Supplementary Information

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Appendix part 1: Supplementary methods

Supplementary Information Text

Literature search

On 11 November 2015, 26 February 2019, and 30 September 2020, we conducted literature searches in the ISI Web of Knowledge database for papers that investigated the interaction of the effects of invasive species and one of the following global environmental change (GEC) stressors: warming; nitrogen deposition; O_2 depletion; drought; CO_2 addition; and altered pH. We searched the Web of Science Core Collection for articles and reviews that were available in English through September 30, 2020. All searches used the following search string: “TS=((Invasi* OR invader* OR exotic* OR alien* OR non-native* OR nonnative* OR non-indigenous OR nonindigenous OR naturalized OR introduc*) AND (Impact* OR effect*) AND (Experim* OR manipula*)”, and an additional search string to describe each GEC type. See **Table S1.1** for full search terms for individual GECs.

We filtered results to twelve ecologically relevant categories (Biodiversity Conservation, Ecology, Entomology, Environmental Sciences, Fisheries, Forestry, Limnology, Marine Freshwater Biology, Oceanography, Plant Sciences, Soil Science, and Zoology) and restricted publication date to 2020 or earlier. Our searches returned 6,192 studies in total.

We had three main design criteria for including a study in our subsequent analyses. The study had to: (1) test the effect of both invasive species and at least one of the GEC stressors; (2) include experimental manipulation of both factors (invasion and GEC, hereafter “INV&GEC”) or experimentally manipulate one factor across a gradient of the other (e.g., an invasive species removal experiment across an elevation gradient as a proxy for a temperature gradient); and (3) measure the direct effect of both experimental manipulations on native species or ecosystems. Each study was reviewed independently by one of the contributing authors. See **Fig. S1.1** for diagram showing steps of filtering studies for inclusion. We included 95 total studies in our meta-analysis; references for these studies are included here (1-95).

Data categorization

Data from each study were extracted by a single author. That person recorded data on the taxonomy of the invasive species used in the study, the type and magnitude of the GEC manipulation, the setting (ecosystem type, continent, type of experimental setup), and the type of measured response (see **Table S1.2** for categories and definitions), in addition to the means, variances, and sample sizes of the experimental treatments. Two of the recorded factors were somewhat subjective: the invasion mechanism (i.e., how the invasive species is thought to influence the measured response) and the “response benefit” (i.e., whether a higher value of the measured response aligns with a benefit to the native species, community, or ecosystem). We referred to the language used by the authors of each study to infer the hypothesized invasion mechanism and whether the response was considered beneficial or detrimental to the system, but this required some subjective interpretation and, in some cases, our own expert knowledge. Thus, we included additional fields in the coded data on the certainty associated with each of these data (“yes” or “no”). The corresponding author confirmed the invasion mechanisms and response benefits for all cases where the original coder had recorded uncertainty in their determination. As a kind of sensitivity analysis to this effect, we also reran analyses without data where the response benefit was uncertain.

Data analysis

Effect size calculation

In order to compare treatment effects across cases, we computed Hedges' *d* effect sizes. Hedges' *d* is an estimate of the standardized mean difference of treatment from baseline and is not biased by small sample size (96). We calculated the effect size (*d*) as:

$$d = \frac{X_T - X_B}{S} J \qquad \text{(Eq. 1)}$$

where X_T is the observed treatment mean response, X_B is the observed baseline mean response, S is the pooled standard deviation, and *J* is a weighting factor based on the number of replicates (96, 97). *S* is calculated as:

$$S = \sqrt{\frac{(n_T - 1)\sigma_T^2 + (n_B - 1)\sigma_B^2}{n_T + n_B - 1}} \qquad \text{(Eq. 2)}$$

and J is calculated as:

$$J = 1 - \frac{3}{4(n_T + n_B - 2) - 1} \qquad \text{(Eq. 3)}$$

where n_T is the number of replicates in the treatment, n_B is the number of replicates in the baseline, σ_T^2 is the treatment standard deviation, and σ_B^2 is the control standard deviation (96). All cases included information on the standard error, standard deviation, or confidence interval around the mean, which we converted to standard deviation.

The variance around *d* was calculated as:

$$var_d = \left(1 - \frac{3}{4(n_T + n_B - 2) - 1}\right)^2 \times \left(\frac{n_T + n_B - 2}{\frac{n_T \times n_B}{n_T + n_B}(n_T + n_B - 4)}\right) \qquad \text{(Eq. 4)}$$

This variance calculation reduces bias in the precision, since it is independent of the magnitude of *d* (98, 99).

The baseline (X_B) for single stressor treatments (invasion or GEC) was the observed control response (X_C). To determine whether observed INV&GEC effects differed from that expected from combining the two single stressors (i.e., to identify whether the interactions between invasion and GEC were additive, antagonistic, or synergistic), we calculated a predicted additive effect by combining the results of the individual stressor treatments:

$$X_p = (X_I - X_C) + (X_{GC} - X_C) + X_C \qquad \text{(Eq. 5)}$$

where X_p is the predicted additive response to interaction treatment, X_I is the observed mean response to invasion treatment, X_{GC} is the observed mean response to global environmental change treatment, and X_C is the mean observed control response (100). Where n_B was specified in Eq. 2 and 3, we used (n_I + n_{GC}) to represent the sample size of the predicted additive response (100). There were 49 cases where X_p was impossibly negative (e.g., a negative value of biomass, survival, or abundance); we replaced these with zeros before calculating the predicted additive Hedges' *d*.

We examined the data for outliers prior to performing meta-analyses. Eight cases had recorded standard deviations of zero for at least one treatment effect, which produced NA's or infinite Hedges' *d* values. After removing these cases, we visually examined the distribution of Hedges' *d* values and removed one case with a Hedges' *d* of over -200, a much higher magnitude than other cases (**Fig.**

S1.2A). We thus analyzed 458 cases from 95 studies, compared to 467 cases from 95 studies in the original dataset.

To test whether the inclusion of other potential outliers affected the results, we compared the results comparing mean effect sizes and treatment effects (Fig. 2 in main text) with a dataset with additional potential outliers removed. We chose to remove an additional 8 cases from this comparison dataset with Hedges' *d*'s with absolute values of 30 or higher, based on z-scores (**Table S1.3**) and visual assessment (**Fig. S1.2B**).

Regression analysis

We fit three types of regression models:

1) A model with treatment as the only predictor, to compare the overall mean effect sizes of the three treatments (**Fig. 2**, main text)
2) Five models (one for each predictor: GEC; invasion mechanism; response class; ecosystem setting; or experiment type) with the predictor and treatment, to compare mean treatment effects across categories of the predictor (**Fig. 3A** and **Fig. 4A**, main text, and **Fig. S2.8**, Appendix part 2)
3) Three models, one for each treatment, comparing the effects of all predictors (GEC, invasion mechanism, response class, ecosystem setting, and experiment type) for that treatment (**Fig. S2.7**, Appendix part 2)

Each model included a random effect for the study identity and treated the calculated effect size (*d*) as distributed normally around a true effect size with variance equal to the calculated variance around *d*. Models that included data on all three treatments (not including the third type described above) also included a random effect for the case identity. All estimated model parameters were given uninformative priors (dnorm(0, 1/10000); dunif(0,100) for standard deviations). Models were run for 50,000 iterations, with 30,000 for adapting and 1,000 for burn-in. We used the Gelman-Rubin's statistic (101) to check for model convergence; all models converged with a Gelman-Rubin's statistic of <=1.01. We also calculated Bayesian p-values comparing: (a) sums of squares differences from the mean; and (b) mean values of observed and simulated data. Bayesian p-values were close to 0.5 for all models, suggesting adequate model fit.

