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Author for correspondence:
Gabriel X. Boldorini
e-mail: gabriel.ariero@ufrpe.br

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Predators control pests and increase yield across crop types and climates: a meta-analysis

Gabriel X. Boldorini[1,2], Matthew A. Mccary[3], Gustavo Q. Romero[4], Kirby L. Mills[5], Nathan J. Sanders[5], Peter B. Reich[6,7], Radek Michalko[8] and Thiago Gonçalves-Souza[1,2,5,6]

[1]Department of Biology, Ecological Synthesis and Biodiversity Conservation Lab, and [2]Graduate Program in Ethnobiology and Nature Conservation, Department of Biology, Federal Rural University of Pernambuco, Recife, Brazil
[3]Department of BioSciences, Rice University, Houston, TX 77005, USA
[4]Department of Animal Biology, Institute of Biology, State University of Campinas, Campinas, Brazil
[5]Department of Ecology and Evolutionary Biology, and
[6]Institute for Global Change Biology, School for Environment and Sustainability, University of Michigan, Ann Arbor, MI, USA
[7]Department of Forest Resources, University of Minnesota, St Paul, MN 55108, USA
[8]Department of Forest Ecology, Faculty of Forestry and Wood Technology, Mendel University in Brno, Zemědělská 3, 613 00 Brno, Czech Republic

GXB, 0000-0001-7581-9043; KLM, 0000-0001-7693-9629; NJS, 0000-0001-6220-6731

Pesticides have well-documented negative consequences to control crop pests, and natural predators are alternatives and can provide an ecosystem service as biological control agents. However, there remains considerable uncertainty regarding whether such biological control can be a widely applicable solution, especially given ongoing climatic variation and climate change. Here, we performed a meta-analysis focused on field studies with natural predators to explore broadly whether and how predators might control pests and in turn increase yield. We also contrasted across studies pest suppression by a single and multiple predators and how climate influence biological control. Predators reduced pest populations by 73% on average, and increased crop yield by 25% on average. Surprisingly, the impact of predators did not depend on whether there were many or a single predator species. Precipitation seasonality was a key climatic influence on biological control: as seasonality increased, the impact of predators on pest populations increased. Taken together, the positive contribution of predators in controlling pests and increasing yield, and the consistency of such responses in the face of precipitation variability, suggest that biocontrol has the potential to be an important part of pest management and increasing food supplies as the planet precipitation patterns become increasingly variable.

1. Introduction

Food security and biodiversity conservation are intertwined challenges to sustainable development [1,2]. Despite efforts to reduce hunger, approximately 670 million people will still be categorized as undernourished in 2030 [3]. Exacerbating this tragedy facing humanity is the fact that 32% (approx. 215 million tonnes) of the world's major crop production (i.e. wheat, rice, maize, potatoes and soya beans) is lost annually, with animal pests alone responsible for approximately 10% of these losses (approx. 21 million tonnes) [4]. Resident enemies (i.e. native species) can mitigate these losses by reducing pest populations, providing ecosystem services known as natural (without human intervention) and conservation (with human intervention) biological control [5]. However, the factors that mediate the effectiveness of resident enemies acting as biological control agents are less understood. Maintaining the

Table 1. Description of predictions, moderators and assumptions of the meta-analysis.

predictions	moderators	assumptions
(i) Predators will reduce populations of pests and increase crop yield	none	predators will exert top-down trophic cascades, due to a high predation pressure on herbivores and by indirectly releasing crops from herbivores [12,43]
(ii) The effect of multiple-species predators on populations of pests will be higher than single-species predators	categorical: predator diversity (i.e. single-species or multiple-species predators)	multiple predators can have higher variation of functional traits than a single predator and perform higher biological control via resource partitioning, facilitation or positive selection effects [15,18,21]
(iv) Temperature increases the negative effect of predators on populations of pests and positive on crop yield. Furthermore, temperature annual range, aridity and precipitation seasonality decreases the negative effect of predators on populations of pests and positive on crop yield	continuous: mean annual temperature, temperature annual range, aridity and precipitation seasonality	temperature increases metabolic activity and food consumption rates [34,43]; predators are more sensitivity to climatic instability (higher temperature and precipitation seasonality) [28,31,34]; predators are also generally more sensitive to drought than their prey [29]
(v) Higher temperature and precipitation seasonality affects positively biological control performed by multiple-species predators and negatively biological control performed by single-species predators	continuous: temperature annual range and precipitation seasonality	crops that have communities with multiple predator species have a greater likelihood of having tolerant predator species that perform biological control even with climatic variability [22]

diversity and impacts of resident enemies while enhancing crop yield is a key goal of balancing biodiversity conservation and food security [6,7].

Resident enemies can have a positive [8,9], negative [10], or no [11] effect on populations of pests that attack crops. Moreover, although trophic cascades in terrestrial systems are common [12,13], even when resident enemies reduce pest damage, their impacts might not lead to increased yield in crops [14]. Exactly when, where, and why resident enemies provide biological control and enhance crop production are still open and pressing questions [15–18]. Therefore, since biological control is recognized as an ecosystem service [19,20], it is essential to understand the factors that influence the efficiency of predators in pest control and consequently on crop yield.

Predators are a key class of resident enemies and recent work has highlighted the effectiveness of multiple predators in suppressing populations of pests [15,17,18,21], though their effectiveness likely depends on functional traits of both the predators (e.g. hunting mode) and the pests (e.g. life stage), species identity, crop type and environmental heterogeneity (e.g. climatic variation) [15,22–26]. Put another way, the impacts of predators on populations of pests might be context dependent.

