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Biological control interventions reduce pest abundance and crop damage while maintaining natural enemies in sub-Saharan Africa: a meta-analysis

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Insect pests are a major challenge to smallholder crop production in sub-Saharan Africa (SSA), where access to synthetic pesticides, which are linked to environmental and health risks, is often limited. Biological control interventions could offer a sustainable solution, yet an understanding of their effectiveness is lacking. We used a meta-analysis approach to investigate the effectiveness of commonly used biocontrol interventions and botanical pesticides on pest abundance (PA), crop damage (CD), crop yield (Y) and natural enemy abundance (NEA) when compared with controls with no biocontrol and with synthetic pesticides. We also evaluated whether the magnitude of biocontrol effectiveness was affected by type of biocontrol intervention, crop type, pest taxon, farm type and landscape configuration. Overall, from 99 studies on 31 crops, we found that compared to no biocontrol, biocontrol interventions reduced PA by 63%, CD by over 50% and increased Y by over 60%. Compared to synthetic pesticides, biocontrol resulted in comparable PA and Y, while NEA was 43% greater. Our results also highlighted that the potential for biocontrol to be modulated by landscape configuration is a critical knowledge gap in SSA. We show that biocontrol represents an effective tool for smallholder farmers, which can maintain yields without associated negative pesticide effects. Furthermore, the evidence presented here advocates strongly for including biocontrol practices in national and regional agricultural policies.

1. Introduction

One of the greatest global challenges of the twenty-first century is meeting the increasing demands for food production while minimizing adverse impacts on biodiversity and ecosystem health [1]. This challenge is particularly critical in

Table 1. Definitions of biological control interventions included in the meta-analysis.

biocontrol intervention	description
botanical pesticides	insecticidal compounds in the form of water, oil or powder extracted from the leaves, seeds, pods, roots, bark, flower or fruits, of plants known to have pesticidal properties either from cultural knowledge or laboratory experiment
augmentation/ introduction	increase the number of parasitoids, predators or entomopathogens by releasing the natural enemy (introduction, inoculation and inundation) or by supplying their food resources
intercropping	simultaneous cultivation of plant species in the same field for most of their growing period, e.g. cereal and beans or other food plants
push–pull	intercropping of maize or other crops with perennial fodder legumes (e.g. <i>Desmodium</i> spp.) to repel (push) pests. A trap crop, a perennial fodder (Napier grass or <i>Brachiaria</i> spp.) is planted around the plot to attract (pull) pests away from the crop
field margins	strip of land between the crop and the field boundaries sown with wildflowers and/or legumes, grass only or naturally regenerated
landscape effect	the effect of distance of cultivated areas to natural habitat, non-crop habitat and/or landscape complexity on the delivery of biocontrol

sub-Saharan Africa (SSA) where the population is predicted to double over the coming decades [2], and food production is hampered by climate change impacts [3], which exacerbates significant yield losses already caused by crop pests [4,5]. For example, the invasion of the fall armyworm (*Spodoptera frugiperda*), which has caused crop losses of about \$3 billion a year in SSA, has become one of the most important threats to maize production [6]. The fall armyworm is also a cause of major damage to other crops, including rice, sorghum, millet, cabbage and tomatoes, demonstrating the vulnerability of smallholder farming to crop pests.

Conventional synthetic pesticides have severe limitations as a means of pest control in SSA because they are economically inaccessible for a large portion of smallholder farmers in the region [7]. Pesticide residues also put human and livestock populations at risk from contaminated food and forage [8,9]. Furthermore, synthetic pesticides may lead to resistance in pest populations [10], and have negative impacts on non-target organisms, such as pollinators and natural enemies, and the ecosystem services that biodiversity provides in the production of food [11–13]. If the reduction of natural enemy populations is greater than that of the pest, this may lead to the resurgence of pests following pesticide applications [14], which is a widely reported problem associated with synthetic pesticides [15].

Biological control methods (hereafter biocontrol), which employ natural enemies of crop pests, have been adopted globally as an alternative approach to synthetic chemical pest control, and are often used as part of an integrated pest management strategy [16,17]. Extensive evidence is available on the responses of natural enemies to the landscape configuration surrounding crop fields [18], which reveals that landscape effects, albeit giving inconsistent responses, may be a key driver of pest regulation by natural enemies. Recent syntheses show consistent positive responses of natural enemies to landscape complexity [13], with higher natural enemy populations in complex versus simple landscapes [19] and a reduction of natural pest control in simplified landscapes [20].

However, meta-analyses of this kind are strongly biased in favour of the Northern Hemisphere, or they are global in scope, and so lack the scale of analysis that might be useful to

policy makers in the SSA region. Furthermore, inputs such as chemicals fertilizers and pesticides are typically much less in Africa, and we would expect the effectiveness of biocontrol strategies to be different. There is a recognized need to develop evidence-based, environmentally friendly biocontrol management strategies in SSA, which boost capacities for their implementation across farming systems, locations and scales. This is exemplified by the Food and Agriculture Organization of the United Nations, who recognize that coordination and collaboration on fall armyworm control will require the implementation of environmentally sustainable pest management practices and policies at the regional, national and farmer-level [21].

In SSA, in addition to conventional biological control approaches that use live natural enemies such as predators, parasitoids and pathogens, smallholder farmers have recently adopted conservation biocontrol methods and plant-based botanical pesticides for the control of crop pests [22]. Conservation biocontrol methods include intercropping, push–pull technology and the maintenance of plant-rich field margins. Growing evidence highlights the potential of biocontrol interventions to reduce pest incidence and increase yield [23,24]. For example, push–pull technology has been shown to be effective against a range of crop pests, particularly maize stem borers [25] and botanical pesticides can reduce pest incidence and enhance yield in vegetable crops [26,27].

Although biocontrol interventions and botanical pesticides may provide sustainable and accessible alternatives to synthetic pesticides, their adoption by smallholder farmers has not been widespread [28]. This may be owing to knowledge gaps relating to their effectiveness and the factors that lead to their success or failure, particularly in comparison to synthetic pesticides. Biocontrol techniques have been applied to numerous crops and targeted a wide variety of pests in the region, yet there is a lack of understanding of how the effectiveness of biocontrol varies across different crop types and pest taxa [28]. Recent research in Tanzania found greater natural enemy diversity in fields surrounded by intercropped fields, suggesting spatial flow of potential biocontrol services across landscapes [29]. However, the established relationship between landscape configuration, natural enemies and pest regulation is almost entirely based

Table 2. Summary table of hierarchical meta-analysis models showing total heterogeneity, i.e. the effects of biocontrol interventions on the outcome measures without moderators (all), and heterogeneities explained by moderators: biocontrol intervention technique (botanical pesticides, field margins, intercropping and push-pull); crop type (cereal, fruits, fibre, pulses and vegetables); target pest taxon (Coleoptera, Hemiptera, Lepidoptera and Blattodea); and farming type (small farms and research farms) with the respective residual heterogeneities.

	d.f.	Q	p-value
pest abundance			
all	326	209370.95	<0.0001
biocontrol intervention	4	5.63	0.2133
technique			
residuals	322	205390.18	<0.0001
crop type	5	2.08	0.8368
residuals	321	58546.03	<0.0001
target pest taxon	5	3.61	0.6065
residuals	321	65549.49	<0.0001
farming type	1	2.74	0.0976
residuals	325	145118.45	<0.0001
crop damage			
all	239	13539.39	0.0120
biocontrol intervention	4	4.87	0.3003
technique			
residuals	235	11354.65	<0.0001
crop type	5	46.14	<0.0001
residuals	234	10586.19	<0.0001
target pest taxon	4	5.49	0.2402
residuals	235	11998.69	<0.0001
farming type	1	2.82	0.0931
residuals	238	13232.17	<0.0001
yield			
all	269	8706587.83	<0.0001
biocontrol intervention	4	23.13	<0.0001
technique			
residuals	265	8686621.24	<0.0001
crop type	5	1.26	0.9387
residuals	264	8697271.27	<0.0001
target pest taxon	5	3.77	0.5823
residuals	264	8691922.59	<0.0001
farming type	1	0.0679	0.7945
residuals	268	8706137.58	<0.0001
natural enemy abundance			
all	69	711.5758	<0.0001
biocontrol intervention	3	6.33	0.0966
technique			
residuals	66	626.78	<0.0001
crop type	4	8.94	0.0624
residuals	65	297.49	<0.0001

(Continued.)

Table 2. (Continued.)

	d.f.	Q	p-value
target pest taxon	2	12.61	0.0018
residuals	67	210.88	<0.0001
farming type	1	0.84	0.3580
residuals	68	303.21	<0.0001

on studies carried out in the global north and some global south regions [30], but very seldom in sub-Saharan regions where farmers are most exposed to food insecurity caused by crop pests [31]. More clarity is needed about the environmental factors affecting biocontrol and botanical pesticide performance in SSA to better assist in smallholder farmer decision-making, and to determine the broader indirect impact of pest management options on biodiversity compared to synthetic pesticides, both on a farm and at a landscape scale.