Estimates of mean Hedges' *d* values depend on the sign (positive or negative) of the treatment effects; thus, we treated the signs of effects as normative (i.e., either beneficial or detrimental to the native species, community, or ecosystem) to make the sign more consistently meaningful. This required some subjectivity in assigning a benefit or detriment classification to measured responses (see above, "Data categorization"). We therefore re-analyzed data in regressions after removing cases with a less certain benefit/detriment distinction, to determine how these cases affected the results. We removed 148 cases where the coding authors reported uncertainty in the benefit/detriment assignment, including all cases with responses classified as nutrients, allocation, or behavior. The resulting dataset comprised 310 cases from 78 studies measuring effects on abundance, biomass, diversity, physiology, reproduction, size, or survival.

Fisher's tests

We used Fisher's tests to examine differences in the types of INV&GEC interactions across categories of predictors (GEC, invasion mechanism, response class, ecosystem setting, and experiment type). However, these tests do not account for potential pseudo-replication between multiple cases from the same study. Thus, we also performed Fisher's tests on a reduced dataset of one case per study. We randomly selected one case per study (i.e., the first case listed in the dataset for each study) after ordering data with the least frequent response classes first, to retain some data for each category of measured response.

Publication bias

We used funnel plots and Spearman's rank correlation tests to look for publication bias in the dataset, comparing the Hedges' *d* scores for invasion, GEC, and INV&GEC treatments to the precision in Hedges' *d* estimates and pooled sample sizes (100, 102). We also examined the relationship between precision and sample sizes and the residuals of the intercept mixed effect model, which accounted for some of the variation in Hedges' *d* scores across studies (102) (**Fig. S2.3**, Appendix part 2).

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Figures and tables

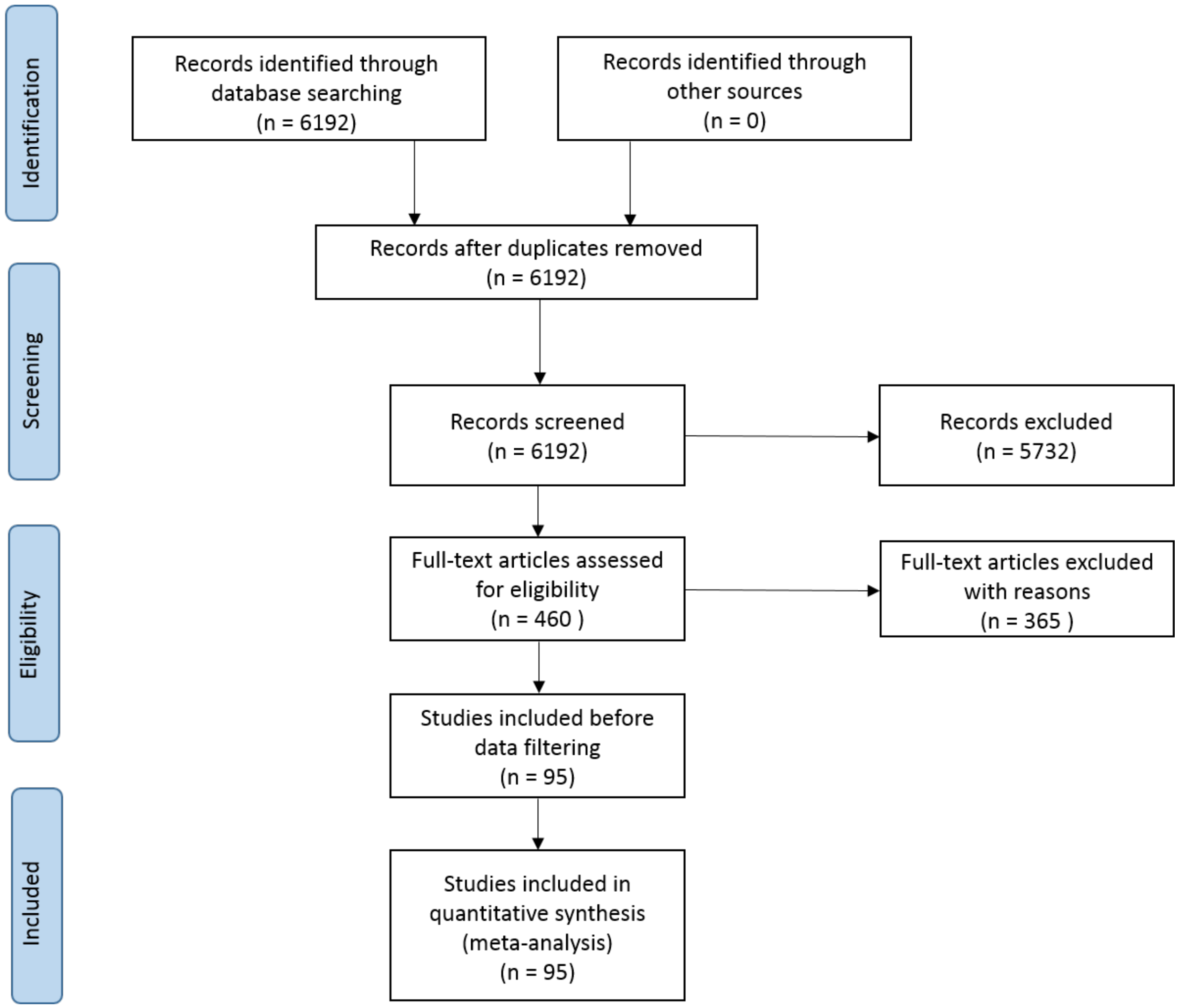

Fig. S1.1. Diagram showing the steps we used to filter studies from the database search to use in analysis and the number of studies excluded and retained at each step.