In fact, climate can influence trophic cascades and biological control in multiple ways. First, predators and pests might respond in different ways to climate; predators are typically more sensitive to climate stressors, such as temperature and drought ([27–31], but see [32,33]). However, predation is projected to increase as temperatures increase, but is expected to decrease as climatic variability increases [34], with the potential for complementary effects of multiple predator species in changing climates [35]. This evidence suggests that impact of biological control will be higher in crop systems as temperature increases, when other climatic conditions (e.g. precipitation) remain stable. However, many models predict increasing variation in precipitation, but it remains an open question how these changes might affect predator–prey interactions or the impacts of biocontrol on crop production [36–42].

To address these knowledge gaps, we performed a meta-analysis of 86 studies and 317 pairwise comparisons testing for the effect of resident predators on populations of pests and/or yield in crop systems. We explored the effectiveness of resident predators to perform biological control among predator groups and crop types. Specifically, we examined: (i) the effect of resident predators on populations of pests and crop yield; (ii) the effect of predator diversity (i.e. treatments with one and two or more predator species, hereafter, single species and multiple species, respectively) on populations of pests; (iii) whether natural and managed (conservation) predator control differ in effects; (iv) the climate effects on the relationship between predators and populations of pests and crop yield; and (v) the climate effects on the relationship between predator diversity and populations of pests (table 1). Overall, our study highlights that predators indirectly promote crop yield and provide a vital ecosystem service that might persist even in the face of ongoing climatic change.

2. Material and methods

(a) Search strategy, selection of studies and data collection

We followed standard guidelines [44,45] to conduct this meta-analysis. We searched for primary studies (January 2021) that investigated the effect of resident predators as biological control agents in crop systems in the two platforms, Web of Science Core collection (1945 to present) and Scopus, without restrictions on years of publication and languages. We use the following string of keywords, combined with Boolean operators and using the 'topic' field in the Web of Science platform (i.e. 'TS=' field tag, which includes titles, keywords and abstracts): Biocontrol OR 'Biological Control' OR Pest NEAR/3 Control OR Predator NEAR/3 Prey AND Abundance OR Density OR 'Crop yield' OR 'Crop damage' OR 'Seed set' OR 'Fruit Development' OR 'Fruit Production' AND Crop OR Cropland OR Tillage OR Cultivation OR Plantation OR Garden. Additionally, we identified suitable studies used in earlier meta-analyses [8,9].

As a result of the search, we evaluated 5024 manuscripts in four steps (see the prisma flowchart, electronic supplementary material, figure S1). First, we removed reviews and book chapters ($n = 490$) from Web of Science and Scopus. Then, we also removed duplicated manuscripts ($n = 81$) from the different sources (i.e. Web of Science, Scopus and two earlier meta-analysis). Second, we read the titles and abstracts of 4453 manuscripts and excluded those that did not address the effect of resident predators on populations of pests and/or crop yield in crop systems. Here, we considered resident predators, resident predator groups that occur naturally in the study area (e.g. were not collected from other regions and implanted in the study area to test biological control) and that provide pest control activities independently of any targeted human intervention (natural biological control) and with human intervention (e.g. the use of flower strips to provide additional resources for predators) to improve biological control [5]. We also excluded studies with other biological control agents (e.g. parasites, parasitoids and pathogens). Despite the importance of these other agents for biological control, as far as we know, the overall effect of resident predators on populations of pests and crop yield and of possible moderators are less studied, especially in field studies (see [18], for example). In the third step, we fully read 168 studies and excluded those that (i) did not measure the effect of resident predators on populations of pests and/or crop yield comparing treatment with and without predators (e.g. using field cages, exclusion nets, cloth bags, acrylic resin fences) and (ii) were not performed on crop systems (i.e. excluding studies performed in greenhouses and laboratories). However, it is important to note that not all predator exclusion studies, for example using exclusion nets, guarantee that other predators (e.g. smaller species that can pass through the exclusion nets) do not enter the system/plot. For a more detailed description of predator communities used in the primary studies and our inclusion criteria for predators' exclusion studies see electronic supplementary material, text S1. After this stage, we obtained 86 suitable studies to extract information. Furthermore, studies that performed different experiments (e.g. using different predator species, crops and sites) were considered as individual pairwise comparisons of effect size (k).

To guarantee a standardized screening and extraction protocol among authors of this meta-analysis, we first selected 50 random manuscripts to be compared among two authors (G.X.B. and T.G.-S.) that independently screening these 50 manuscripts in a 'training' spreadsheet. Then, we compared the decision (i.e. select or exclude the manuscript) and fixed potential issues in the decision criteria. After correcting screening bias and answering all doubts from authors about the extracted data, we split the papers into two blocks that were extracted by two authors (G.X.B. and T.G.-S.). After the end of this stage, the leading author screened all papers (including those used in earlier meta-analysis: [8,9]) to assess extraction quality and to fix potential incorrect information.