Quantitative analyses have been conducted on the performance of biocontrol agents [32], on the impact of landscape context on augmentative biocontrol [33] and pest and natural enemy responses [13]. However, none of these approaches have focussed specifically on the sub-Saharan region showing a geographical bias, nor have they evaluated the efficacy of different biocontrol interventions on pest populations and their damage to crops.

Here, we aim to better understand the key factors driving the success or failure of biocontrol interventions using quantitative meta-analysis. We broaden the definition of biocontrol interventions to encompass biological control using live organisms, as well as conservation agriculture and plant-derived botanical pesticides, which represent more recent pest control innovations. There has been very little assessment of their efficacy, especially botanical pesticides, as alternatives to synthetic chemical pesticides. Specifically, we posed the following questions: (i) what are the effects of biocontrol interventions on the management of insect crop pests in SSA? (ii) are these effects consistent across biocontrol techniques, crop types, target pests and farming systems? (iii) how does the effectiveness and impact of biocontrol interventions on crop pests and non-target insects compare to synthetic pesticides? and (iv) does the surrounding landscape configuration affect the efficacy of biocontrol interventions?

We hypothesized that pest abundance (PA) and crop damage (CD) would decrease, and crop yield (Y) would increase in crops subject to biocontrol interventions, that the impact on natural enemy abundance (NEA) would be less than that of synthetic chemical pesticides, and that these effects would be enhanced in fields surrounded by greater landscape complexity.

2. Material and methods

(a) Data collection and inclusion criteria

To identify candidate studies, we screened a dataset included in a systematic map review carried out by Ratto *et al.* [28] that described the existing literature on biocontrol interventions for insect pests of crops in SSA. Ratto *et al.* [28] systematically searched Web of Science All Databases and Scopus, using a combination of search terms relating to a wide range of biocontrol

techniques and insect pests (e.g. biocontrol, intercrop*, army-worm), agricultural settings (e.g. agri*, farm*) and the target geographical location (e.g. SSA, Southern Africa) (electronic supplementary material, table S1). The grey literature was captured by conducting additional searches on Google and Google Scholar and by searching websites of relevant institutions (electronic supplementary material, table S2). This mapping review covered a period between 2005 and April 2021 and was summarized narratively, with no quantitative analysis performed.

We integrated this initial dataset (149 articles) [28] with a follow up search of relevant papers published between April 2021 and December 2021 using the same search term combination. This search yielded 146 articles potentially appropriate for our review. We used the RepOrting standards for Systematic Evidence Syntheses (ROSES) [34] (electronic supplementary material, figure S1). Only articles published after 2005 were included to reflect modern biocontrol practices and to determine biocontrol effectiveness within a short timeframe. We focused on the sub-Saharan region, which has a large population of smallholder farmers who depend on local food production, and who suffer substantial incidences of insect pest outbreaks and CD that threatens their food security.

We included in the definition of biocontrol interventions any practice that uses natural enemies of pests, or chemical products derived from nature, for the control of pest populations. These include the augmentation, introduction or inoculation of natural enemies (i.e. predators, parasitoids and entomopathogens, such as bacteria, viruses and fungi), and conservation biocontrol (table 1). Conservation biocontrol was defined as the manipulation of habitat to enhance NEA and diversity [24] and included push-pull technology, intercropping and the maintenance of field margins. Botanical pesticides, defined as substances derived from natural materials (e.g. plant extracts), were also included.

To ensure biologically meaningful comparisons, we applied further inclusion criteria. Only articles that quantitatively measured biocontrol performance on the outcome measures were included in the analysis. Only studies with replicated treatments at one or more sites were included. We screened studies wherein PA, CD, Y or NEA (hereafter 'outcome measures') were compared between crops following the implementation of a biocontrol intervention and untreated crops. We also extracted, where available, data on the outcome measures in crops treated with synthetic pesticides. Measures of CD included dead hearts (i.e. drying of the central shoot), damage to stems (e.g. stem tunnelling), pods, leaves, fruits, shoots that were specific to the target pests. Y was reported as either kg ha^{-1} or tonne ha^{-1} , which was standardized to the latter for analysis.

We categorized the sites that had been exposed to a biocontrol intervention as 'treatment', with those that were left untreated as 'negative control (-)' and those treated with synthetic pesticides as 'positive control (+)'. The mean, standard deviation and sample size of outcome measures were recorded for both the treatment and controls. When data were presented only in figures, we extracted data using IMAGEJ software [35]. We contacted the lead authors of the studies that had incomplete data.

For articles that presented multiple years of data sampling at the same site, we used the most recent data to control for non-independence of temporal data [36]. When the study was conducted in two or more spatially independent sites, we recorded them as independent observations. When a study presented outcome measures for several successive weeks, we averaged the means and recorded it as a single effect size. When different concentrations or different types of biocontrol agent were applied (e.g. entomopathogens and botanical pesticides), we used the highest concentration and recorded each biocontrol type as an independent observation. The screening resulted in a total of 99 articles and 512 studies included in the analysis (figure 1; electronic supplementary material, table S3 and figure S1).

(b) Statistical analysis

In our meta-analysis, the log of the response ratio ($\ln RR$) represents the influence of biocontrol interventions on the outcome measures and expresses the proportional difference between the treatment and the control groups [37]:

$$\ln RR = \ln(x_1) - \ln(x_2),$$

where x_1 is the mean of the outcome measure when biocontrol is applied (treatment), and x_2 is the mean of the outcome measures under the untreated condition (control -) or after synthetic pesticide application (control +).

All outcome measures were analysed separately (PA, CD, Y and NEA). Fitted random effects models were used to calculate the overall means and 95% confidence intervals (CI) for each outcome measure to determine if biocontrol interventions significantly affected the outcome measures when compared to control areas (both untreated and pesticide treated). Random effect models do not assume that any variation in the effect size is due only to sampling error, and, instead, allow for a real random component of variation in effect size between studies (e.g. regional differences in study location). An effect of biocontrol intervention was considered significant if the 95% biased-corrected bootstrap CI of the effect size did not overlap zero [38].

Meta-regression was used to explore sources of heterogeneity across each dataset. Our analysis focussed on the following ecological, environmental and experimental parameters: (i) biocontrol technique; (ii) crop type; (iii) target pest taxon; and (iv) farming system. However, we could not use landscape complexity as a moderator as we found too few studies that investigated landscape context. To elucidate the variability of biocontrol efficacy across biocontrol techniques, we grouped studies according to whether they applied botanical pesticides, intercropping, field margins (border planting including legumes, sorghum or wild grasses), push-pull or augmentation/introduction methods. To determine if the effectiveness of biocontrol was dependent on crop type, we classified the study focus crops into cereal, fibre, fruits, vegetables and pulses. We did not include stimulants (e.g. coffee and cocoa) and nuts owing to small sample sizes. To establish whether biocontrol effectiveness varied across different pest insect taxa, we classified studies according to taxon of the targeted pest (Coleoptera, Hemiptera, Lepidoptera and Blattodea). Lastly, we classified studies into two field types: small farm (real smallholder farming conditions) and research farm (experimental field within a research centre), to identify any difference between these systems. Large commercial horticulture farms were not included in the meta-analysis as we primarily focussed on smallholder farmers and their food security. The above parameters were tested one by one as a sole moderator (i.e. fixed effects) for each outcome measure. To account for multiple comparisons from the same article, each model included 'study' nested within 'article' as random effects. The mean log response ratios and upper and lower bounds of 95% CI around the mean were back-transformed with the formula $(e^{\ln R} - 1) * 100$ and expressed as per cent change relative to the controls to facilitate interpretation.