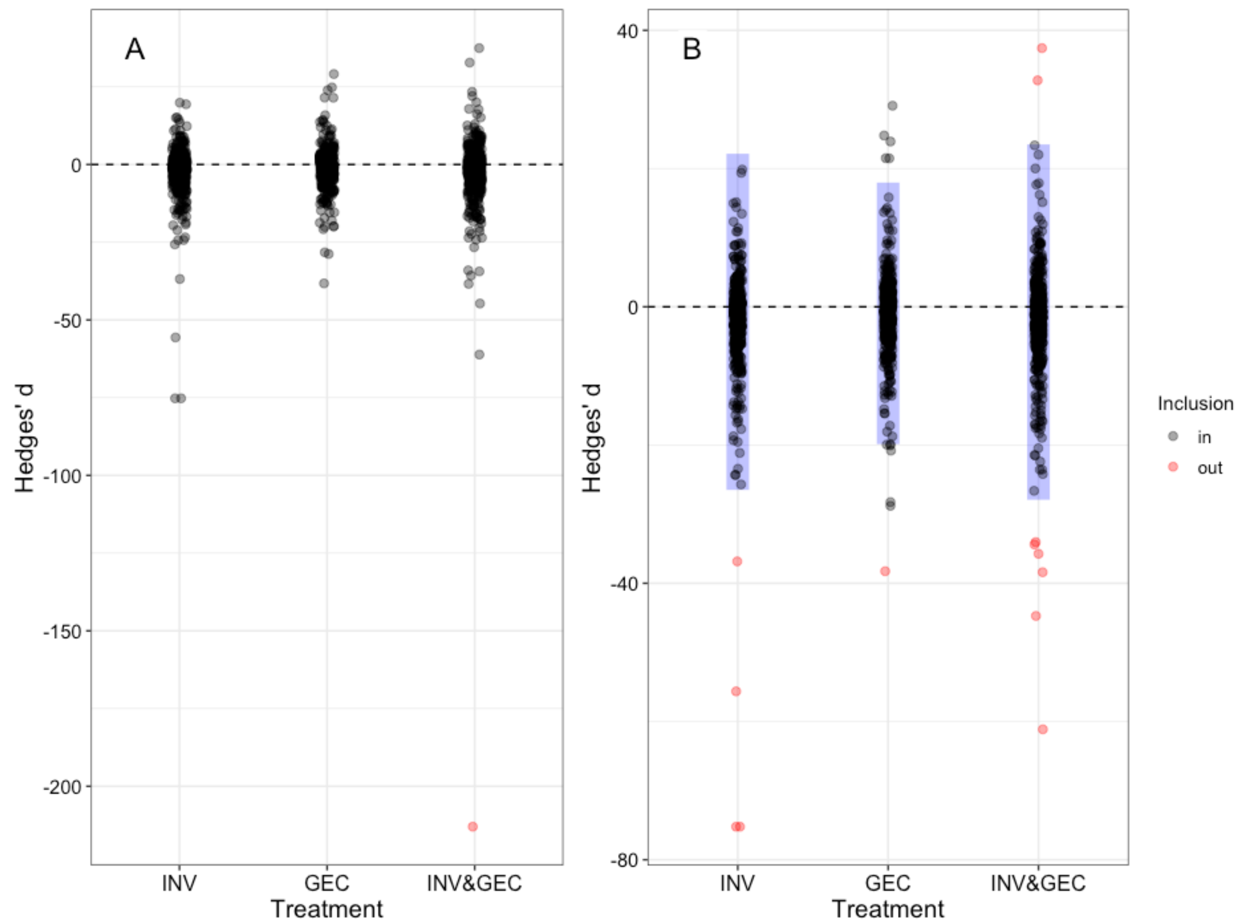

Figure S1.2. Visual assessment of Hedges' *d* distributions and outliers. We removed one case with a Hedges' *d* value < -200 (A), in addition to eight cases with NA or infinite Hedges' *d* values, from the dataset prior to analysis (shown in red). To examine the effect of potential outliers on results, we performed a secondary analysis on a dataset clipped to exclude cases with Hedges' *d* values with an absolute value of 30 or higher (B; excluded points shown in red). This cutoff was chosen based on visual examination of outliers and because this value approximated three standard deviations around the mean of each treatment (z-scores, shown as blue shaded areas in B; see **Table S1.3**).

Table S1.1. Full search terms used in Web of Science to find papers focusing on invasions and one or more global environmental change (GEC) factors.

GEC type	Full search term
Warming	TS=((Invasi* OR invader* OR exotic* OR alien* OR non-native* OR nonnative* OR non-indigenous OR nonindigenous OR naturalized OR introduc*) AND (Impact* OR effect*) AND (Experim* OR manipula*) AND (Warm* OR heat* Or thermal OR temperature increase OR temperature manipulation* OR climate change experiment))
Nitrogen deposition	TS=((Invasi* OR invader* OR exotic* OR alien* OR non-native* OR nonnative* OR non-indigenous OR nonindigenous OR naturalized OR introduc*) AND (Impact* OR effect*) AND (Experim* OR manipula*) AND (Nitrogen AND (deposition OR fertili* OR add* OR suppl* OR enrich* OR enahnc* OR applic* OR input*)))
O_2 depletion	TS=((Invasi* OR invader* OR exotic* OR alien* OR non-native* OR nonnative* OR non-indigenous OR nonindigenous OR naturalized OR introduc*) AND (Impact* OR effect*) AND (Experim* OR manipula*) AND (eutroph* OR hypoxia OR oxygen OR anoxi* OR oxygen deplet* OR O2 deplet*))
Drought	TS=((Invasi* OR invader* OR exotic* OR alien* OR non-native* OR nonnative* OR non-indigenous OR nonindigenous OR naturalized OR introduc*) AND (Impact* OR effect*) AND (Experim* OR manipula*) AND (Drought OR water stress* OR rainout OR rain out OR rain-out OR precipitation exclusion* OR rain exclusion* OR precipitation removal*))
CO_2 addition	TS=((Invasi* OR invader* OR exotic* OR alien* OR non-native* OR nonnative* OR non-indigenous OR nonindigenous OR naturalized OR introduc*) AND (Impact* OR effect*) AND (Experim* OR manipula*) AND ((CO2 OR carbon dioxide) AND (increase* OR enhance* OR enrich* OR elev*)))
Altered pH	TS=((Invasi* OR invader* OR exotic* OR alien* OR non-native* OR nonnative* OR non-indigenous OR nonindigenous OR naturalized OR introduc*) AND (Impact* OR effect*) AND (Experim* OR manipula*) AND (pH))

Table S1.2. Definitions and ecological scales of response class categories used as predictors in meta-analysis.

Response class	Definition	Scale
Abundance	Number or density of individuals	Species, community
Allocation	Carbon or size allocation to different tissues (e.g., specific leaf area, height:width ratio)	Species, community
Behavior	Individual activity, such as aggressive or feeding behaviors	Species
Biomass	Mass of individuals or populations, including proxy measures such as chlorophyll a concentration in freshwater systems	Species, community
Diversity	Biodiversity (e.g., species richness, evenness)	Community
Physiology	Metabolic or immune processes or related enzyme activity	Species
Nutrient	Nutrient concentrations in tissues, nutrient or other resource availability, or ecosystem-level carbon or nutrient cycling	Species, community, ecosystem
Reproduction	Reproductive output or development of reproductive tissues (e.g., flowers)	Species, community
Size	Body size, limb/body part size, or growth	Species, community
Survival	Survivorship or mortality rate	Species, community

Table S1.3. Means, standard deviations, and z-scores of Hedges' *d* values for each treatment (excluding values greater than 200 or less than -200).

Treatment	Mean +/- SD	Z-score bounds
Invasion	-2.18 +/- 8.10	(-22.14—26.49)
GEC	-0.95 +/- 6.31	(-17.97—19.86)
INV&GEC	-2.21 +/- 8.57	(-23.49—27.92)