From these 86 remaining studies (electronic supplementary material, table S6), we extracted the following information: (i) site coordinates; (ii) crop type such as apple, tomato, maize, etc.; (iii) crop species; (iv) predator group; (iv) number of predator species used in the experiment; (vi) treatment (i.e. exclusion or inclusion); (vii) means, standards deviations/errors and sample sizes both from treatment and control extracted from text, tables, appendices and graphs; (viii) response variable (e.g. predation rate, abundance or density of pests and crop yield or biomass). For studies that did not explicitly present the coordinates, we used the location that was provided (e.g. park, city, state) and searched coordinates on the internet (for a similar decision, see [46]). We used predator group as the common name of the taxonomic group. For example, if the predator was from the species *Pardosa astrigera* (Araneae), we classified them as spiders. We only kept predator groups that had more than three studies ($n > 3$), and those with fewer than three studies were grouped into larger classifications (e.g. invertebrates and vertebrates). If the study used only one species (e.g. removing all predators before starting the experiment and then add this specifically predator species to the plot. See for example, [47,48]), we extracted the species name and classified it as a single predator, and if the study used two or more species (see for example, [49,50]), we classified them as multiple predators. A more detailed description of the number of studies per predator group, crop types and predator diversity (single species or multiple species) is provided in the electronic supplementary material (electronic supplementary material, figure S2). Furthermore, if the study compared populations of pests and/or crop yield between a predator exclusion treatment (predator absence) and a control (predator presence), we classified it as an exclusion experiment. If the study included predators (predator presence) and compared them to a control (predator absence), we classified it as an inclusion experiment. We also used these two types of experiments as moderators to see if they influenced the meta-analysis results. Because the effect sizes for both studies were comparable, we merged them in the statistical analysis (see below). Since we merged the extracted data from exclusion and inclusion experiments, we reversed the measures (i.e. treatment and control) in the studies that included predators so that negative and positive effect sizes of both experiment types indicated consistent effects of predator presence. Finally, data that were not presented in the text but were in the figures were collected with the 'Juicr' package version 0.1 [51]. Furthermore, all the studies that met our criteria provided means, sample size and measures of variance (in the text or figures), however, most studies reported the standard error, and to calculate the effect size, we transformed it into the standard deviation.

We also extracted annual (i.e. using the experiment year of each study) bioclimatic variables (i.e. annual mean temperature, temperature annual range and precipitation seasonality) from Worldclim 2.0 [52] and Thornthwaite Aridity Index from Envirem [53] with 2.5 arc-minutes (approx. 5 km) using each study's coordinates. Moreover, because there are studies with different temporal scales (some lasted days, some lasted a year), we collected data (i.e. mean, standard deviation and sample size) from the last measure made in the study, when they did not report a general measure (see [21,54,55], for similar decisions).

We included in our meta-analysis 86 studies and 317 pairwise comparisons testing for the effect of resident predators on populations of pests and/or yield in crop systems. We obtain 76 studies that tested the effect of resident predators on populations of pests in crop systems. Specifically, 51 studies tested natural biological control and 25 tested conservation biological control. Furthermore, 54 studies used exclusion treatments and compared pest suppression with non-exclusion treatment (control) and 22 used inclusion treatments and compared pest suppression in treatments without predators (control). We also examined whether the impacts of predators varied among bats, birds, bugs (i.e. Hemiptera), beetles, spiders and other invertebrates (i.e. Arthropoda predators that did not have three or more studies or studies that mixed Arthropoda species). Overall, the studies included in our meta-analysis covered 32 countries and 28 different crop systems.

(b) Statistical analysis

All study analyses were performed in RStudio 4.3.2 [56] with the 'Metafor' package (v. 4.4-0) [57]. We calculated the effect size as the log transformed ratio of means (lnR) [58] using escalc function. Here, positive effect size values represent lower populations of pests and higher crop yield with the presence of predators. To facilitate the interpretation of the results, we back-transformed the lnR values [(exp lnR −1)]×100, to obtain the differences between treatment and control in percentages (see [59], for example).

To calculate the overall effect size of predator on populations of pests and crop yield we use a three-level meta-analysis model (with restricted maximum-likelihood (REML) as a between-study heterogeneity estimator), with the rma.mv function. We choose this model because our data contain studies with multiple effect sizes so we cannot consider these effects as independent measures. Therefore, we included in all models (see below) two random effects: study identity and effect size identity. Furthermore, species are phylogenetically related, so we included in the models crop species as random effects and phylogeny as a correlation matrix (based on [60]). We reported these two different models because the statistical power of phylogenetic analysis is limited when there are many effect sizes coming from the same study species [61].

To explore the effects of predators on populations of pests and crop yield we performed an analysis with categorical moderators (i.e. predator group and crop type) and to calculate the effect of predator diversity on populations of pests, we use multiple and single predators as categorical moderators also using a three-level meta-analysis model (with REML). Furthermore, to calculate whether climate moderates the overall effects of predators in populations of pests and crop yield and the predator diversity effect on populations of pests, we performed a meta-regression with effect size measures (lnR) as the response variable and the climate variables as predictor variables. We only maintain in the model climatic variables that were not strongly correlated (less than 0.8, see electronic supplementary material, figure S7). We also standardized the climatic variables (scale to zero mean and unit variance) before fitting the models. The values of AICc (Akaike's selection criterion) were used to compare complex models (with all predictor variables) and simple models (removing predictors) with the anova.rma function.

We also used the anova function to perform a test of moderators (Wald-type test (Qm)) to contrast the effects of single-species and multiple-species predators on populations of pests. And we used the var.comp function ('dmetar' package, [62]) to calculate the I^2 statistic to access the amount of variation not attributable to sampling error (i.e. the percentage of heterogeneity between studies). As we perform a three-level meta-analysis model, we can calculate the total I^2 and this heterogeneity variance to true effect size difference within studies (i.e. clustering pairwise comparisons of the same study) and between studies.

(c) Sensitivity analysis

To assess publication bias in our results, we first visually inspected the relationship of effect size to study standard deviation using contour-enhanced funnel plots [63]. We also tested for possible publication bias performing two uni-moderator multilevel meta-regression: one including the square root of the inverse of effective sample size as the moderator and the other including the year of publication (mean-centred) as the moderator [60]. We also performed a multiple moderator publication bias test, which can model both heterogeneity and non-independence, including square root of the inverse of effective sample size, year of publication, and study treatment as moderators [60]. These methods could provide information about the existence of small-study effect (i.e. effect sizes based on small sample sizes tend to be larger) after accounting for non-independence between effect sizes and indicates if positive results are published earlier than negative results [60].

