86.5 (-96.7, -44.8)	0.005	9.19	0.002	27825	<0.001
	2	250	-0.08 (-1.67, 1.51)	-7.7 (-81.2, 353.4)	0.922				
Exit	1	938	-1.92 (-3.31, -0.52)	-85.3 (-96.3, -40.6)	0.007	13.34	<0.001	28514	<0.001
	2	97	0.93 (-0.91, 2.78)	153.8 (-59.9, 1506.1)	0.323				
Drft	1	589	-1.57 (-3.05, -0.09)	-79.1 (-95.2, -8.2)	0.038	8.51	0.014	28815	<0.001
	2	345	-2.04 (-3.65, -0.43)	-87.0 (-97.4, -35.0)	0.013				
	3	101	0.87 (-1.21, 2.95)	138.1 (-70.3, 1808.5)	0.414				

Table S16*. Pairwise comparisons of freshwater insect abundance responses to mining among biological trait levels. ΔlnRR represents the estimated difference in mean log response ratio between the first and second trait levels listed in each comparison. Negative values indicate a lower, or more negative, response for the first trait level. Pairwise p-values are shown before and after adjustment for multiple comparisons using the Holm method. SE = standard error; z = test statistic. More detailed definitions of levels are provided in Table S17.*

Trait	Comparison (trait levels)	ΔlnRR	SE	z	p (pairwise)	p (Holm)
Female dispersal (Disp)	1 (low) **vs.** 2 (high)	-1.924	0.635	-3.031	0.002	0.002
Adult ability to exit water (Exit)	1 (absent) **vs.** 2 (present)	-2.847	0.780	-3.652	<0.001	<0.001
Occurrence in drift (Drft)	1 (rare) **vs**. 2 (common)	0.475	0.647	0.734	0.463	0.463
	1 (rare) **vs.** 3 (abundant)	-2.433	0.951	-2.557	0.011	0.022
	2 (common) **vs.** 3 (abundant)	-2.907	1.011	-2.876	0.004	0.012

Table S17. *Biological traits, trait levels and associated hypotheses used in the analysis of freshwater insect abundance responses to mining. Trait definitions and classifications were based on Poff et al.* [5]. *For each trait, the table describes the rationale for its inclusion and the expected variation in abundance responses among trait levels.*

Trait	Levels	Reason for inclusion
Female dispersal (Disp)	1) Low (<1 km flight before laying eggs) 2) High (>1 km flight before laying eggs)	Female flight distance before oviposition constrains the spatial scale over which taxa can move both away from disturbed reaches and into them from unaffected source populations [6,7]. Greater dispersal capacity may therefore buffer local abundance declines by facilitating escape from unsuitable conditions and immigration into mining-impacted sites. Low-dispersal taxa are therefore expected to show stronger abundance declines.
Adult ability to exit water (Exit)	1) Absent (not including emergence) 2) Present	Aquatic adults capable of leaving the water outside emergence may temporarily avoid localised episodes of poor water quality or contaminated habitat [8]. Taxa lacking this ability remain continuously exposed while in the aquatic adult stage and are therefore expected to show stronger abundance declines at mining-impacted sites.
Occurrence in drift (Drft)	1) rare (catastrophic only) 2) common (typically observed) 3) abundant (dominant in drift samples)	Drift facilitates downstream dispersal and redistribution among stream habitats [9]. Taxa abundant in drift are therefore expected to show weaker abundance declines at mining-impacted sites because frequent movement and replenishment from upstream sources can partially offset local losses.

Table S18. *Comparison of alternative random-effects structures for species abundance models in freshwater and terrestrial ecosystems. Candidate structures included random intercepts for mines nested within studies, with or without an additional random intercept for species or genus. Models were compared separately for each realm using the corrected Akaike information criterion (AICc), Akaike information criterion (AIC) and Bayesian information criterion (BIC). The structure highlighted in bold showed the best model fit for both realms and was retained for the species abundance analyses.*

Realm	Random effects	AICc	AIC	BIC
Freshwater	**(1 | Study/Mine) + (1 | Species)**	20703	20703	20726
	(1 | Study/Mine) + (1 | Genus)	26037	26037	26060
	(1 | Study/Mine)	47859	47859	47876
Terrestrial	**(1 | Study/Mine) + (1 | Species)**	326620	326620	326637
	(1 | Study/Mine) + (1 | Genus)	745636	745636	745653
	(1 | Study/Mine)	1285495	1285495	1285508