We assessed publication bias in a number ways. We first visually assessed funnel plots for strong asymmetries (electronic supplementary material, figure S2) and ran Egger's regression test [39,40] and the trim-and-fill test [41]. Visual inspection of the funnel plots revealed symmetrical distribution of effect size around the meta-analytical mean of all outcome measures apart from PA. Egger's test indicated that publication bias was significant for the PA ($z = -2.1065$, $p = 0.0352$), which was inconsistent with the trim-and-fill tests that showed no missing studies for all datasets. Furthermore, we evaluated the sensitivity of our analysis by computing an influential case diagnostic and comparing fitted models with and without influential effect sizes; influential outliers were defined as those effect sizes whose hat values were two times larger than the average hat value and standardized

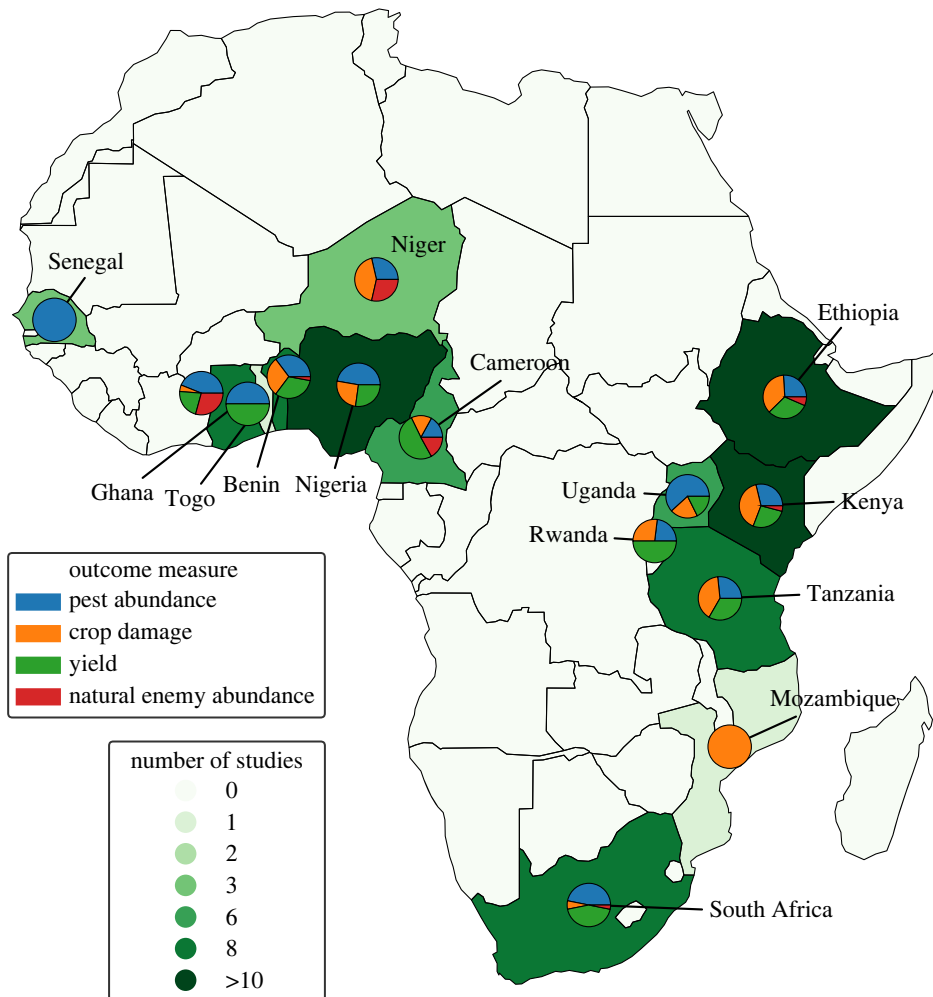


Figure 1. Geographical distribution map of studies included in the meta-analysis; colour coded by number of studies recorded per country. The pie charts show the outcome measures for each country, with blue, orange, green and red in the pie charts showing the proportion of outcomes for pest abundance, crop damage, yield and natural enemy abundance, respectively. (Online version in colour.)

residual values exceeding 3.0 [42] (electronic supplementary material, figures S3–S4). We also estimated the Rosenberg fail-safe number on all datasets, which is the number of non-significant unpublished studies required to eliminate a significant overall effect size (Rosenberg [43]). All statistical analyses were performed using the ‘metafor’ package in R (v. 4.1.2) [44].

3. Results

(a) Comparison with no pest control

Overall, relative to farms without any pest control method, biocontrol interventions had a strong negative effect on PA and CD, which were reduced by 55 and 60%, respectively (table 2; figure 2). Crops subject to biocontrol exhibited a 62% increase in Y. However, we found no significant overall effect of biocontrol on NEA (-19%) (figure 2). There was substantial heterogeneity for all outcome measures, suggesting unexplained variation (PA, $I^2 = 54.98\%$; CD, $I^2 = 51.35\%$; Y, $I^2 = 69.20\%$, NEA, $I^2 = 92.35\%$) (figure 2). Hence, we used meta-regression to elucidate the effect of potential moderators.

(b) Factors affecting biocontrol effectiveness

(i) Biocontrol intervention technique

Overall, the most tested biocontrol approaches were botanical pesticides ($n = 244$), followed by intercropping ($n = 163$)

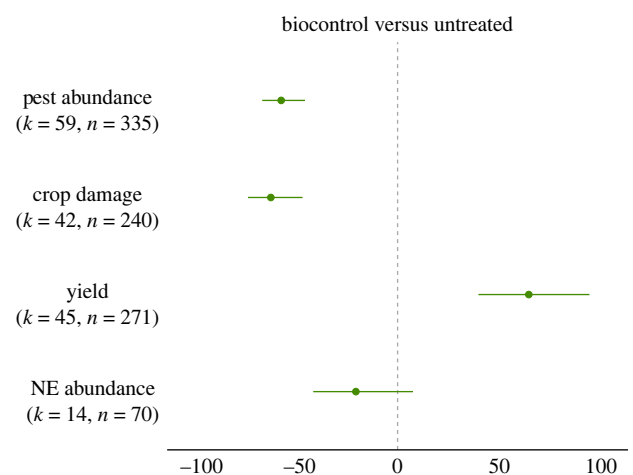


Figure 2. Changes in pest abundance, crop damage, yield and natural enemy (NE) abundance when biocontrol interventions are implemented compared to untreated crops (untreated/monocropping). The values are expressed in percentage with 95% bias-corrected confidence intervals. Results that cross zero indicate no significant difference between control and treatment groups. k = number of articles, n = number of effect sizes. (Online version in colour.)

and push–pull ($n = 46$), followed by both field margins ($n = 38$) and augmentation/introduction ($n = 38$). We found that Y was significantly affected by the nature of the biocontrol intervention, with botanical pesticides and push–pull

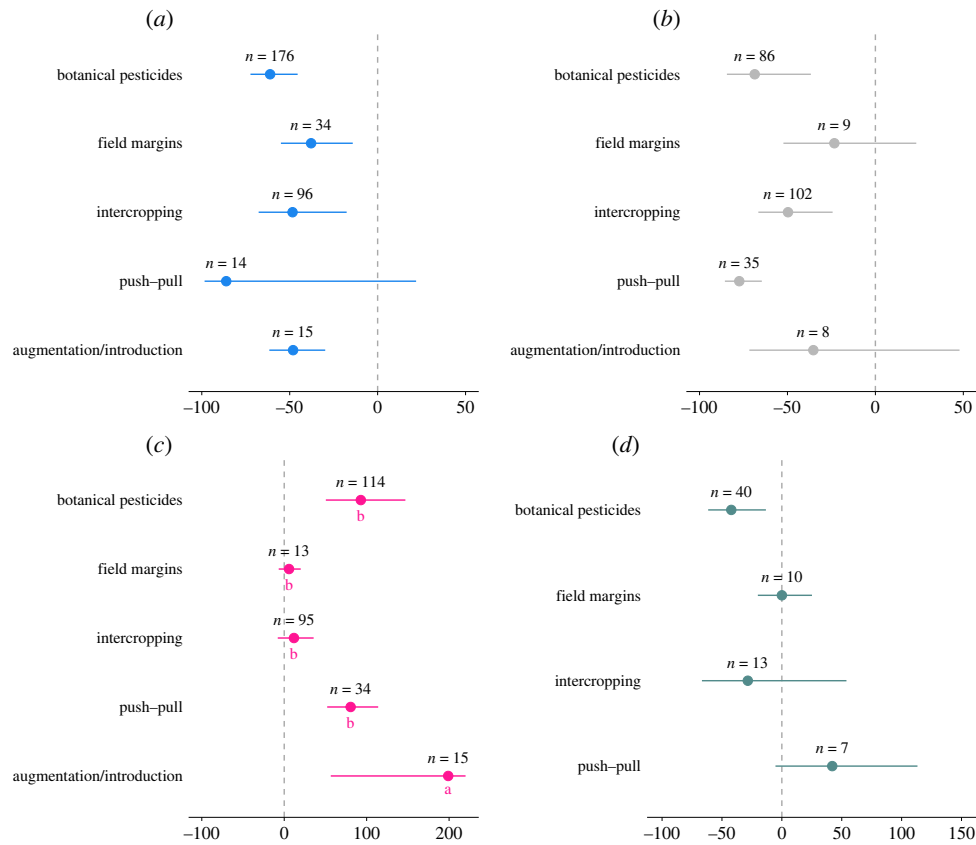


Figure 3. Changes in (a) pest abundance, (b) crop damage, (c) yield and (d) natural enemy abundance when biocontrol interventions are implemented compared to untreated crops (untreated/monocropping). The values are expressed in percentage with 95% bias-corrected confidence intervals categorized as botanical pesticides, field margins, intercropping, push-pull, and augmentation/introduction. Results that cross zero indicate no significant difference between control and treatment groups; n = number of effect sizes. (Online version in colour.)

increasing Y by 92 and 80%, respectively (table 2; figure 3c). By contrast, the specific biocontrol technique adopted had no significant effect on PA, CD or contrasting effects on NEA.