Finally, we also used the Rosenthal fail-safe number to test how many unpublished studies with non-significant results had to be added to the analysis to change the observed significant overall effect sizes to non-significant [64]. Whether the number of observations included in the study is greater than 5n + 10 the results are considered robust against publication bias [64]. Since we had no major changes in our results, we present the results of the sensitivity analysis in the electronic supplementary material (see electronic supplementary material, text S2 and S2 and figures S3 to S6).

3. Results

(a) Descriptive overview

Specifically, we included 76 studies and 270 pairwise comparisons testing for the effect of resident predators on populations of pests in crop systems. Furthermore, we included 19 studies and 47 pairwise comparisons that investigated the effects of predators biological control on crop yield (figure 1, electronic supplementary material, figure S1).

(b) Predators increase both pest control and crop yield

Both natural and conservation biological control reduced pest populations (natural: lnR = 0.57, confidence interval (CI) = 0.42 to 0.72; conservation: lnR = 0.5, CI = 0.29 to 0.72, electronic supplementary material, table S1), and since these two types of biological control are provided by resident predators and their effect sizes were similar ($Qm_1 = 0.25$, $p = 0.61$, electronic supplementary material, table S2), we investigated the effect of resident predators by merging natural and conservation biological control studies. Across all studies, predators reduced pest populations by 73% (i.e. comparing crops with and without predators; lnR = 0.55, CI = 0.43 to 0.67; $Qt = 1532.4$, d.f. = 269, $p < 0.0001$, $I^2 = 91.9\%$, figure 2). Beetles, birds, spiders and other invertebrate predators were all effective biocontrol agents (figure 2, electronic supplementary material, table S1). We failed to detect an impact of bats and hemipterans on pest populations, perhaps due to low number of pairwise comparisons ($k = 4$ and $k = 10$, respectively), as their effect sizes were similar to several of the other predator groups (figure 2, electronic supplementary material, table S1). The presence of predators reduced populations of pests among the different crop types (figure 2, electronic supplementary material, table S1). Specifically, they reduced pests by 51% in cereal crops (lnR = 0.41, CI = 0.18 to 0.64, $p < 0.001$), by 103% in fruit tree crops (lnR = 0.71, CI = 0.45 to 0.96, $p < 0.0001$), and in oils and protein crops (lnR = 0.7, CI = 0.31 to 1.1, $p < 0.001$), by 62% in vegetable crops (lnR = 0.48, CI = 0.21 to 0.75, $p < 0.001$), and by 73% in other crops (lnR = 0.55, CI = 0.30 to 0.8, $p < 0.0001$). Furthermore, in models that account for phylogenetic non-independence the impacts of predators on pest populations were similar (i.e. not changing magnitude and significance of effect sizes. See electronic supplementary material, table S1).

The presence of predators on crops increased crop yield by 25% (lnR = 0.22, CI = 0.09 to 0.35; $Qt = 195.1$, d.f. = 46, $p < 0.0001$, $I^2 = 95.6\%$, figure 3, electronic supplementary material, table S3), indicating a positive overall top-down cascading effect. When we

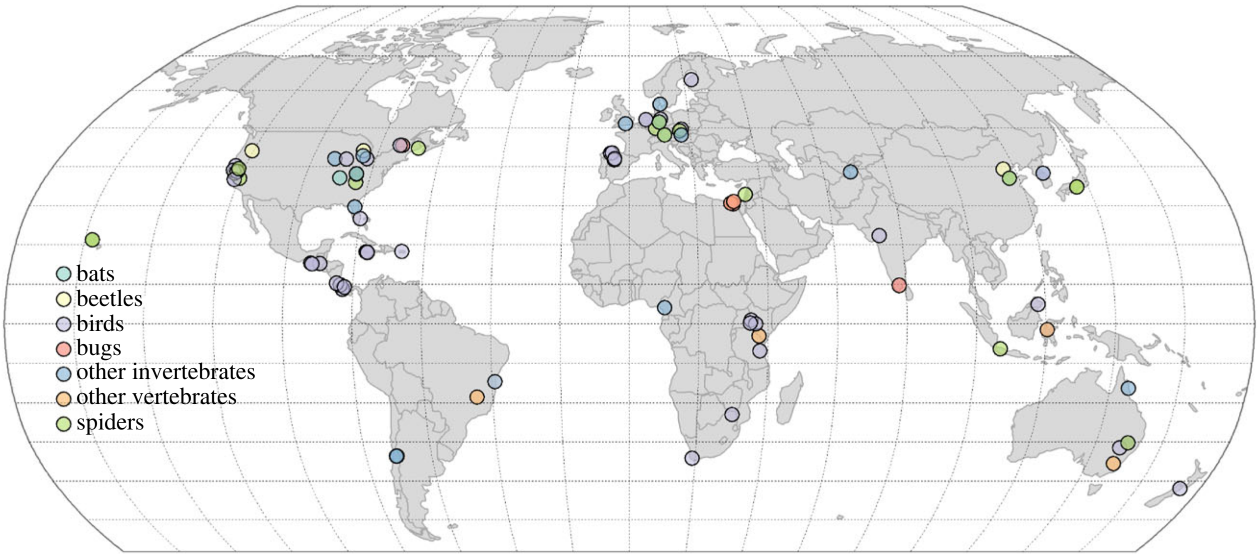

Figure 1. Distribution of studies on the effect of predators on pest populations and/or crop yield (by predator groups) in crop systems included in this meta-analysis.