***Table S19**. Linear relationships between species richness responses to mining and distance from mining disturbance across realms and taxonomic groups. Results are from mixed-effects meta-regression models in which log-transformed distance, log(distance+1), was included as a continuous fixed effect. Models were fitted separately for each realm and for each taxonomic group within each realm. The intercept represents the estimated mean log response ratio (lnRR) at the mining disturbance (distance = 0 km), and the coefficient for log(distance+1) represents the change in lnRR with increasing distance. Positive coefficients indicate that responses become less negative or more positive with distance, whereas negative coefficients indicate increasingly negative responses. N = number of effect sizes; CI = confidence interval; Q_M = omnibus test of the distance moderator; QM_p = associated p-value.*

Realm	Taxonomic group	N	Intercept (95% CI)	log(dist+1) (95% CI)	p-value	Q_M	Q_M_p
Freshwater	All taxa	111	-1.39 (-1.71, -1.08)	0.18 (0.17, 0.19)	<0.001	1906.69	<0.001
	Invertebrates	36	-0.35 (-0.59, -0.11)	0.02 (0.00, 0.03)	0.022	5.24	0.022
	Plants	18	-2.03 (-2.14, -1.92)	0.18 (0.17, 0.20)	<0.001	655.48	<0.001
	Vertebrates	41	-0.86 (-1.25, -0.47)	0.13 (0.10, 0.15)	<0.001	119.64	<0.001
	Microorganisms & algae	16	-3.76 (-4.77, -2.76)	0.43 (0.41, 0.45)	<0.001	2468.61	<0.001
Terrestrial	All taxa	60	-0.57 (-0.96, -0.19)	0.01 (0.00, 0.01)	<0.001	20.25	<0.001
	Invertebrates	12	-0.77 (-1.31, -0.23)	-0.01 (-0.01, -0.00)	0.001	10.69	0.001
	Plants	17	-2.10 (-3.72, -0.49)	0.35 (0.29, 0.40)	<0.001	136.13	<0.001
	Vertebrates	15	-1.29 (-3.14, 0.55)	0.22 (-0.32, 0.76)	0.429	0.62	0.429
	Microorganisms & algae	16	-0.61 (-1.06, -0.16)	0.04 (0.03, 0.04)	<0.001	123.05	<0.001

Table S20. *Quadratic relationships between species richness responses to mining and distance from mining disturbance across realms and taxonomic groups. Results are from mixed-effects meta-regression models in which linear and quadratic terms for log-transformed distance, log(distance+1) and log(distance+1)^2, were included as continuous fixed effects. Models were fitted separately for each realm and for each taxonomic group within each realm. The intercept represents the estimated mean log response ratio (lnRR) at the mining disturbance (distance = 0 km). The linear and quadratic coefficients describe the shape of the relationship between lnRR and distance. The p-values for the linear and quadratic terms test whether each coefficient differs from zero while accounting for the other term, whereas the omnibus Q_M test assesses whether the two distance terms jointly explain variation in lnRR. For terrestrial vertebrates, the quadratic term could not be estimated because the available observations contained too few distinct distance values, therefore only the linear coefficient is reported. See Table S19 for definitions of the remaining terms and metrics.*

Realm	Taxonomic group	N	Intercept (95% CI)	log(dist+1) (95% CI)	p (linear term)	log(dist+1)^2 (95% CI)	p (quadratic term)	Q_M	Q_M_p
Freshwater	All taxa	111	-1.38 (-1.70, -1.06)	0.16 (0.14, 0.18)	<0.001	0.00 (-0.00, 0.00)	0.092	1909.63	<0.001
	Invertebrates	36	-0.39 (-0.63, -0.16)	0.17 (0.12, 0.23)	<0.001	-0.02 (-0.03, -0.01)	<0.001	39.22	<0.001
	Plants	18	-2.01 (-2.13, -1.90)	-0.12 (-0.26, 0.01)	0.071	0.04 (0.02, 0.06)	<0.001	675.88	<0.001
	Vertebrates	41	-0.22 (-0.52, 0.08)	-0.16 (-0.24, -0.08)	<0.001	0.02 (0.01, 0.02)	<0.001	158.52	<0.001
	Microorganisms & algae	16	-3.38 (-5.03, -1.74)	-0.26 (-0.36, -0.16)	<0.001	0.09 (0.07, 0.10)	<0.001	2646.54	<0.001
Terrestrial	All taxa	60	-0.57 (-0.96, -0.18)	0.12 (0.10, 0.14)	<0.001	-0.01 (-0.02, -0.01)	<0.001	158.45	<0.001
	Invertebrates	12	-0.89 (-1.37, -0.40)	0.31 (0.28, 0.35)	<0.001	-0.04 (-0.04, -0.04)	<0.001	361.03	<0.001
	Plants	17	-17.64 (-32.04, -3.25)	8.32 (6.86, 9.79)	<0.001	-0.57 (-0.67, -0.46)	<0.001	253.73	<0.001
	Vertebrates	15	-1.29 (-3.14, 0.55)	-	-	-	-	0.62	0.429
	Microorganisms & algae	16	-0.63 (-1.09, -0.16)	-0.00 (-0.03, 0.03)	0.944	0.01 (0.00, 0.01)	0.007	130.47	<0.001