(ii) Crop type

Across all outcome measures, the impact of biocontrol was measured predominantly in cereal crops ($n = 457$), followed by pulses ($n = 155$), vegetables ($n = 207$), fruits ($n = 28$) and fibres ($n = 43$). Biocontrol had an overall significant negative effect on PA across all crop types, with cereal pests showing a 61% reduction, followed by vegetable pests with a 54% reduction (table 2; figure 4a). PA in pulses and fruits showed a 52 and 39% decrease in pests, respectively (figure 4a).

We found that biocontrol had a strong negative effect on CD in all crop types tested: cereal: 60%, vegetables: 46%, pulses: 44% and fruits: 38% (figure 4b). Y was positively affected by biocontrol, but this varied according to crop type; Y in vegetables increased by 57% and pulses by 61% while cereals and fibres showed an increase of 36 and 29%, respectively (figure 4c). The specific crop type in which biocontrol interventions were tested did not influence the abundance of natural enemies (NEA, $p = 0.06$; figure 4d).

(iii) Target pest taxon

Biocontrol interventions had a significant negative effect on the abundance of all pest taxa, with lepidopteran pests showing the greatest decline (-63%) (table 2; figure 5a). The CD of all taxa was strongly negatively affected by biocontrol interventions, with damage caused by Blattodea showing a 79%

reduction with biocontrol implementation (figure 5b). We found that exposure to biocontrol interventions had a significant positive effect on Y where Coleoptera, Lepidoptera and Blattodea were the targeted pests (figure 5c, Coleoptera: 157%; Lepidoptera: 65%; and Blattodea 51%). There was no detectable effect of pest taxon on NEA response to biocontrol (figure 5d).

(iv) Comparison of research and farmers' fields

Across all outcome measures, effect sizes did not differ significantly between farming types. In terms of cropping systems, the size of the negative effect of biocontrol on PA was marginally higher in smallholder farms (66%) than in research farms (48%) (table 2; figure 6a). CD showed a similar pattern, where reduction in small holder farms (-69%) marginally exceeded that of research farms (45%) (figure 6b). With regards to Y , the proportional increase was almost equal in the two cropping types (small farm: 59% and research farm 67%). In neither case was NEA affected by biocontrol interventions.

(v) Comparison with synthetic pesticides

The effectiveness of biocontrol interventions compared to synthetic pesticides was measured mostly for botanical pesticides ($n = 339$), followed by intercropping ($n = 26$) and augmentation/introduction ($n = 23$). We found no studies comparing the effect of field margins or push-pull with pesticides on their ability to control crop pests.

Although biocontrol interventions showed marginally greater PA and damage, and reduced Y compared to synthetic pesticides, we found no significant difference between the two

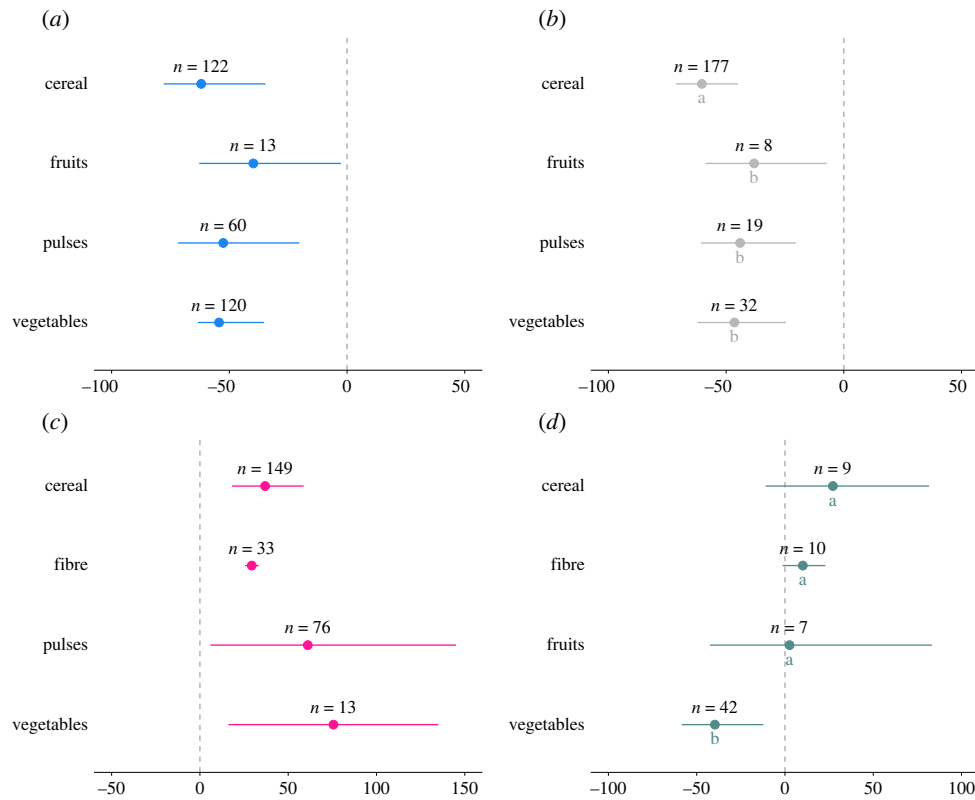


Figure 4. Changes in (a) pest abundance, (b) crop damage, (c) yield and (d) natural enemy abundance when biocontrol interventions are implemented compared to untreated crops (untreated/monocropping). The values are expressed in percentage with 95% bias-corrected confidence intervals categorized as cereal, fibre, fruits, pulses and vegetables where available. Results that cross zero indicate no significant difference between control and treatment groups; n = number of effect sizes. (Online version in colour.)

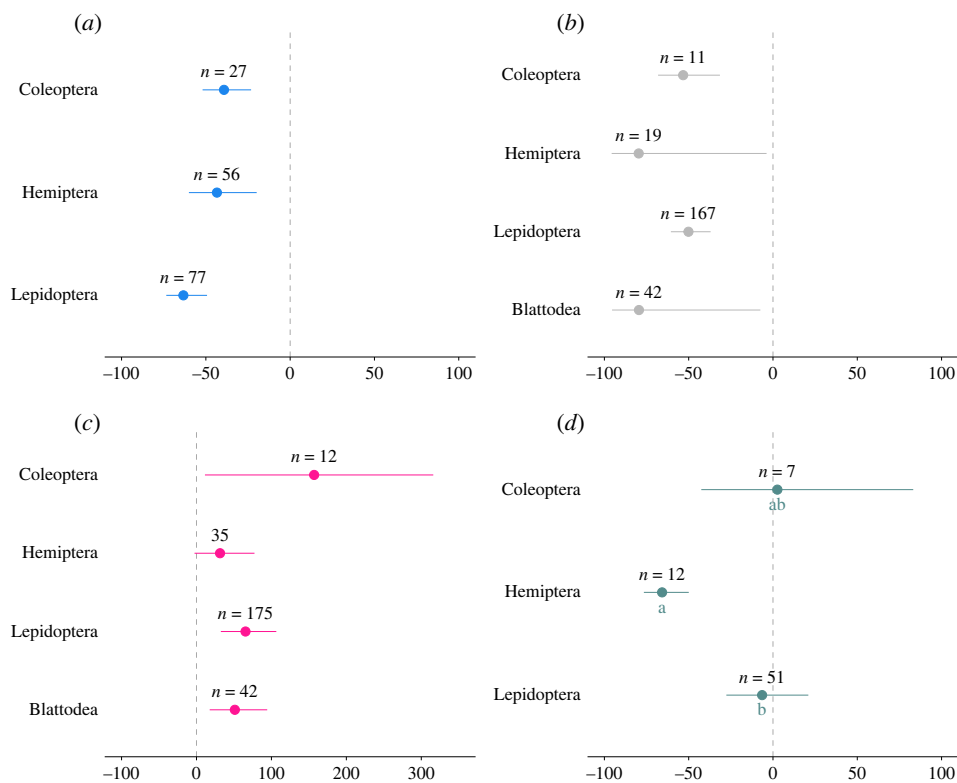


Figure 5. Changes in (a) pest abundance, (b) crop damage, (c) yield and (d) natural enemy abundance when biocontrol interventions are implemented compared to untreated crops (untreated/monocropping). The values are expressed in percentage with 95% bias-corrected confidence intervals categorized as Coleoptera, Hemiptera, Lepidoptera and Blattodea where available. Results that cross zero indicate no significant difference between control and treatment groups; n = number of effect sizes. (Online version in colour.)

treatments (figure 7; PA: 23%; CD: 87%; Y: -7%; NEA: 43%). Conversely, the abundance of natural enemies was significantly greater following biocontrol implementation compared to the application of synthetic pesticides (43%) (figure 7).