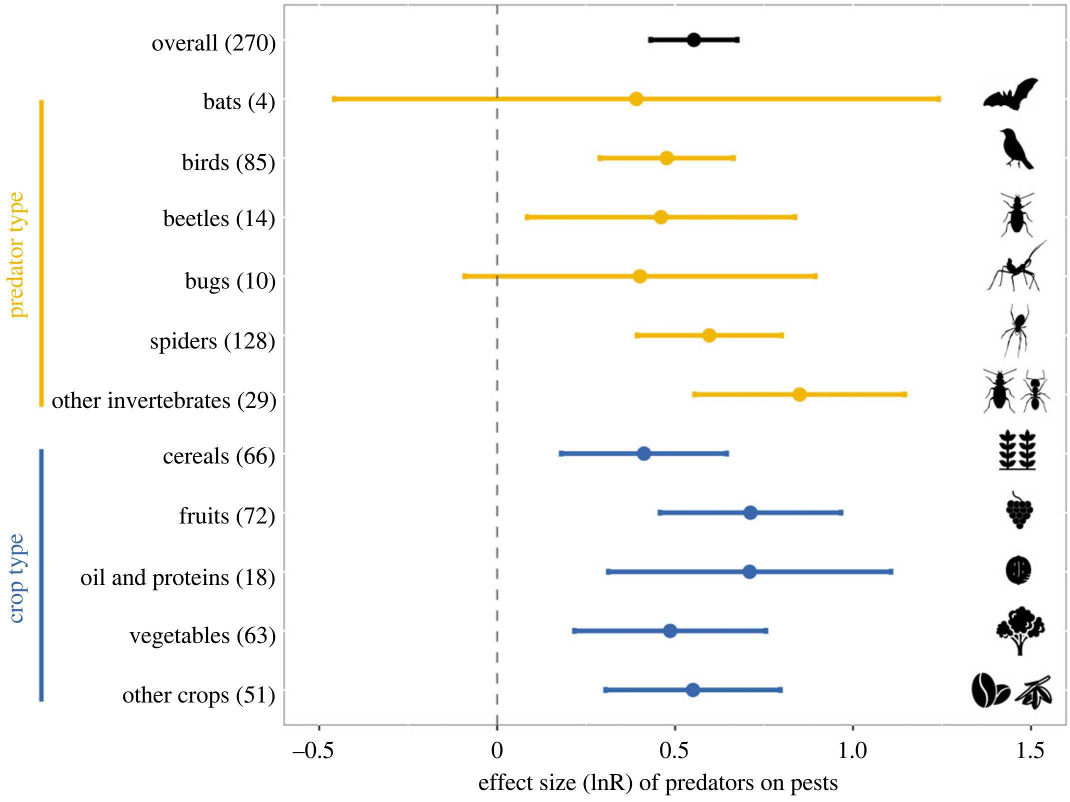

Figure 2. Predator impacts on populations of pests. Points and lines represent mean effect size and confidence intervals (95% CIs). Positive values denote lower populations of pests in the presence of predators. Colours represent the effects by predator groups and crop types, specifically, yellow for predators and blue for crops. The numbers inside parentheses (on the side of predators and crops) are pairwise comparisons (k). Significant results are represented by the lines of effects that did not 'cross' the dashed line (the zero on the *x*-axis). Silhouettes are from http://phylopic.org/ and are licensed under a Creative Commons licence.

evaluated the overall effect of predator presence on crop yield among the different predator groups, we found that beetles (lnR = 0.22, CI = 0.01 to 0.44, p = 0.03), birds (lnR = 0.21, CI = 0.00 to 0.42, *p* = 0.04), and other invertebrates (lnR = 0.31, CI = 0.10 to 0.52, *p* = 0.002) increased crop yield. The increase in crop yield in the presence of predators was consistent among vegetable (lnR = 0.23, CI = 0.03 to 0.43, *p* = 0.02) and other crops (i.e. coffee, cocoa and apple, lnR = 0.28, CI = 0.03 to 0.52, *p* = 0.02). There was no significant effect of predators on cereal yields (although the effect was positive), which may reflect the low number of studies (*n* = 4) and pairwise comparisons (*k* = 13). However, when we consider phylogenetic non-independence, we failed to detect an impact of predators on crop yield (electronic supplementary material, table S3). Specifically, the effect sizes showed a similar magnitude but became non-significant for overall effect (lnR = 0.23, CI = – 0.14 to 0.61; Qt = 195.05, d.f. = 46, *p* = 0.22), beetles (lnR = 0.24, CI = – 0.17 to 0.65, *p* = 0.25), birds (lnR = 0.34, CI = – 0.07 to 0.76, *p* = 0.10), other invertebrates (lnR = 0.22, CI = – 0.18 to 0.64, *p* = 0.27), vegetables (lnR = 0.27, CI = – 0.20 to 0.75, *p* = 0.26) and other crops (lnR = 0.2, CI = – 0.37 to 0.78, *p* = 0.48), and remained similar to spiders (lnR = 0.26, CI = – 0.14 to 0.67, *p* = 0.20), other vertebrates (lnR = 0.06, CI = – 0.2 to 0.75, *p* = 0.83) and cereals (lnR = 0.2, CI = – 0.36 to 0.77, *p* = 0.48).