Appendix part 2: Supplementary results

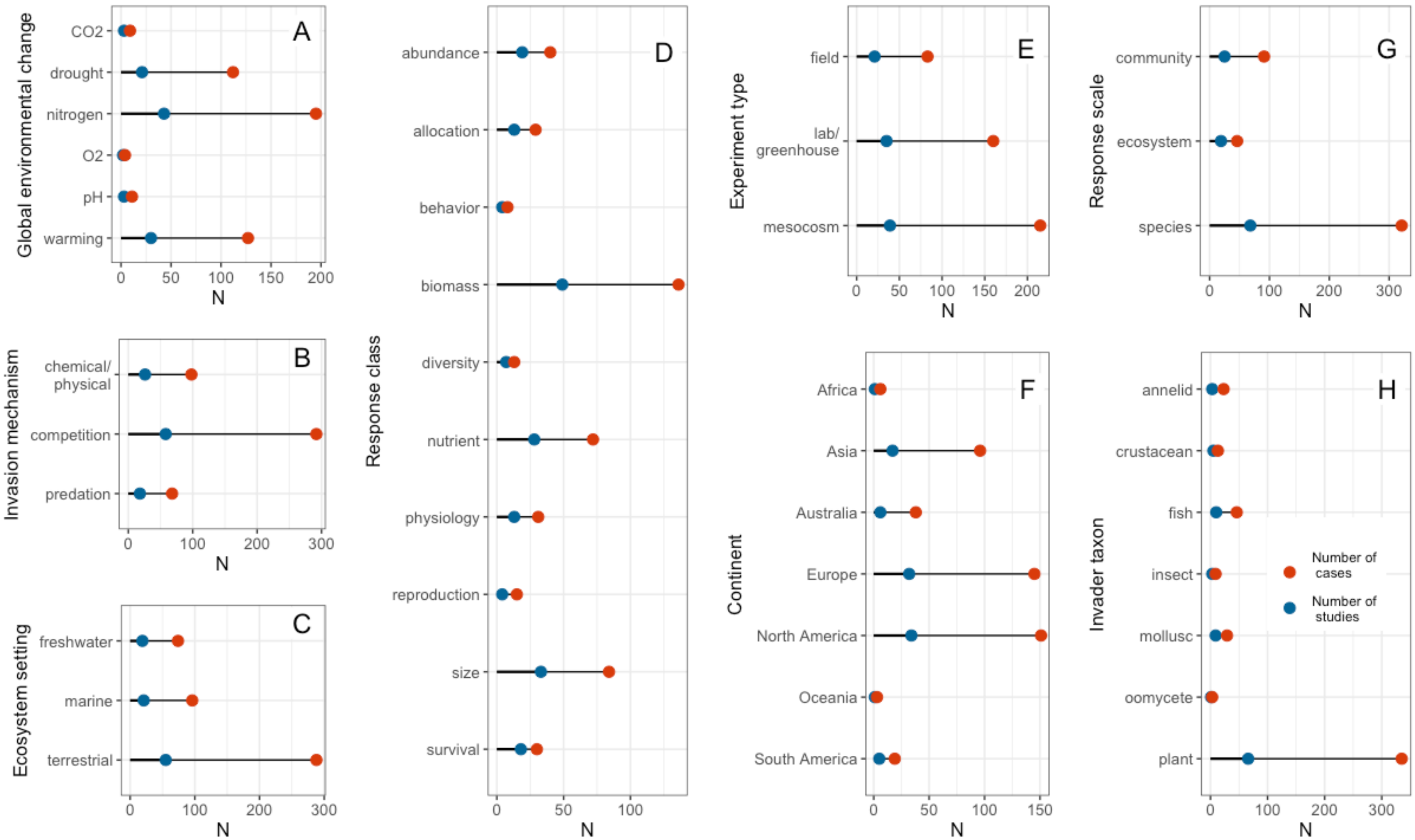

Figure S2.1. Numbers of cases and studies in each category in the dataset used for analysis (total n_{cases} = 458, $n_{studies}$ = 95). Most studies contributed multiple cases because they measured multiple responses, focused on multiple species, or examined multiple global environmental changes.

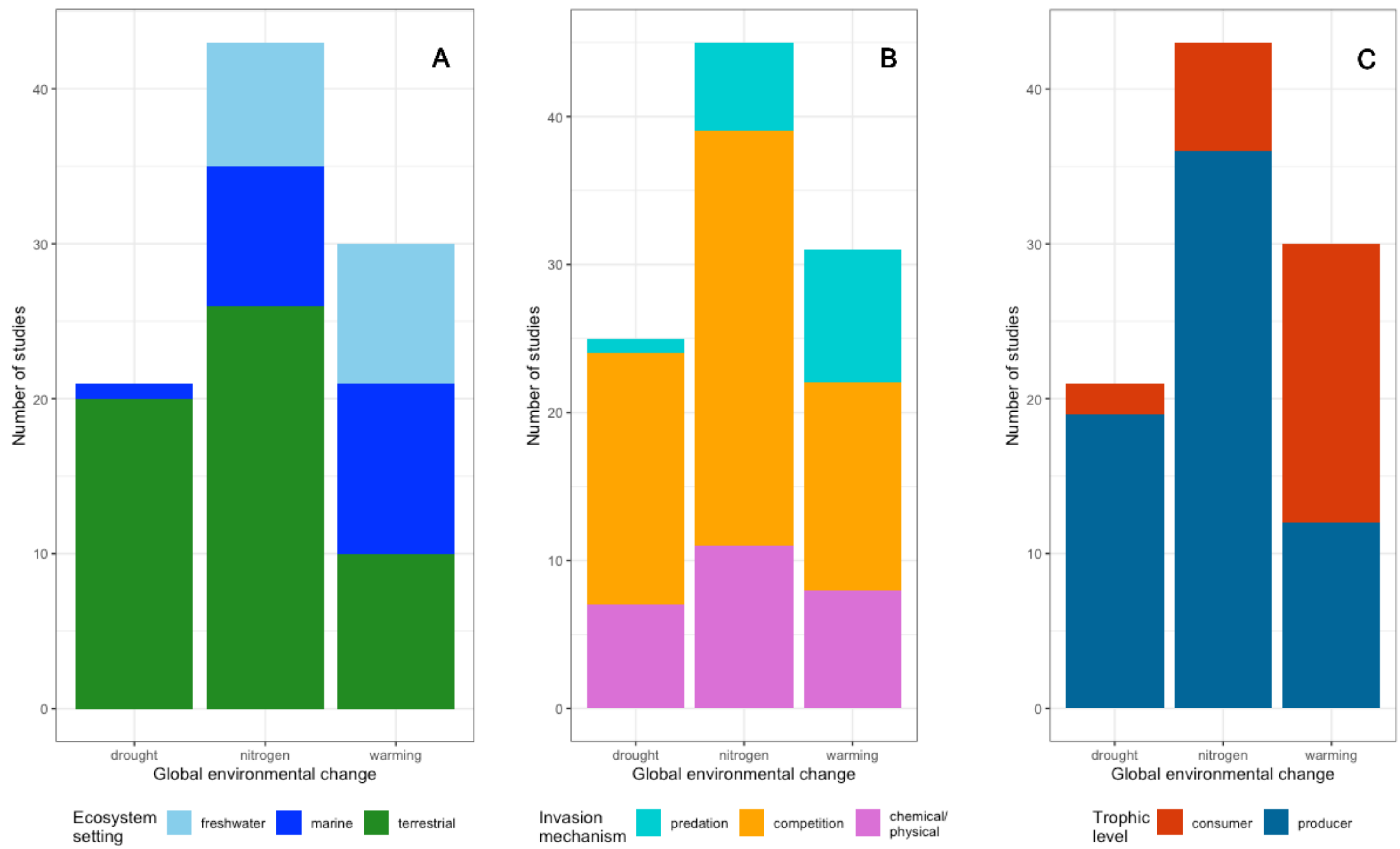

Figure S2.2. Relationships between global environmental change (GEC) type and ecosystem setting (A), invasion mechanism (B), and trophic level of invasive species (C) across studies in the dataset used for analysis. Note that a single study could have multiple invasive species, but each study only occurred in one ecosystem setting.