(c) Landscape configuration

Our search yielded seven studies that explored the effect of landscape configuration on biocontrol delivered to crops in SSA. Four studies showed a positive effect of proximity to natural habitat, or proportion of natural habitat within a given buffer, on natural enemy activity (i.e. parasitism and predation) [45–48]. Only three studies explored the interactive effects of landscape complexity and farm management on pest control effectiveness [49–51]. All studies found an interactive effect of management and landscape configuration, though the low sample size did not allow for quantitative analysis here.

4. Discussion

In this study, we identified the overall effectiveness of biocontrol techniques in controlling insect pests of crops in SSA, and identified patterns across biocontrol interventions, pest taxa, crop types and experimental design. Using a set of hierarchical meta-analyses, we found that biocontrol interventions effectively reduced PA and CD by over 50%, while increasing Y by more than 60%. The size of the yield increases highlights the great challenge posed by insect pests to smallholder crop production, which is in line with recent evidence estimating high crop losses to pests, especially in the absence of any control intervention [52,53]. The substantial yield increase that biocontrol can provide could have an enormous impact on sub-Saharan food security if these practices are scaled up to regional level. Crucially, we showed comparable performance of biocontrol and synthetic pesticides on PA, CD and Y, and a significant reduction in the loss of natural enemies, particularly following botanical pesticides application.

(a) Biocontrol effectiveness across biocontrol intervention techniques

PA and CD were negatively affected by biocontrol across all interventions. Push-pull and botanical pesticides had the greatest effect on Y, increasing production by 92 and 80%, respectively. This may be owing to the highly effective companion crops used in push-pull technologies, which release bioactive chemicals that repel pests and attract natural enemies, while also suppressing *Striga*, a parasitic weed which causes up to 100% yield losses across SSA [54]. The large yield increase observed in our synthesis may be owing to a combination of the pest repellent and weed suppression abilities of push-pull implementation. Our findings reveal the potential of botanical pesticides to be an effective method of pest control in SSA. However, two-thirds of the studies included here were carried out on research farms, which may be under more controlled settings compared to more realistic field conditions, potentially inflating the observed effect size.

Our review captured a small number of studies on classical biocontrol interventions, including augmentation, despite successful examples, such as the control of the cassava mealybug (*Phenacoccus manihoti*) by the encyrtid wasp (*Anagyrus lopezi*) [55]. Conceivably these interventions may

be hampered by the high costs involved in their research and production, such as insect rearing facilities [56], and the growing concerns on the environmental risks of releasing exotic species [57]. Therefore, they may only be implemented for highly widespread and devastating pests such as the cassava mealybug or the tomato leaf miner (*Tuta absoluta*).

(b) Biocontrol effectiveness across crop type and pest taxon

Cereals were the most studied crops in our meta-analysis, conceivably because they play a central role in the region's food security, accounting for about 50% of total crop area and caloric intake [58]. Nonetheless, other crop types, such as fruits, pulses and fibre should be included in future research in this area. Our study provides strong evidence of the effectiveness of biocontrol across all taxa, particularly against lepidopteran crop pests. The potential of biocontrol to reduce cereal CD by 60% is encouraging given the devastating damage caused, particularly on maize, by caterpillars including fall armyworm (*Spodoptera frugiperda*), diamond-back moth (*Plutella xylostella*), crambid cereal stemborer (*Chilo partellus*) and maize stemborer (*Busseola fusca*).

(c) Biocontrol effect on natural enemies and non-target pests

Understanding the effect of biocontrol on natural enemy populations is crucial as they are both an indication of pest control potential and a measure of the impact of the pest control method on non-target species. Our results showed no overall change in NEA following biocontrol application when compared to untreated fields, although we found a significant decline in NEA following botanical pesticide application. The most likely explanation for this is that the interventions have reduced prey availability for natural enemies, making them move to other more profitable foraging locations, which has been shown in previous studies on intercropping where pest number, not the interventions, influenced PA [59,60]. However, the direct negative impact of some interventions, such as some broad-spectrum botanical pesticides, cannot be excluded [61]. The existing evidence for the effect of botanical pesticides on non-target species is conflicting, with some research showing that plant extracts such as neem, garlic and eucalyptus may cause mortality and have sub-lethal effects on beneficial insects [62,63], while other studies found no detrimental effect of pepper and garlic extract on natural enemy populations [24,64]. More research is needed to draw robust inferences on the repercussions of botanical pesticides on beneficial/non-target species before considering large-scale adoption.

Evidence is more consistent on the positive response of natural enemy populations to biocontrol interventions such as push-pull and field margins [65,66], which is in line with evidence from the global north on the benefits of habitat enhancement on natural enemy density and diversity [67,68]. However, we found that only 14% of the studies measured NEA following biocontrol application in SSA. NEA should be measured more consistently in future studies to further elucidate direct and indirect effects of biocontrol on non-target species.

Furthermore, the most common outcome measures reported in the studies focussed on the abundance of pests and/or natural enemies, while we did not find studies

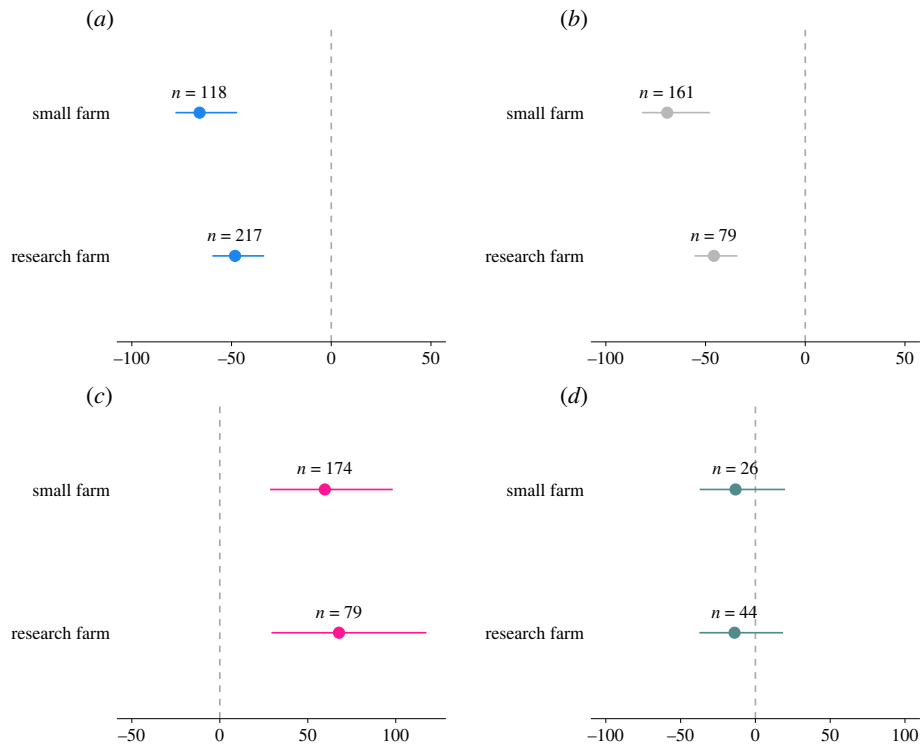


Figure 6. Changes in (a) pest abundance, (b) crop damage, (c) yield and (d) natural enemy abundance when biocontrol interventions are implemented compared to untreated crops (untreated/monocropping). The values are expressed in percentage with 95% bias-corrected confidence intervals categorized as small farms and research farms. Results that cross zero indicate no significant difference between control and treatment groups; n = number of effect sizes. (Online version in colour.)