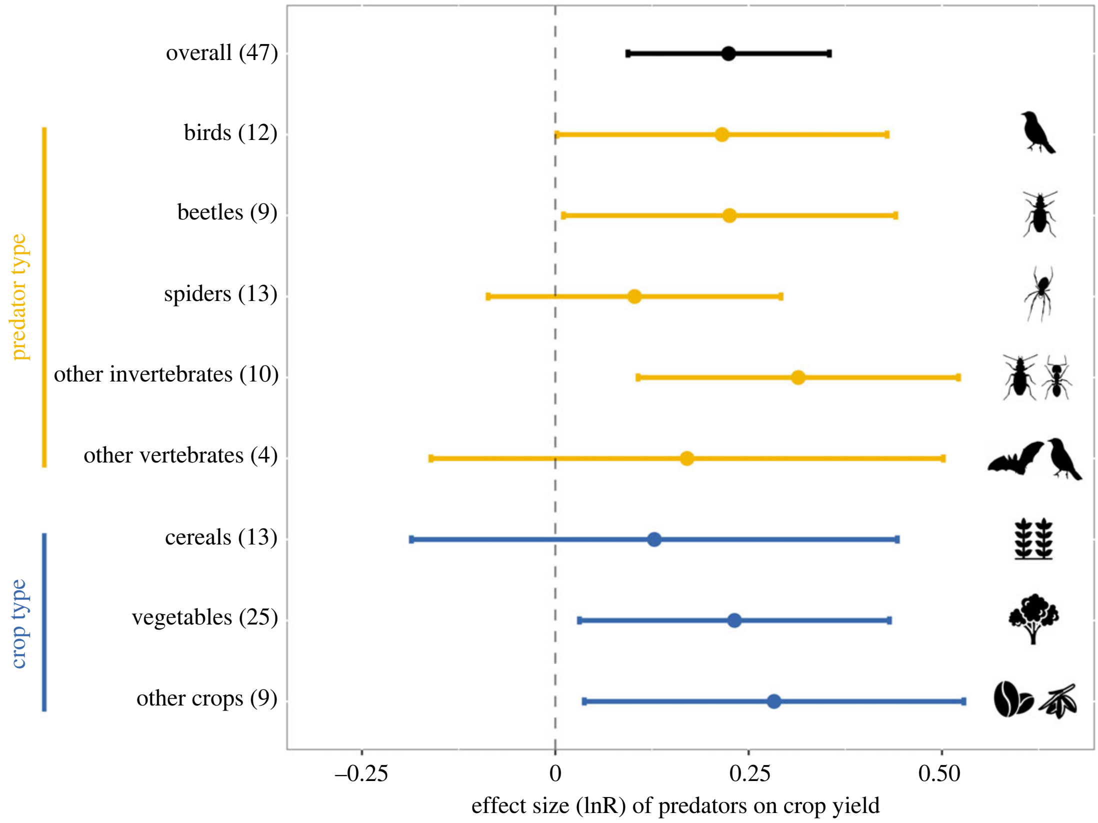

Figure 3. Predator impacts on crop yield. Points and lines represent mean effect size and confidence intervals (95% CIs). Positive values denote higher crop yield in the presence of predators. Colours represent the effects by predator groups and crop types, specifically, yellow for predators and blue for crops. The numbers inside parentheses (on the side of predators and crops) are pairwise comparisons (k). Significant results are represented by the lines of effects that did not 'cross' the dashed line (the zero on the *x*-axis). Silhouettes are from http://phylopic.org/ and are licensed under a Creative Commons licence.

(c) Crops with single and multiple predators had similar pest control

The impacts of multiple predator species on pest populations were similar to the impacts of single predator species when compared to treatments without predators. We found that single-species predator treatments reduced pest populations by 60% (lnR = 0.47, CI = 0.2 to 0.73, $p < 0.001$, figure 4, electronic supplementary material, table S4). Likewise, populations of pests decreased by 69% (lnR = 0.52, CI = 0.36 to 0.68, $p < 0.0001$) in multiple-species predator treatments compared to predator-exclusion treatments. These impacts were statistically indistinguishable ($Qm_1 = 0.12$, $p = 0.72$, electronic supplementary material, table S2) suggesting that in crops, multiple-species predators did not perform higher biological control than single-species predator. This was true, regardless of whether the predators were birds, beetles or spiders (figure 4, electronic supplementary material, tables S2 and S4). Furthermore, in models that account for phylogenetic non-independence the impacts of predator diversity on pest populations were similar (i.e. not changing magnitude and significance of effect sizes. See electronic supplementary material, table S4).

(d) Precipitation seasonality increases pest control performed by predators

To investigate whether climatic factors alter the impacts of biological control, we performed meta-regressions using mean annual temperature, temperature annual range, annual precipitation and aridity (table 1) as continuous moderators and the effect sizes as response variables. We found that precipitation seasonality (the only climatic variable included after model selection) had a positive relationship with predator effects on populations of pests (slope: 0.16, $p = 0.0064$; figure 5), indicating that predators reduce populations of pests more strongly in sites with higher precipitation seasonality. When we included phylogeny, the results were similar (slope: 0.16, $p = 0.0073$). Furthermore, when we tested if climatic factors alter the effect of single-species and multiple-species predators on populations of pests, none of climatic factors were correlated to the effect sizes. Similarly, climatic factors did not affect predators' effect on crop yield (electronic supplementary material, table S5).

4. Discussion

Predators in crop systems reduced populations of pests and increased crop yields in a way that was consistent among predator groups and crop types. Surprisingly, the impact of a single predator species was equivalent to the impacts of multiple predator species on pest populations, and the only climatic factor that mediated the impacts of predators was precipitation seasonality. Crops in more seasonal regions had lower populations of pests due to biological control performed by predators. Taken together, this evidence indicates that predators are effective resident agents of biological control across crop types, and any predicted changes in climate (i.e. increased precipitation seasonality) will likely enhance their impacts on crop pests.