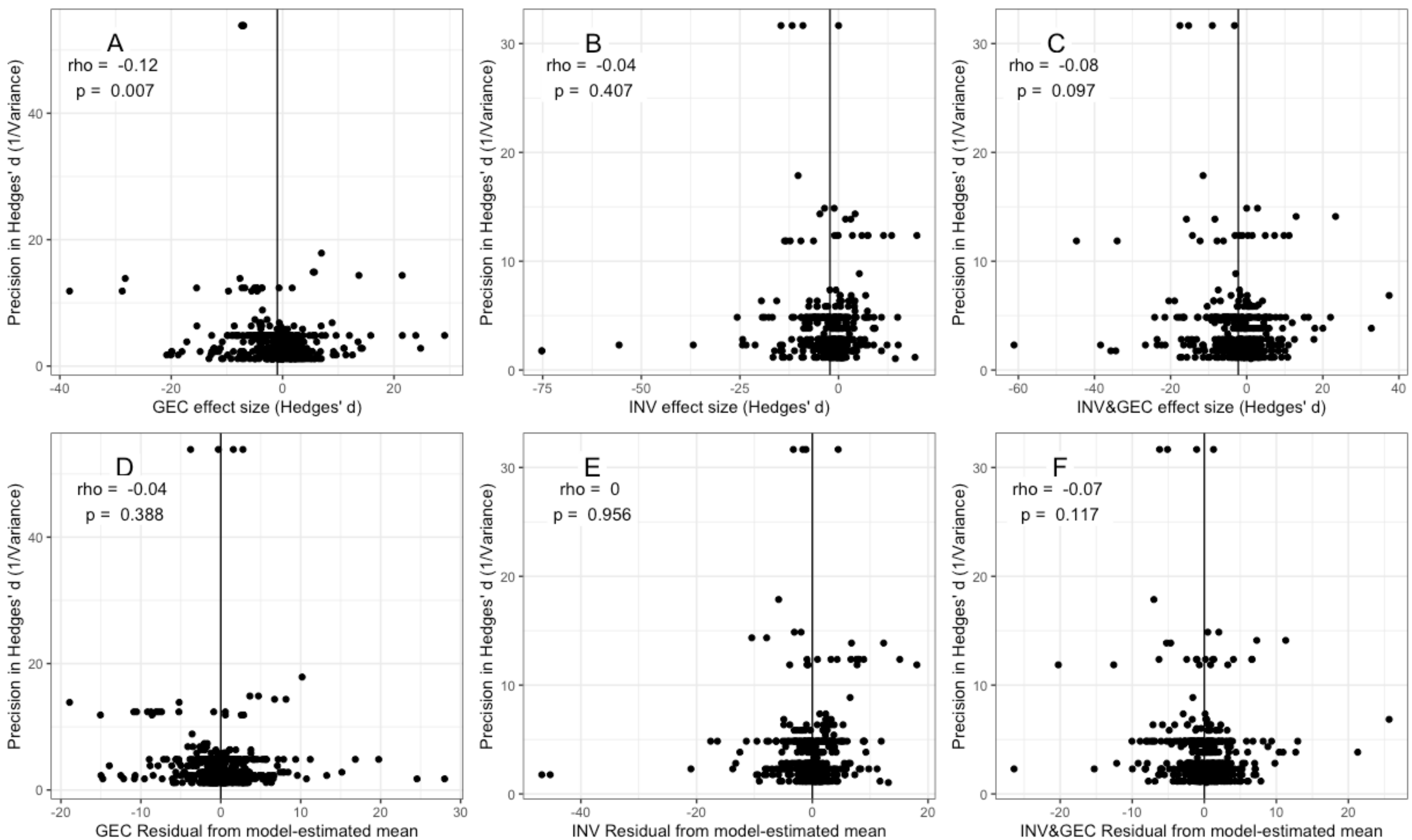

Figure S2.3. Funnel plots examining potential publication bias in the dataset used for analysis, comparing the precision in Hedges' *d* values to: 1) the Hedge's *d* values (top row) and 2) the residuals of the mixed effects model estimating the means of each treatment (bottom row). Results of Spearman's rank correlation tests are shown in the top right corner of each panel. There was some evidence of publication bias in the data (A-C), particularly for global environmental change (GEC) treatments (A), with more negative Hedges' *d* values in studies with high precision and high sample sizes. However, accounting for differences in studies with random effects largely removed this trend (D-F).

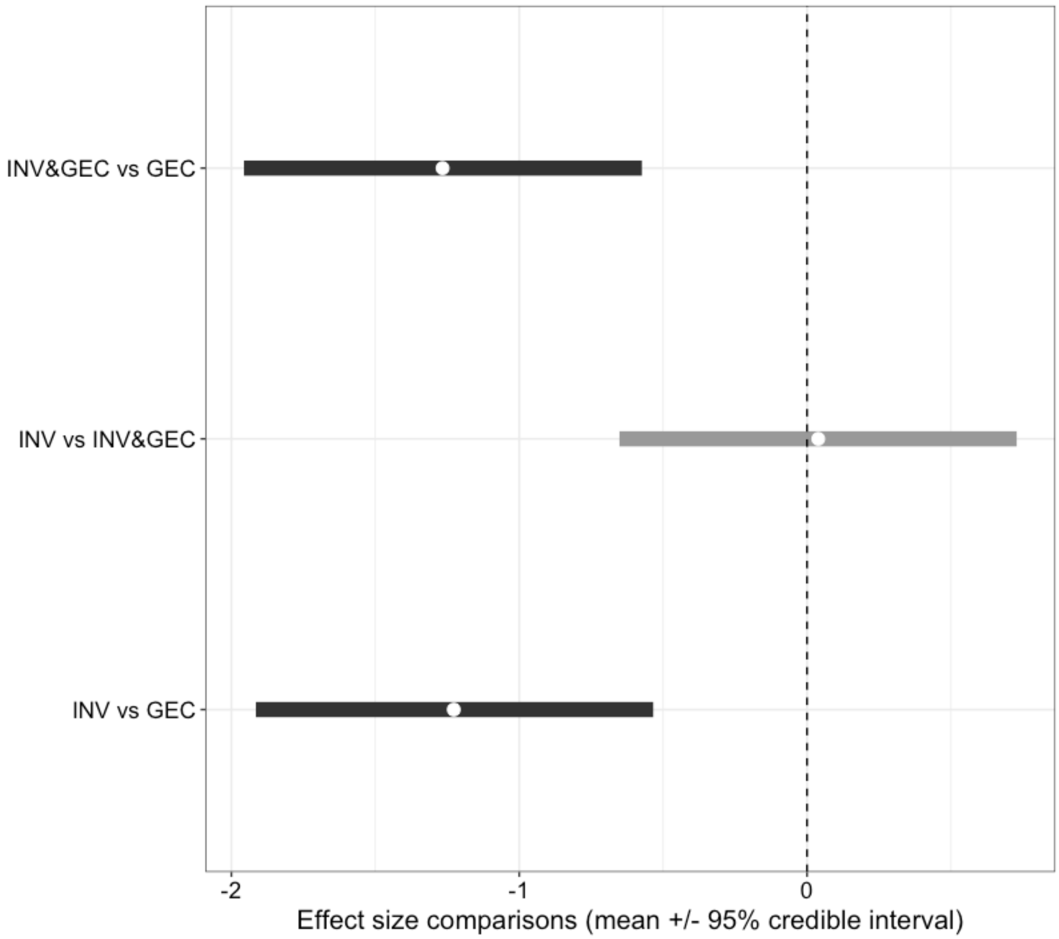

Figure S2.4. Invasion (INV) and combined invasion and global environmental change (INV&GEC) effects were both significantly more negative than GEC effects across all cases and studies. Bars represent the differences between the estimated mean Hedges’ *d*’s of the GEC, invasion, and INV&GEC treatments estimated from a Bayesian mixed-effect model, with white circles showing the mean and grey bars showing the 95% credible interval of the posterior distribution. Credible intervals that do not cross the zero line (dark grey bars) are considered significantly different from zero.