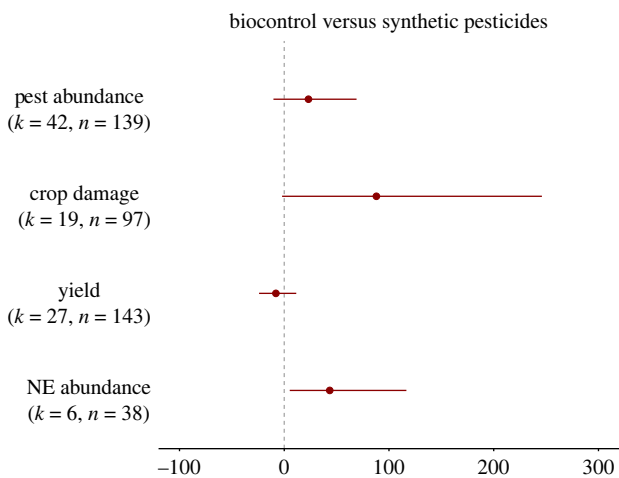


Figure 7. Changes in pest abundance, crop damage, yield and natural enemy (NE) abundance when biocontrol interventions are implemented compared to crops treated with synthetic pesticides. The values are expressed in percentage with 95% bias-corrected confidence intervals. Results that cross zero indicate no significant difference between control and treatment groups. k = number of articles, n = number of effect sizes. (Online version in colour.)

measuring their species diversity or functional group diversity. However, it has been shown that biocontrol is strengthened by increased natural enemy richness [69,70], and this is consistent across temperate and tropical regions [71]. Ecosystem functioning can be stabilized by functional redundancy, by enabling functional groups to compensate for individual species fluctuations and increase the resilience of ecosystem against species loss [72,73]. This is particularly relevant to understand the long-term impact of biocontrol on natural enemy communities and their pest suppression ability and should be explored in future research.

(d) Biocontrol effectiveness compared to synthetic pesticides

When compared to synthetic pesticides, biocontrol interventions had a similar impact on PA and CD, which is a critical finding for farmers who cannot access or afford chemicals. Crucially, NEA was significantly reduced after synthetic pesticide application even over the short timescales of the studies examined. In the long term there could be greater reductions in pest and crop damage following biocontrol as a result of more abundant and diverse communities of natural enemies. In terms of a reduction in the negative environmental impacts associated with chemical pesticides, the benefits provided by more resilient natural enemy populations could be one of several indirect positive effects of opting out of conventional pesticide use. It is worth noting that most comparisons with synthetic pesticides were measured against botanical pesticides, therefore inferences for other biocontrol methods should be made with caution. Future research should aim to determine the effectiveness of biocontrol approaches, such as push-pull, when compared to synthetic pesticides to fill this knowledge gap.

A possible limitation of this study is the potential selection bias towards significant results, causing an over-representation in the published literature, a criticism that could be levelled against all meta-analyses. The two tests we used to assess publication bias yielded conflicting results; hence, it is hard to know with certainty the scale of publication bias towards results where an effect was found. However, we show that crop losses to pests are significantly higher in untreated fields, supporting the idea that any crop protection intervention has the potential to improve yields substantially. The size of the yield gains shown in the current meta-analysis suggests there is a big opportunity to raise yields with biocontrol interventions.

(e) Landscape configuration and biocontrol

Our study set out to answer the question, ‘does the surrounding landscape configuration affect the effectiveness of biocontrol interventions?’, which has led to positive responses of natural enemies to landscape complexity in studies outside of the SSA region [13]. However, we found a paucity of studies investigating either the effect of landscape configuration on biocontrol effectiveness, or the relationship between landscape configuration and NEA. The research we found indicated a significant decrease of natural enemy density and predation/parasitism activity with isolation from natural habitat (e.g. [45,48]). This is in line with recent research showing a similar effect of landscape complexity on pollinators and natural enemies in sub-Saharan regions [74,75] and a larger body of research particularly in the global north [13,19,76].

Furthermore, the sparse evidence we found focusing on the effect of landscape configuration on biocontrol effectiveness showed inconsistent results. Midega *et al.* [49] found that semi-natural habitat acted as a source of lepidopteran pests to the maize crop fields in Kenya, while Kebede *et al.* [50] demonstrated that landscape simplification overrode the effect of intercropping practices and was the main driver of pest infestation levels. A key avenue for future research would involve large scale studies to identify clear patterns in the relationship between landscape complexity and natural enemy activity and the ecosystem service delivered to sub-Saharan agricultural systems. Additionally, recent evidence from SSA showed that natural enemy diversity in crop fields is dependent on the land management of neighbouring fields [29]. This highlights the need for further multi-scale studies to identify potential variation in biocontrol effectiveness across different land management contexts.

5. Conclusion

Our findings provide, to our knowledge, the first quantitative synthesis of biocontrol effectiveness in SSA, indicating that biocontrol interventions have the potential to substantially reduce CD, increase Y while maintaining natural enemy

populations within sub-Saharan agricultural systems. Our results further suggest that biocontrol has comparable performances to synthetic pesticides with reduced adverse impact on beneficial insects and ecosystems, which makes it an effective alternative intervention for farmers who do not have access to pesticides, while it can maintain Y without associated negative pesticide effects. Given the case against chemical use in Africa [9], the efficacy of biocontrol options demonstrated in this meta-analysis provides a strong regionally focused evidence base for policy- and decision-makers to be persuaded of their validity as an alternative to chemicals. Overall, our results encourage an update to national agricultural policies, which inconsistently feature biocontrol, and can support policy makers in the design of more resilient and sustainable pest management practices across the sub-Saharan region.

Data accessibility. Data used in these analyses are available from the Dryad Digital Repository: <https://doi.org/10/50161/dryad.s1rm8pkbw> [77].

The data are provided in the electronic supplementary material [78].

Authors' contributions. F.R.: conceptualization, data curation, formal analysis, methodology, writing—original draft, writing—review and editing; T.B.: conceptualization, methodology, writing—review and editing; S.M.: writing—review and editing; R.M.: writing—review and editing; Z.K.: writing—review and editing; A.M.: writing—review and editing; J.P.: writing—review and editing; S.M.Sallu.: writing—review and editing; S.W.: writing—review and editing; K.W.: conceptualization, methodology, writing—review and editing; S.M.Sait.: conceptualization, funding acquisition, methodology, writing—review and editing.

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

Conflict of interest declaration. The authors declare that there are no competing interests.

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References

- Godfray HJ *et al.* 2010 Food security: the challenge of feeding 9 billion people. *Science* (1979) **327**, 812–818. (doi:10.1126/science.1185383)
- Rosegrant MW *et al.* 2009 *Agriculture and food security under global change: prospects for 2025/2050*. Washington, DC: International Food Policy Research Institute.
- Lobell DB, Schlenker W, Costa-Roberts J. 2011 Climate trends and global crop production since 1980. *Science* (1979) **333**, 616–620. (doi:10.1126/science.1204531)
- Lenné J. 2000 Pests and poverty: the continuing need for crop protection research. *Outlook Agric.* **29**, 235–250. (doi:10.5367/00000000101293301)
- Oerke E-C, Dehne H-W. 2004 Safeguarding production—losses in major crops and the role of crop protection. *Crop Prot.* **23**, 275–285. (doi:10.1016/j.cropro.2003.10.001)
- Stokstad E. 2017 New crop pest takes Africa at lightning speed. *Science* (1979) **356**, 473 LP–473474. (doi:10.1126/science.356.6337.473)
- Ahissou BR, Sawadogo WM, Bokonon-Ganta AH, Somda I, Verheggen F. 2021 Integrated pest management options for the fall armyworm *Spodoptera frugiperda* in West Africa: challenges and opportunities. A review. *Biotechnol. Agronomy Soc. Environ.* **25**, 192–207. (doi:10.25518/1780-4507.19125)
- Nesser GAA, Abdelbagi AO, Hammad AMA, Tagelseed M, Laing MD. 2016 Levels of pesticides residues in the White Nile water in the Sudan. *Environ. Monit. Assess.* **188**, 374. (doi:10.1007/s10661-016-5367-3)
- Jepson PC, Murray K, Bach O, Bonilla MA, Neumeister L. 2020 Selection of pesticides to reduce human and environmental health risks: a global guideline and minimum pesticides list. *Lancet Planet Health* **4**, e56–e63. (doi:10.1016/S2542-5196(19)30266-9)
- Sawadogo MW, Somda I, Nacro S, Legrève A, Verheggen FJ. 2020 Insecticide susceptibility level and control failure likelihood estimation of Sub-Saharan African populations of tomato leafminer: evidence from Burkina Faso. *Physiol. Entomol.* **45**, 147–153. (doi:10.1111/phen.12332)
- Kennedy CM *et al.* 2013 A global quantitative synthesis of local and landscape effects on wild bee pollinators in agroecosystems. *Ecol. Lett.* **16**, 584–599. (doi:10.1111/ele.12082)
- Lossy EJ, Vaughan M, Losey JE, Vaughan M. 2006 The economic value of ecological services provided by insects. *Bioscience* **56**, 311–323. (doi:10.1641/0006-3568(2006)56[311:tevoes]2.0.co;2)