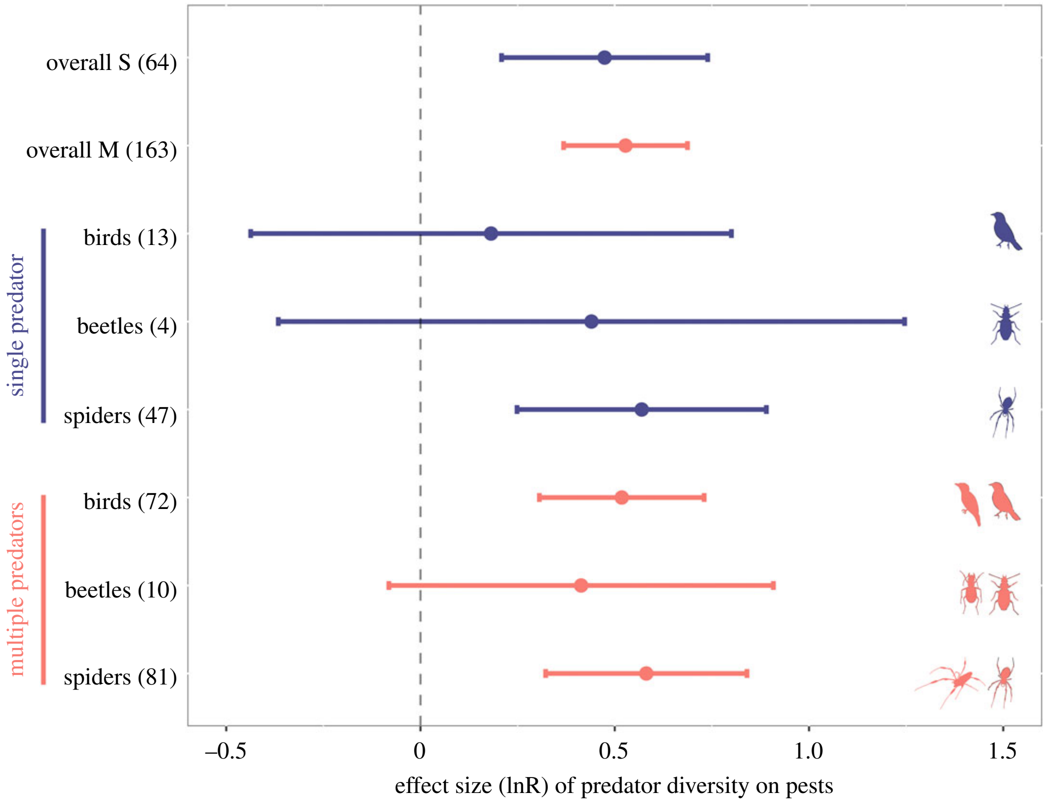

Figure 4. Predator diversity impacts on populations of pests. Points and lines represent mean effect size and confidence intervals (95% CIs). Positive values denote lower populations of pests in the presence of predators. Colours represent the effects of predator diversity, specifically, purple for single-species predators (i.e. one predator species) and red for multiple-species predators (i.e. two or more predator species). The numbers inside parentheses (on the side of predators and crops) are pairwise comparisons (k). Significant results are represented by the lines of effects that did not 'cross' the dashed line (the zero on the *x*-axis). Silhouettes are from http://phylopic.org/ and are licensed under a Creative Commons licence.

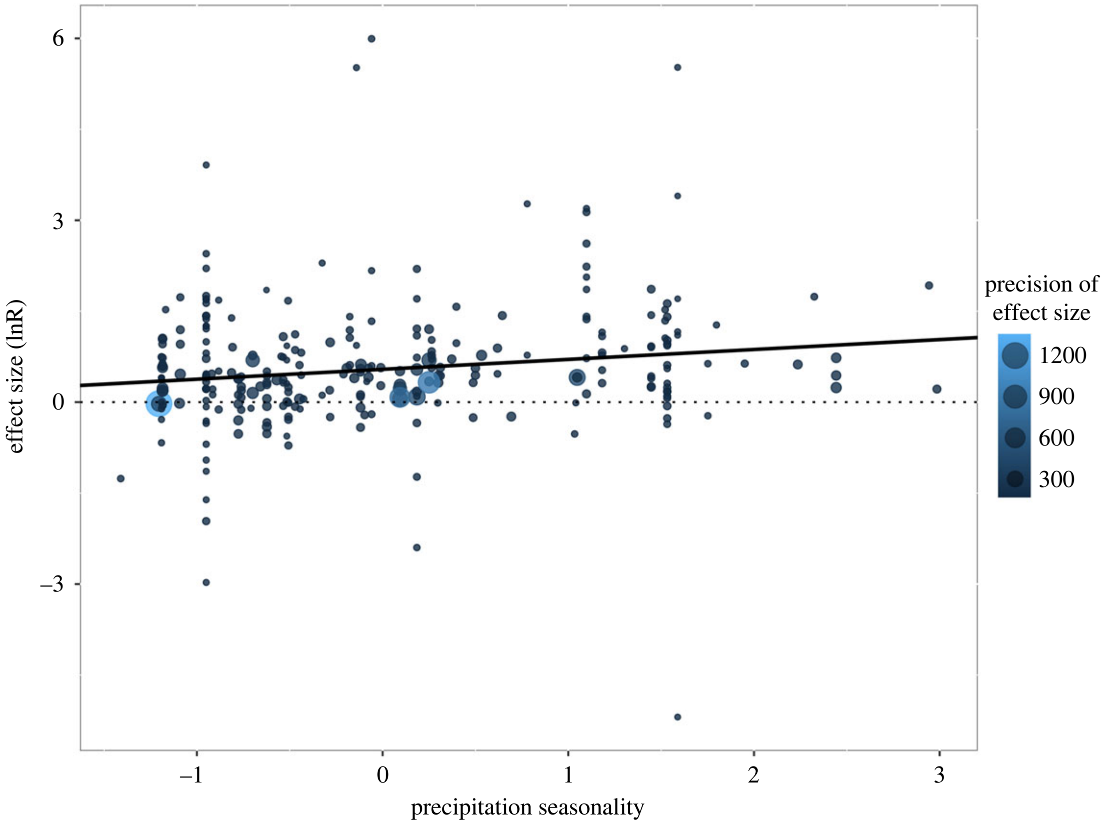

Figure 5. The effect of precipitation seasonality on predator impacts on populations of pests. Dots represent pairwise comparisons (k) of predators' effects on populations of pests. Positive values denote lower populations of pests in the presence of predators. Colour and size of dots represent the precision of effect size (i.e. the inverse of effect size's variance). Bigger and clearer (blue scale) dots denote more precise effects. Note that the values of precipitation seasonality are standardized (scale to zero mean and unit variance).