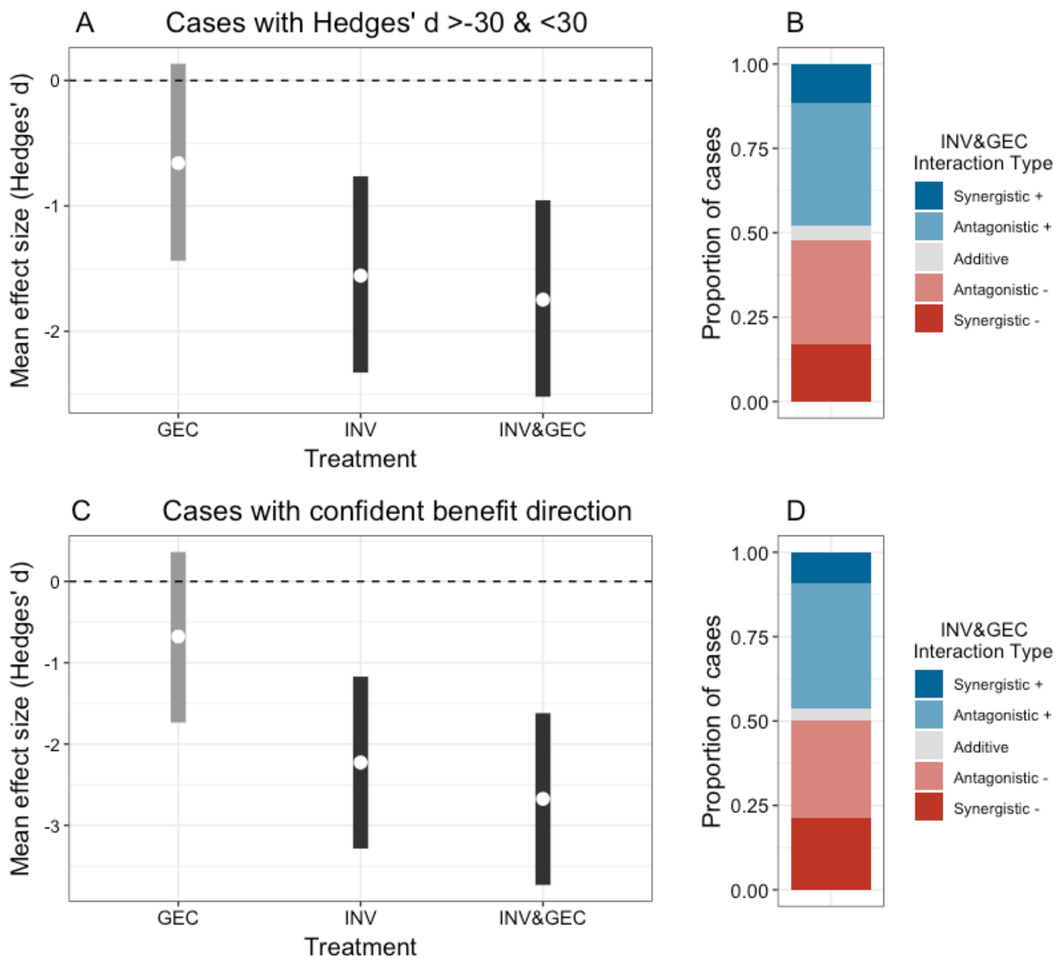

Figure S2.5. Results comparing treatment mean effect sizes and the distributions of combined stressor (INV&GEC) interaction types were robust to treatment of outliers (top row) and assessment of whether a higher value of a measured response was considered beneficial or detrimental to the ecosystem (bottom row). We re-ran analyses with subsets of the data with mean effect sizes ranging from -30 to 30 (compared to -200 to 200 in the main analysis; see SI part 2; n_{cases} = 450, $n_{studies}$ = 95) and with only cases with responses for which we were able to confidently assess whether a higher value indicated a beneficial or detrimental outcome (n_{cases} = 310, $n_{studies}$ = 78). Results are similar to those reported in the main text (**Fig. 2**). Mean effect sizes (Hedges' *d*) of invasion (INV) and INV&GEC treatments were more negative than global environmental change (GEC) treatments (A, C; white circles show the mean and grey bars show the 95% credible interval of the posterior distribution for each treatment mean). Antagonistic interactions were most common, and synergistic interactions were mostly more negative than expected from the individual stressor effects ("Synergistic (-)"; B, D).

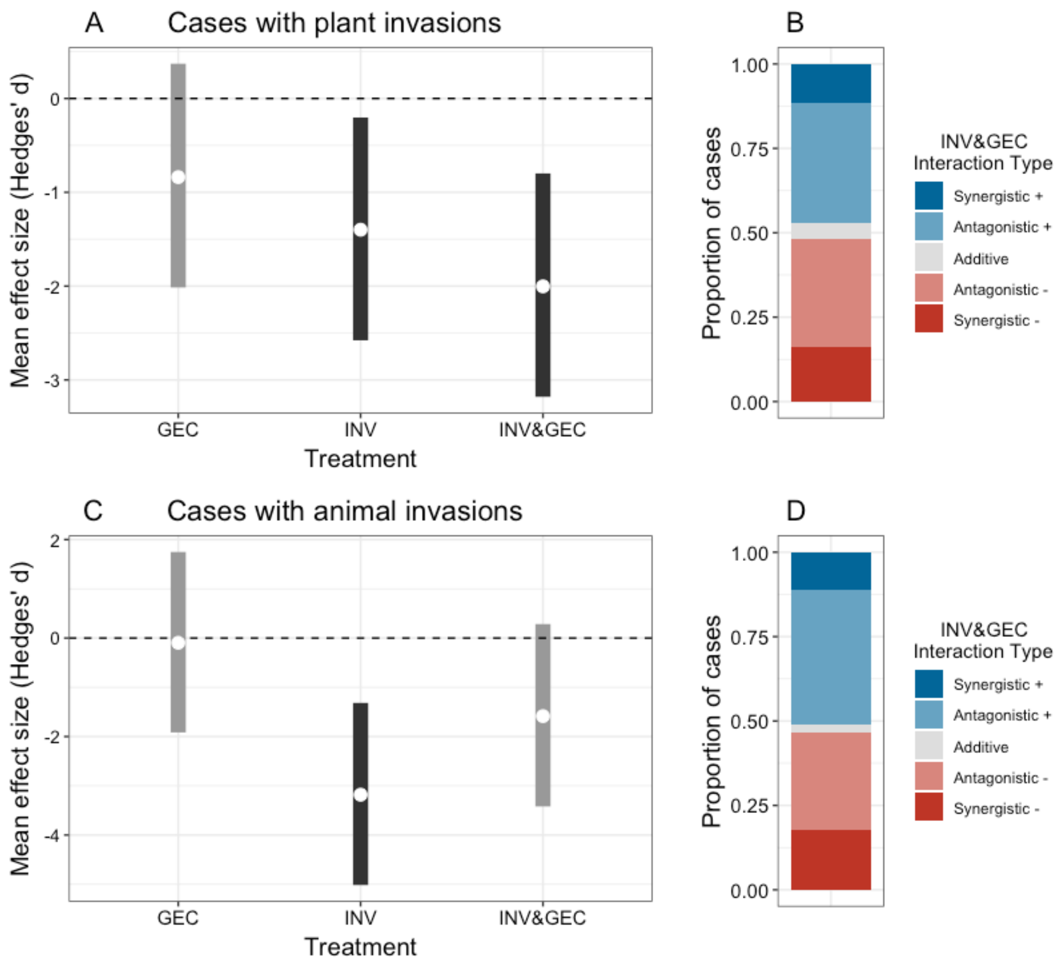

Figure S2.6. Mean effect sizes and the distribution of combined stressor (INV&GEC) interaction types were somewhat similar between studies of plant (top row) and animal (bottom row) invasive species. In studies of both plant and animal invasions, mean effect sizes (Hedges' *d*) of invasion (INV) and INV&GEC treatments were more negative than global environmental change (GEC) treatments (A, C; white circles show the mean and grey bars show the 95% credible interval of the posterior distribution for each treatment mean). Antagonistic interactions were most common, and synergistic interactions were mostly more negative than expected from the individual stressor effects ("Synergistic (-)"; B, D) in studies of both plant and animal invasions. Most studies focused on plant invasions (n_{cases} = 335, $n_{studies}$ = 66), and the overall trends described in the main text are similar to those of plant studies. Animal invasion studies were less common (n_{cases} = 120, $n_{studies}$ = 28) but showed similar trends.