13. Chaplin-Kramen R, O' Rourke M, Blitzer EJ, Kremen C. 2011 A meta-analysis of crop pest and natural enemy response to landscape complexity. *Ecol. Lett.* **14**, 922–932. (doi:10.1111/j.1461-0248.2011.01642.x)
14. Janssen A, van Rijn PCJ. 2021 Pesticides do not significantly reduce arthropod pest densities in the presence of natural enemies. *Ecol. Lett.* **24**, 2010–2024. (doi:10.1111/ele.13819)
15. Guedes RNC, Smaghe G, Stark JD, Desneux N. 2016 Pesticide-induced stress in arthropod pests for optimized integrated pest management programs. *Annu. Rev. Entomol.* **61**, 43–62. (doi:10.1146/annurev-ento-010715-023646)
16. Giles KL, McCornack BP, Royer TA, Elliott NC. 2017 Incorporating biological control into IPM decision making. *Curr. Opin. Insect. Sci.* **20**, 84–89. (doi:10.1016/j.cois.2017.03.009)
17. Baker BP, Green TA, Loker AJ. 2020 Biological control and integrated pest management in organic and conventional systems. *Biol. Control* **140**, 104095. (doi:10.1016/j.biocontrol.2019.104095)
18. Karp DS *et al.* 2018 Crop pests and predators exhibit inconsistent responses to surrounding landscape composition. *Proc. Natl Acad. Sci. USA* **115**, E7863–E7870. (doi:10.1073/pnas.1800042115)
19. Bianchi FJJA, Booij CJH, Tschamtké T. 2006 Sustainable pest regulation in agricultural landscapes: a review on landscape composition, biodiversity and natural pest control. *Proc. R. Soc. B* **273**, 1715–1727. (doi:10.1098/rspb.2006.3530)
20. Rusch A *et al.* 2016 Agricultural landscape simplification reduces natural pest control: a quantitative synthesis. *Agric. Ecosyst. Environ.* **221**, 198–204. (doi:10.1016/j.agee.2016.01.039)
21. F.A.O. 2020 The global action for fall armyworm control: action framework 2020–2022. (doi:10.4060/ca9252en)
22. Sporleder M, Lacey LA. 2013 Chapter 16 - Biopesticides. In *Insect pests of potato* (eds A Alyokhin, C Vincent, P Giordanengo), pp. 463–497. San Diego, CA: Academic Press.
23. Farsia Djidjoni P, Nchiwan NE, Koehler H. 2021 Comparative experimental effects of intercropping and cypermethrin on insect pest infestation and yield of maize, cowpea and okra in two cameroonian agro-ecological zones. *AgriEngineering* **3**, 383–393. (doi:10.3390/agriengineering3020025)
24. Amoabeng BW, Stevenson PC, Mochiah BM, Asare KP, Gurr GM. 2020 Scope for non-crop plants to promote conservation biological control of crop pests and serve as sources of botanical insecticides. *Sci. Rep.* **10**, 1–15. (doi:10.1038/s41598-020-63709-x)
25. Midega CAO, Pittchar JO, Pickett JA, Hailu GW, Khan ZR. 2018 A climate-adapted push-pull system effectively controls fall armyworm, *Spodoptera frugiperda* (J E Smith), in maize in East Africa. *Crop Prot.* **105**, 10–15. (doi:10.1016/j.cropro.2017.11.003)
26. Mpumi N, Machunda RL, Mtei KM, Ndakidemi PA. 2020 Insecticidal efficacy of *Syzygium aromaticum*, *Tephrosia vogelii* and *Croton dichogamus* extracts against *Plutella xylostella* and *Trichoplusiani* on *Brassica oleracea* crop in Northern Tanzania. *AIMS Agric. Food* **6**, 185–202. (doi:10.3934/agrfood.2021012)
27. Odewole AF, Adebayo TA, Babarinde SA, Awolokun GS. 2020 Insecticidal activity of aqueous indigenous plant extracts against insect pests associated with cucumber (*Cucumis sativus* L.) in Southern Guinea Savannah Zone of Nigeria. *Arch. Phytopathol. Plant Prot.* **53**, 230–246. (doi:10.1080/03235408.2020.1741854)
28. Ratto F *et al.* 2022 Biological control interventions and botanical pesticides for insect pests of crops in sub-Saharan Africa: a mapping review. *Front. Sustain. Food Syst.* **6**, 1–6. (doi:10.3389/fsufs.2022.883975)
29. Tripathi HG *et al.* 2022 Climate-smart agriculture and trade-offs with biodiversity and crop yield. *Front. Sustain. Food Syst.* **6**, 1–12. (doi:10.3389/fsufs.2022.868870)
30. Gurr GM *et al.* 2016 Multi-country evidence that crop diversification promotes ecological intensification of agriculture. *Nat. Plants* **2**, 1–4. (doi:10.1038/NPLANTS.2016.14)
31. Steward PR, Shackelford G, Carvalheiro LG, Benton TG, Garibaldi LA, Sait SM. 2014 Pollination and biological control research: are we neglecting two billion smallholders. *Agric. Food Secur.* **3**, 1–13. (doi:10.1186/2048-7010-3-5)
32. Stiling P, Cornelissen T. 2005 What makes a successful biocontrol agent? A meta-analysis of biological control agent performance. *Biol. Control* **34**, 236–246. (doi:10.1016/j.biocontrol.2005.02.017)
33. Perez-alvarez R, Brian AN, Poveda K. 2019 Effectiveness of augmentative biological control depends on landscape context. *Sci. Rep.* **9**, 1–15. (doi:10.1038/s41598-019-45041-1)
34. Haddaway NR, Macura B, Whaley P, Pullin AS. 2018 ROSES RepOrting standards for Systematic Evidence Syntheses: pro forma, flow-diagram and descriptive summary of the plan and conduct of environmental systematic reviews and systematic maps. *Environ. Evid.* **7**, 7. (doi:10.1186/s13750-018-0121-7)
35. Schneider CA, Rasband WS, Eliceiri KW. 2012 NIH Image to ImageJ: 25 years of image analysis. *Nat. Methods* **9**, 671–675. (doi:10.1038/nmeth.2089)
36. Gurevitch J, Hedges LV. 1993 Meta-analysis: combining the results of independent experiments. In *Design and analysis of ecological experiments*, pp. 378–398. New York, NY: Chapman and Hall.
37. Hedges LV, Gurevitch J, Curtis PS. 1999 The meta-analysis of response ratios in experimental ecology. *Ecology* **80**, 1150–1156. (doi:10.1890/0012-9658(1999)080[1150:TMAORR]2.0.CO;2)
38. Koricheva J, Gurevitch J, Mengersen K. 2013 *Handbook of meta-analysis in ecology and evolution*. Princeton, NJ: Princeton University Press.
39. Nakagawa S, Santos ESA. 2012 Methodological issues and advances in biological meta-analysis. *Evol. Ecol.* **26**, 1253–1274. (doi:10.1007/s10682-012-9555-5)
40. Egger M, Davey Smith G, Schneider M, Minder C. 1997 Bias in meta-analysis detected by a simple, graphical test. *Brit. Med. J.* **315**, 629–634. (doi:10.1136/bmj.315.7109.629)
41. Duval S, Tweedie R. 2000 Trim and fill: a simple funnel-plot-based method of testing and adjusting for publication bias in meta-analysis. *Biometrics* **56**, 455–463. (doi:10.1111/j.0006-341X.2000.00455.x)
42. Habeck CW, Schultz AK. 2015 Community-level impacts of white-tailed deer on understory plants in North American forests: a meta-analysis. *AOB Plants* **7**, plv119. (doi:10.1093/aobpla/plv119)
43. Rosenberg MS. 2005 The File-Drawer Problem Revisited: A General Weighted Method for Calculating Fail-Safe Numbers in Meta-Analysis. *Evolution*, vol. 59, no. 2, pp. 464–68. JSTOR, <http://www.jstor.org/stable/3448935> (accessed 21 Nov. 2022).
44. Viechtbauer W. 2010 Conducting meta-analyses in R with the metafor package. *J. Stat. Softw.* **36**, 1–48.
45. Soti V, Thiaw I, Debaly ZM, Sow A, Diaw M, Fofana S, Diakhate M, Thiaw C, Brevault T. 2019 Effect of landscape diversity and crop management on the control of the millet head miner, *Heliocheilus albipunctella* (Lepidoptera: Noctuidae) by natural enemies. *Biol. Control* **129**, 115–122. (doi:10.1016/j.biocontrol.2018.10.006)
46. Kebede Y, Bianchi F, Baudron FF, Abraham K, de Valença A, Tittone P, de Valença A, Tittone P. 2018 Implications of changes in land cover and landscape structure for the biocontrol potential of stemborers in Ethiopia. *Biol. Control* **122**, 1–10. (doi:10.1016/j.biocontrol.2018.03.012)
47. Milligan MC, Johnson MD, Garfinkel M, Smith CJ, Njoroge P, Gar M, Smith CJ, Njoroge P. 2016 Quantifying pest control services by birds and ants in Kenyan coffee farms. *Biol. Conserv.* **194**, 58–65. (doi:10.1016/j.biocon.2015.11.028)
48. Henri DC, Jones O, Tsiattalos A, Thebault E, Seymour CL, van Veen FJFF, Thébault E, Seymour CL, van Veen FJFF. 2015 Natural vegetation benefits synergistic control of the three main insect and pathogen pests of a fruit crop in Southern Africa. *J. Appl. Ecol.* **52**, 1092–1101. (doi:10.1111/1365-2664.12465)
49. Midega CAO, Jonsson M, Khan ZR, Ekomb B. 2014 Effects of landscape complexity and habitat management on stemborer colonization, parasitism and damage to maize. *Agric. Ecosyst. Environ.* **188**, 289–293. (doi:10.1016/j.agee.2014.02.028)
50. Kebede Y, Bianchi FJAJA, Baudron FFF, Tittone P. 2019 Landscape composition overrides field level management effects on maize stemborer control in Ethiopia. *Agric. Ecosyst. Environ.* **279**, 65–73. (doi:10.1016/j.agee.2019.04.006)
51. Tsafack N, Menozzi P, Brevault T, Soti V, Deconchat M, Ouin A. 2013 Effects of landscape context and agricultural practices on the abundance of cotton bollworm *Helicoverpa armigera* in cotton fields: a case study in northern Benin. *Int. J. Pest Manag.* **59**, 294–302. (doi:10.1080/09670874.2013.852270)
52. Oerke EC. 2006 Crop losses to pests. *J. Agric. Sci.* **144**, 31–43. (doi:10.1017/S0021859605005708)
53. Savary S, Willocquet L, Pethybridge SJ, Esker P, McRoberts N, Nelson A. 2019 The global burden