Predators increased crop yield and reduced pest populations. This finding is consistent with previous studies indicating that predators can reduce insect and pest abundance and benefit crops [8,9,18,43]. Our study reinforces the role of predators on suppression of terrestrial herbivore populations [65,66] and demonstrates the importance of predators as a biological control agent in a variety of crop systems. This result also highlights that predators could reduce pest populations and increasing yield even in crop systems, which tend to be simpler environments than natural or semi-natural habitats and could lead to more strong species interactions ([67], but see for example enemies' hypothesis: [68,69]). Although the influence of landscape context on biological control is outside the scope of our study, other possible explanations might be that landscape complexity at different scales is also important for biological control, and pest control in crops inserted in complex landscapes may benefit from additional resources [70,71]. Furthermore, to the best of our knowledge, our study is the first to suggest positive indirect effects of predators on crop yield across predator groups and crop types. Taken together, these results suggest a broad effectiveness of resident predators as biological control agents. However, we realize that publication bias likely occurs, such that only those studies that show success of biological control agents are likely to be published [72]. Furthermore, we suggest that the results on the effect of predators on crop yield should be interpreted with caution, since we failed to find an impact of predators on yield when phylogeny was considered. It is important to note that the phylogeny was conducted with a limited number of species (i.e. 13 species), and a few species accounted for many effect size measures. Therefore, this meta-analysis also indicates that there are few manipulative-field studies assessing the impact of natural predators on crop yield. More manipulative-field studies in different crop species are necessary to obtain more accurate results.

Biological control performed by multiple predator species was no more effective than that performed by single predator species, regardless of the predator group (i.e. beetles, birds and spiders). This result differs from previous work showing that multiple species of natural enemies (i.e. predator, parasitoid, pathogen) were more effective at reducing pest abundance than single species of natural enemies [18]. However, our study compared only predators, and the variability of predator traits (e.g. body size, hunting mode and dietary specialization) may be lower than the natural enemies' groups tested in previous work [18]. This may explain why we found no difference in biological control between crops with one predator and those with multiple predator species. Despite being beyond the scope of this study, functional traits of predators and prey may be determining factors for the relationship between predator diversity and biological control [15,22,40]. In addition, intraguild predation in multiple predator treatments could favour prey release and alleviate the negative effects of predation on pest populations [10,73]. On the other hand, our study highlights that overall, a single species of resident predator can provide pest control at least as strongly as multiple species.

Predator effects on pests were higher in regions with more precipitation seasonality. Similarly, a previous meta-analysis also showed that predator-mediated biological control on aphids increased with increasing precipitation seasonality [74]. The positive effect of precipitation seasonality on biological control can be explained by how predators and prey respond to precipitation seasonality in terms of their physiology and behaviour. For example, lower water availability can increase plant consumption by herbivores and predator and prey interactions in order to maintain their water balance [42,75,76]. Consequently, this process could favour biological control. However, if this drought condition persists, pest populations may decrease, due to high predation pressure and low plant nutrient availability and could therefore result in a decline in predator populations [42]. On the other hand, greater water availability could favour biological control via bottom-up effects [42]. Taken together, precipitation seasonality can favour pest control by favouring predation pressure in conditions of low water availability and by preventing predator populations from declining as water availability increases.

Our meta-analysis also highlights key gaps in studies on biological control by predators. Few studies have been conducted in crop systems in the Global South, neglecting the importance of predators as natural enemies of pests and the factors that affect biological control in countries with high biodiversity and food production [77]. Some predator groups, such as bats, are still poorly studied in experiments to measure the effect of bat diversity on biological control, although their importance as consumers of pests is widely recognized [78,79]. Finally, some of our results should be interpreted with caution because of the low number of studies and large variation in effect size (e.g. effect of vertebrates group on crop yield).

Here, we demonstrate top-down effects of resident predators on populations of pests, which cascade down to enhance crop yield. Furthermore, we show that a single species of resident predator can provide pest control at least as strongly as multiple species. This is important as it highlights how beneficial it is to conserve natural predator species in crop systems. More importantly, our results confirm that resident predators can act as a buffer against climate change [80,81], providing biological control services in crop systems. This is because global climate projections predict that precipitation will become more variable in some regions, with changes in the frequency and intensity of precipitation [36,82]. We therefore argue that future studies should incorporate climate-mediated cascade effects of top-down pest control to better understand the ecological processes that maintain this key ecosystem service. This can help to develop optimal strategies for biological control management to mitigate the effects of climate change on agricultural systems and food production [83–85]. Our meta-analysis suggests that, even in regions with high precipitation seasonality and regardless of the natural occurrence of one or several species, predators are broadly effective at controlling pests and increasing yield in a variety of crop systems. While implementing biological control at scales necessary to increase crop production to minimize global hunger is a daunting challenge, our results indicate that carefully deploying biological control should be carefully considered.

Ethics. This work did not require ethical approval from a human subject or animal welfare committee.

Data accessibility. The data and R code supporting this article are included in the electronic supplementary material [86].

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

Authors' contributions. G.X.B.: conceptualization, data curation, formal analysis, writing—original draft, writing—review and editing; M.A.M.: writing—review and editing; G.Q.R.: conceptualization, writing—review and editing; K.L.M.: formal analysis, writing—review and editing; N.J.S.: writing—review and editing; P.B.R.: writing—review and editing; R.M.: data curation, writing—review and editing; T.G.-S.: conceptualization, data curation, formal analysis, writing—original draft, writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

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