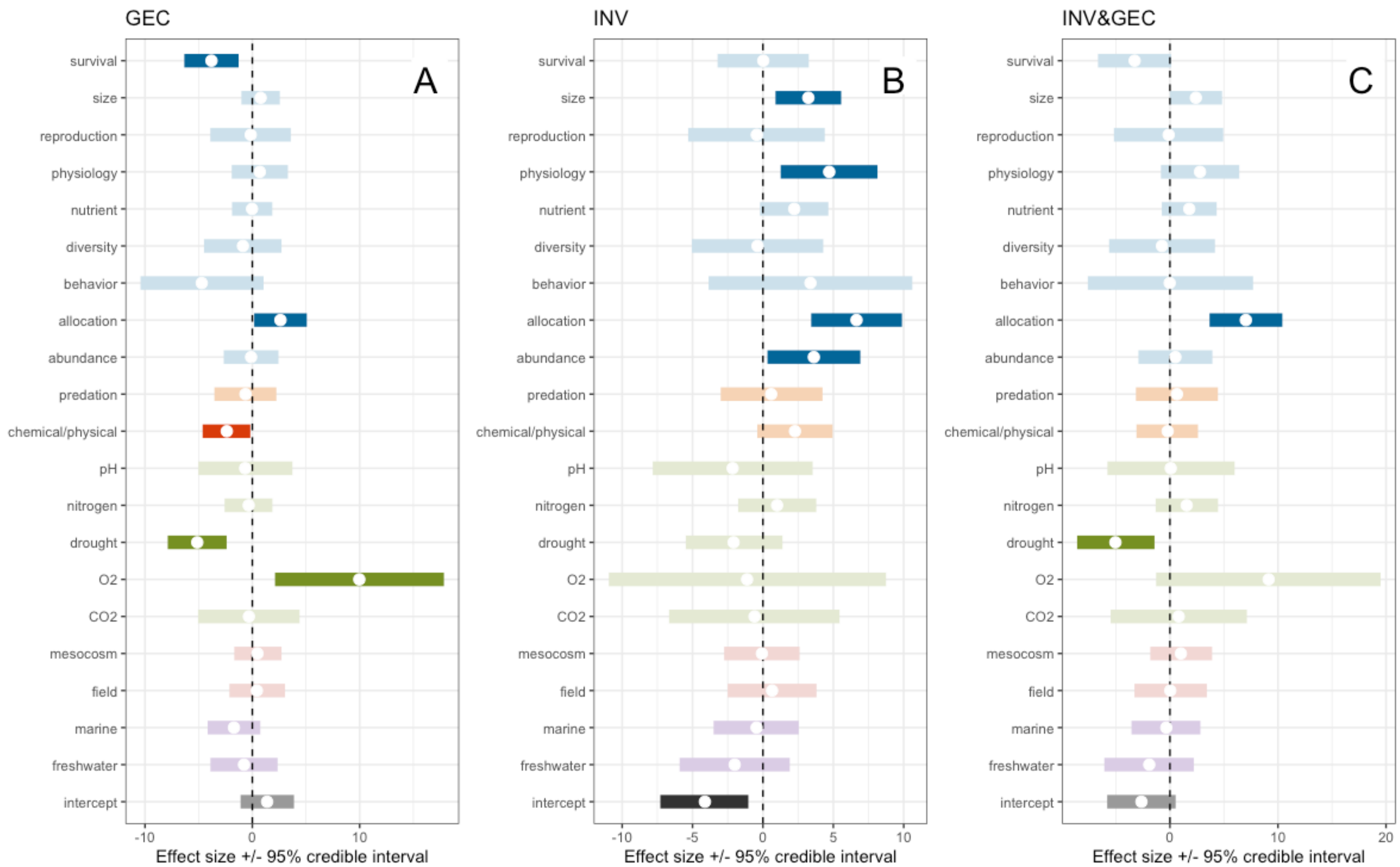

Figure S2.7. Results of full mixed-effect models predicting Hedges' *d*'s of each treatment. Effects are considered non-significant if 95% credible intervals cross zero (shown in lighter colors). Bars are color-coded by predictor variable (purple = ecosystem setting, red = experiment type, green = global environmental change factor, orange = invasion mechanism, blue = response class). Intercepts represent warming studies with competitive invasions in a terrestrial lab/greenhouse experiment and cases where the measured response was biomass. Invasion (INV) effects were generally negative across categories (i.e., without significant differences from the negative intercept) except for significantly less detrimental effects on abundance, allocation, body size, and physiology. Global environmental change (GEC) and combined (INV&GEC) effects were more negative with drought and on tissue allocation. GEC effects were less detrimental with depleted O_2 ($n_{studies}$ = 2) and more detrimental in studies with invasions acting via chemical/physical mechanisms.

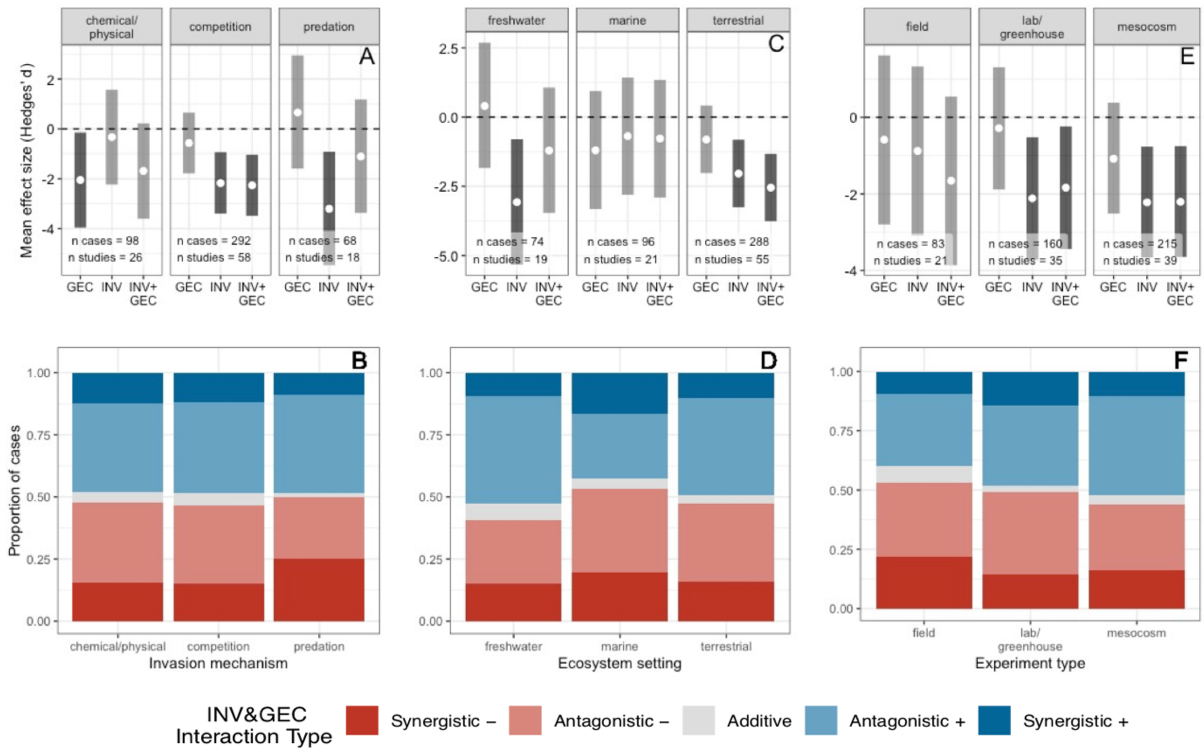

Figure S2.8. Mean effect sizes (Hedges' *d*) of invasion (INV), global environmental change (GEC) and combined (INV&GEC) treatments (top) and distributions of INV&GEC interaction types (bottom) across invasion mechanisms (A-B), ecosystem settings (C-D), and experiment types (E-F). White circles show the mean and grey bars show the 95% credible interval of the posterior distribution for the mean effect size for each GEC type (A, C, E). Credible intervals that do not cross the zero line (dark grey bars) are considered significantly different from zero. Invasion and INV&GEC effects were negative, on average, in terrestrial systems, with competitive invaders, and in lab/greenhouse studies and mesocosm studies. Invasion effects were also negative, on average, with invasive species acting via predation and in freshwater systems. However, none of these effects were significant when controlling for other variation across cases (see **Fig. S2.7**). GEC effects tended to be negative with invasive species acting via chemical/physical impacts, perhaps because most of these studies focused on terrestrial plants (**Fig. S2.2**). There was no difference in the distributions of interaction types across any of these predictors (B, D, F).