- of pathogens and pests on major food crops. *Nat. Ecol. Evol.* **3**, 430–439. (doi:10.1038/s41559-018-0793-y)
54. Khan ZR, Midega CA00, Pittchar JO, Murage AW, Birkett MA, Bruce TJAA, Pickett JA. 2014 Achieving food security for one million sub-Saharan African poor through push-pull innovation by 2020. *Phil. Trans. R. Soc. B* **369**, 20120284. (doi:10.1098/rstb.2012.0284)
55. Norgaard RB. 1988 The biological control of cassava mealybug in Africa. *Am. J. Agric. Econ.* **70**, 366–371. (doi:10.2307/1242077)
56. Neuenschwander P. 2004 Harnessing nature in Africa biological pest control can benefit the pocket, health and the environment. *Nature* **432**, 801–802.
57. Van Lenteren JC, Bale J, Bigler F, Hokkanen HMT, Loomans AJM. 2006 Assessing risks of releasing exotic biological control agents of arthropod pests. *Annu. Rev. Entomol.* **51**, 609–634. (doi:10.1146/annurev.ento.51.110104.151129)
58. Robinson S, Mason d'Croz D, Islam S, Sulser TB, Robertson RD, Zhu T, Gueneau A, Pitois G, Rosegrant MW. 2015 International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) version 3.1. *Int. Food Policy Res. Inst. (IFPRI)*, 128 pp.
59. Huss CP, Holmes KD, Blubaugh CK. 2022 Benefits and risks of intercropping for crop resilience and pest management. *J. Econ. Entomol.* **115**, 1350–1362. (doi:10.1093/jee/toac045)
60. Chi BJ, Zhang DM, Dong HZ. 2021 Control of cotton pests and diseases by intercropping: a review. *J. Integr. Agric.* **20**, 3089–3100. (doi:10.1016/S2095-3119(20)63318-4)
61. Ndakidemi B, Mtei K, Ndakidemi PA. 2016 Impacts of synthetic and botanical pesticides on beneficial insects. *Agric. Sci.* **07**, 364–372. (doi:10.4236/as.2016.76038)
62. Maia MF, Moore SJ. 2011 Plant-based insect repellents: a review of their efficacy, development and testing. *Malar. J.* **10**, S11. (doi:10.1186/1475-2875-10-S1-S11)
63. Simmonds MSJ, Manlove JD, Blaney WM, Khambay BPS. 2002 Effects of selected botanical insecticides on the behaviour and mortality of the glasshouse whitefly *Trialeurodes vaporariorum* and the parasitoid *Encarsia formosa*. *Entomol. Exp. Appl.* **102**, 39–47. (doi:10.1046/j.1570-7458.2002.00923.x)
64. Fening KO, Amoabeng BW, Adama I, Mochiah MB, Braimah H, Owusu-Akyaw M, Narveh E, Ekyem SO. 2013 Sustainable management of two key pests of cabbage, *Brassica oleracea* var. *capitata* L. (Brassicaceae), using homemade extracts from garlic and hot pepper. *Org. Agric.* **3**, 163–173. (doi:10.1007/s13165-014-0058-2)
65. Midega CAO, Khan ZR, van den Berg J, Ogot CKPO, Dippenaar-Schoeman AS, Pickett JA, Wadhams LJ. 2008 Response of ground-dwelling arthropods to a 'push-pull' habitat management system: spiders as an indicator group. *J. Appl. Entomol.* **132**, 248–254. (doi:10.1111/j.1439-0418.2007.01260.x)
66. Koji S, Khan ZR, Midega CAO. 2007 Field boundaries of *Panicum maximum* as a reservoir for predators and a sink for *Chilo partellus*. *J. Appl. Entomol.* **131**, 186–196. (doi:10.1111/j.1439-0418.2006.01131.x)
67. Blaauw BR, Isaacs R. 2012 Larger wildflower plantings increase natural enemy density, diversity, and biological control of sentinel prey, without increasing herbivore density. *Ecol. Entomol.* **37**, 386–394. (doi:10.1111/j.1365-2311.2012.01376.x)
68. Holland JM, Douma JC, Crowley L, James L, Kor L, Stevenson DRW, Smith BM. 2017 Semi-natural habitats support biological control, pollination and soil conservation in Europe. A review. *Agron Sustain. Dev.* **37**, 31. (doi:10.1007/s13593-017-0434-x)
69. Griffin JN, Byrnes JEK, Cardinale BJ. 2013 Effects of predator richness on prey suppression: a meta-analysis. *Ecology* **94**, 2180–2187. (doi:10.1890/13-0179.1)
70. Katano I, Doi H, Eriksson BK, Hillebrand H. 2015 A cross-system meta-analysis reveals coupled predation effects on prey biomass and diversity. *Oikos* **124**, 1427–1435. (doi:10.1111/oik.02430)
71. Letourneau DK, Jedlicka JA, Bothwell SG, Moreno CR. 2009 Effects of natural enemy biodiversity on the suppression of arthropod herbivores in terrestrial ecosystems. *Annu. Rev. Ecol. Syst.* **40**, 573–592. (doi:10.1146/annurev.ecolsys.110308.120320)
72. Rosenfeld JS. 2002 Functional redundancy in ecology and conservation. *Oikos* **98**, 156–162. (doi:10.1034/j.1600-0706.2002.980116.x)
73. Hooper DU *et al.* 2005 Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. *Ecol. Monogr.* **75**, 3–35. (doi:10.1890/04-0922)
74. Ratto F, Steward P, Sait SM, Pryke JS, Gaigher R, Samways MJ, Kunin W. 2021 Proximity to natural habitat and flower plantings increases insect populations and pollination services in South African apple orchards. *J. Appl. Ecol.* **58**, 2540–2551. (doi:10.1111/1365-2664.13984)
75. Jordon MW, Hackett TD, Aboagye-Antwi F, Eziah VY, Lewis OT. 2022 Effects of distance from semi-natural habitat on fall armyworm (*Spodoptera frugiperda*, J. E. Smith) and its potential natural enemies in Ghana. *Bull. Entomol. Res.* **112**, 343–353. (doi:10.1017/S0007485321000894)
76. Shackelford G, Steward PR, Benton TG, Kunin WE, Potts SG, Biesmeijer JC, Sait SM. 2013 Comparison of pollinators and natural enemies: a meta-analysis of landscape and local effects on abundance and richness in crops. *Biol. Rev.* **88**, 1002–1021. (doi:10.1111/brv.12040)
77. Ratto F *et al.* 2022 Data from: Biological control interventions reduce pest abundance and crop damage while maintaining natural enemies in sub-Saharan Africa: a meta analysis. Dryad Digital Repository. (<https://doi.org/10.5061/dryad.s1rn8pkbw>)
78. Ratto F *et al.* 2022 Biological control interventions reduce pest abundance and crop damage while maintaining natural enemies in sub-Saharan Africa: a meta-analysis. Figshare. (doi:10.6084/m9.figshare.c.6307537)