Table S21. *Linear relationships between species abundance responses to mining and distance from mining disturbance across realms and taxonomic groups. Results are from mixed-effects meta-regression models in which log-transformed distance, log(distance+1), was included as a continuous fixed effect. Models were fitted separately for each realm and for each taxonomic group within each realm. The intercept represents the estimated mean log response ratio (lnRR) at the mining disturbance (distance = 0 km), and the coefficient for log(distance+1) represents the change in lnRR with increasing distance. Positive coefficients indicate that responses become less negative or more positive with distance, whereas negative coefficients indicate increasingly negative responses. N = number of effect sizes; CI = confidence interval;* Q_M *= omnibus test of the distance moderator; QM_p = associated p-value.*

Realm	Taxonomic group	N	Intercept (95% CI)	log(dist+1) (95% CI)	p-value	Q_M	Q_M_p
Freshwater	All taxa	959	-1.28 (-1.96, -0.61)	0.03 (0.01, 0.06)	0.002	10.08	0.002
	Invertebrates	795	-1.40 (-2.13, -0.67)	0.03 (0.01, 0.06)	0.001	10.33	0.001
	Vertebrates	117	-0.48 (-2.27, 1.30)	-0.11 (-0.60, 0.38)	0.656	0.20	0.656
	Microorganisms & algae	46	-4.10 (-5.90, -2.30)	0.47 (0.10, 0.84)	0.012	6.27	0.012
Terrestrial	All taxa	415	-1.01 (-6.12, 4.10)	0.38 (0.37, 0.39)	<0.001	12091.65	<0.001
	Invertebrates	377	-3.15 (-3.92, -2.38)	0.38 (0.37, 0.39)	<0.001	12091.40	<0.001
	Vertebrates	38	4.01 (-18.31, 26.33)	-0.81 (-9.35, 7.74)	0.854	0.03	0.854

Table S22. *Quadratic relationships between species abundance responses to mining and distance from mining disturbance across realms and taxonomic groups. Results are from mixed-effects meta-regression models in which linear and quadratic terms for log-transformed distance, log(distance+1) and log(distance+1)^2, were included as continuous fixed effects. Models were fitted separately for each realm and for each taxonomic group within each realm. The intercept represents the estimated mean log response ratio (lnRR) at the mining disturbance (distance = 0 km). The linear and quadratic coefficients describe the shape of the relationship between lnRR and distance. The p-values for the linear and quadratic terms test whether each coefficient differs from zero while accounting for the other term, whereas the omnibus Q_M test assesses whether the two distance terms jointly explain variation in lnRR. For terrestrial vertebrates, the quadratic term could not be estimated because the available observations contained too few distinct distance values, therefore only the linear coefficient is reported. See Table S19 for definitions of the remaining terms and metrics.*

Realm	Taxonomic group	N	Intercept (95% CI)	log(dist+1) (95% CI)	p (linear term)	log(dist+1)^2 (95% CI)	p (quadratic term)	Q_M	Q_M_p
Freshwater	All taxa	959	-1.33 (-2.01, -0.65)	-0.03 (-0.10, 0.05)	0.514	0.01 (-0.00, 0.02)	0.115	12.55	0.002
	Invertebrates	795	-1.47 (-2.21, -0.72)	-0.03 (-0.10, 0.05)	0.520	0.01 (-0.00, 0.02)	0.115	12.80	0.002
	Vertebrates	117	-0.49 (-2.41, 1.43)	-0.10 (-1.31, 1.10)	0.866	-0.00 (-0.14, 0.14)	0.987	0.19	0.910
	Microorganisms & algae	46	-4.11 (-9.68, 1.47)	0.89 (-6.57, 8.35)	0.815	-0.04 (-0.83, 0.74)	0.911	1.11	0.574
Terrestrial	All taxa	415	-10.39 (-19.01, -1.77)	4.15 (4.01, 4.30)	<0.001	-0.23 (-0.24, -0.22)	<0.001	14665.21	<0.001
	Invertebrates	377	-17.01 (-19.39, -14.63)	4.16 (4.01, 4.30)	<0.001	-0.23 (-0.24, -0.22)	<0.001	14666.66	<0.001
	Vertebrates	38	4.01 (-18.31, 26.33)	-	-	-	-	0.03	0.854

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