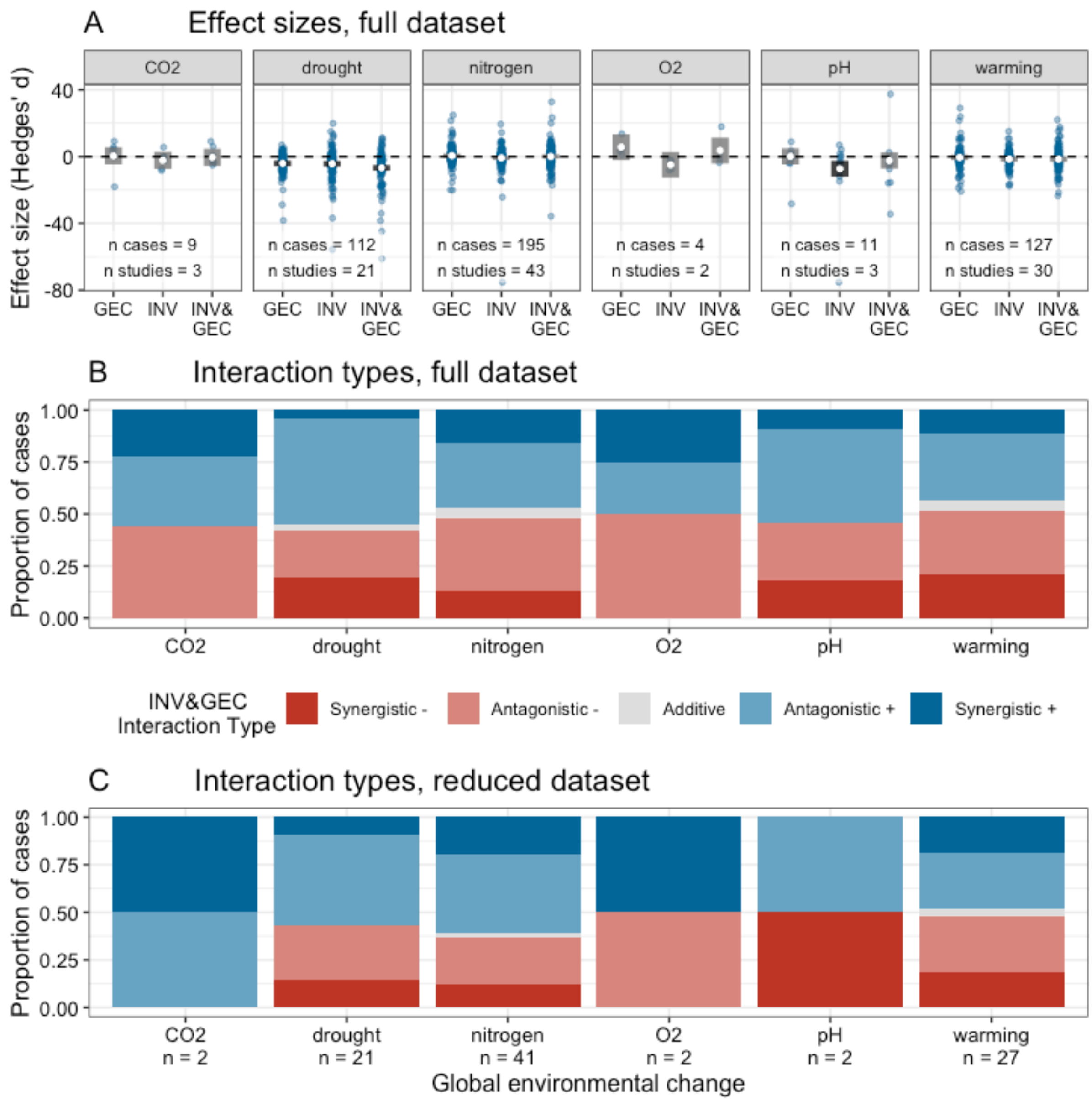

Figure S2.9. Effect sizes (Hedges' *d*) of invasion (INV), global environmental change (GEC) and combined (INV&GEC) treatments (A) and distributions of INV&GEC interaction types within the full dataset used for analysis (B) and the dataset reduced to one case per study (C) across global environmental change (GEC) types. (A) Colored points represent calculated Hedges' *d*'s from individual cases. White circles show the mean and grey bars show the 95% credible interval of the posterior distribution for the mean effect size for each GEC type. Credible intervals that do not cross the zero line (dark grey bars) are considered significantly different from zero. (B) INV&GEC interaction types varied across GECs (simulated p-value = 0.017) in the full dataset (see panel A for sample sizes). (C) There were no differences in INV&GEC interaction types across GECs in the reduced dataset with only one case per study (simulated p-value = 0.916).

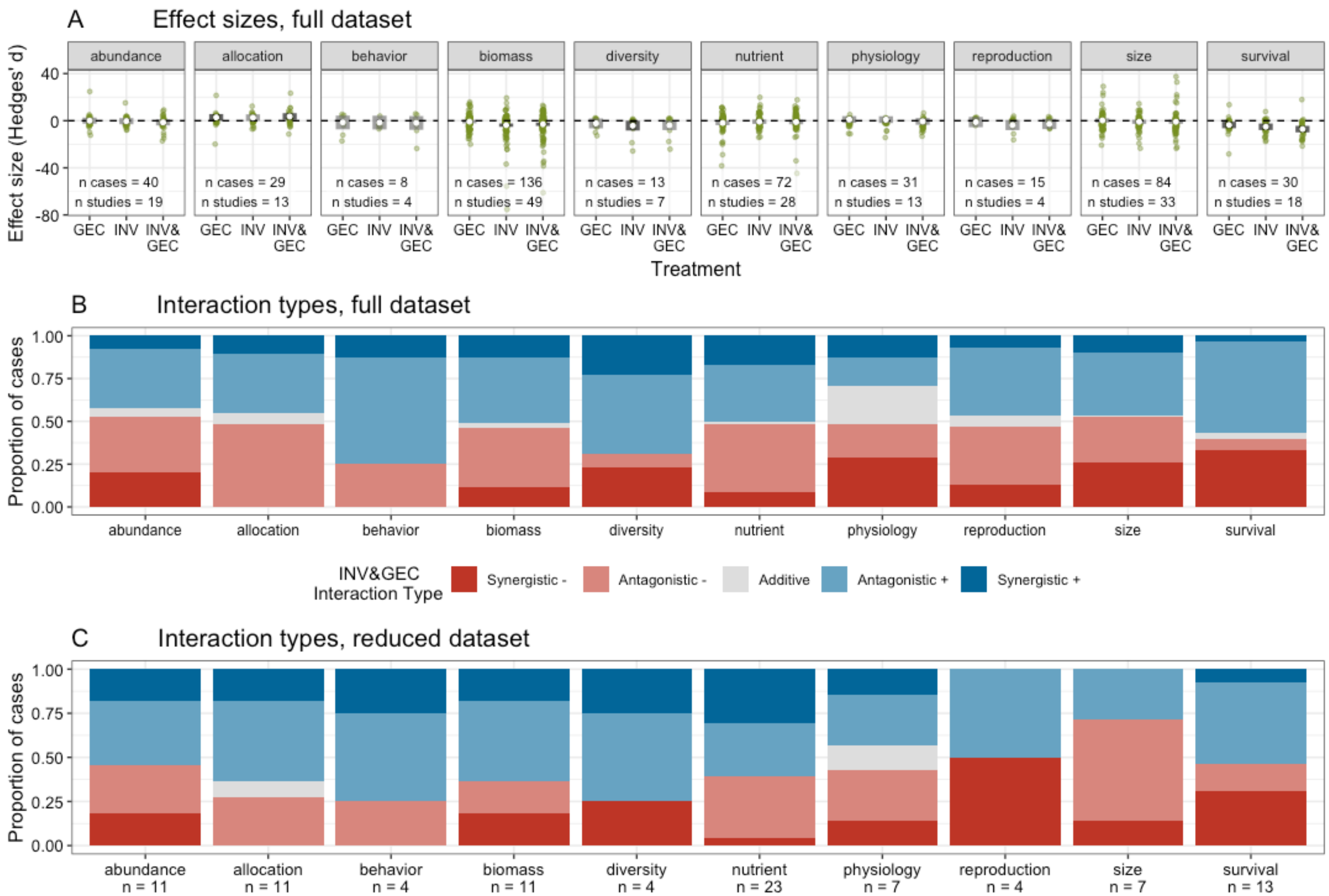

Figure S2.10. Effect sizes (Hedges' *d*) of invasion (INV), global environmental change (GEC) and combined (INV&GEC) treatments (A) and distributions of INV&GEC interaction types within the full dataset used for analysis (B) and the dataset reduced to one case per study (C) across response classes. (A) Colored points represent calculated Hedges' *d*'s from individual cases. White circles show the mean and grey bars show the 95% credible interval of the posterior distribution for the mean effect size for each response class. Credible intervals that do not cross the zero line (dark grey bars) are considered significantly different from zero. (B) INV&GEC interaction types varied across response classes (simulated p-value = 0.001) in the full dataset (see panel A for sample sizes). (C) There were no differences in INV&GEC interaction types across response classes in the reduced dataset of one case per study (simulated p-value = 0.680).