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

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Abstract

Insect pests are a major challenge to smallholder crop production in sub-Saharan Africa, 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 conducted a meta-analysis of 5 commonly-used biocontrol interventions to quantify i) the magnitude of their effects when compared with no control and with synthetic pesticides, and ii) how effectiveness is determined by landscape composition. Overall, compared to no control, biocontrol interventions reduced pest abundance by 63%, crop damage by over 50%, and increased crop yield by over 60%. Compared to synthetic pesticides, biocontrol produced comparable yields, and natural enemy abundance was 43% greater. Our results suggest that biocontrol represents an effective intervention for farmers who do not have access to pesticides, while it can maintain yields without associated negative pesticide effects. However, the potential for biocontrol to be affected by landscape composition is a critical knowledge gap in sub-Saharan Africa.

Introduction

One of the greatest global challenges of the twenty-first century is meeting the increasing demands for human food production while minimising adverse impacts on biodiversity and ecosystem health (Godfray et al. 2010). This challenge is particularly critical in sub-Saharan Africa (SSA) where the population is predicted to double over the coming decades (Rosegrant et al. 2009) and food production is hampered both by climate change impacts (Lobell et al. 2011) and significant yield losses caused by crop pests (Lenné 2000; Oerke & Dehne 2004). 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 (Stokstad 2017). The fall armyworm is also a cause of major damage to other crops including rice, sorghum, millet, cabbage, and tomatoes (CABI, 2018), 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 (Ahissou et al. 2021). Pesticide residues also put human and livestock populations at risk from contaminated food and forage (Nesser et al. 2016; Jepson et al. 2020). Furthermore, synthetic pesticides may lead to resistance within pest populations (Sawadogo et al. 2020), 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 (Losey et al. 2006; Chaplin-Kramen et al. 2011; Kennedy et al. 2013). 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 (Janssen and van Rijn 2021), which is a widely reported problem associated with synthetic pesticides (Guedes et al. 2016).

Biological control methods (hereafter biocontrol), which employ natural enemies of crop pests, have been promoted globally as an alternative approach to pest control, and are often used as part of an integrated pest management strategy (Giles *et al.* 2017; Baker *et al.*2020). Extensive evidence is available on the responses of natural enemies to the landscape composition surrounding crop fields (Karp et al. 2018), which reveals that landscape effects are a key driver of pest regulation by natural enemies. Recent syntheses show consistent positive responses of natural enemies to landscape complexity (Chaplin-Kramen et al. 2011), a reduction of natural pest control in simplified landscapes (Rusch et al. 2016), and higher natural enemy populations in complex versus simple landscapes (Bianchi et al. 2006).

In SSA, smallholder farmers have employed conservation biocontrol methods and botanical pesticides for the control of crop pests (Sporleder & Lacey 2013). Conservation biocontrol methods include intercropping, push-pull and field margins (Table 1). Growing evidence highlights the potential of biocontrol interventions to reduce pest incidence and increase yield (Amoabeng *et al.* 2020; Farsia Djidjonri *et al.* 2021). For example, push-pull technology has been shown to be effective against a range of crop pests, particularly maize stemborers (Midega *et al.* 2018), and plant-based botanical pesticides can reduce pest incidence and enhance yield in vegetables crops (Mpumi *et al.* 2020; Odewole *et al.* 2020).

Although biocontrol interventions may provide sustainable and accessible alternatives to synthetic pesticides, their adoption by smallholder farmers has not been widespread (Ratto *et al* . 2022). This may be due 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 (Ratto *et al.*2022). Recent research in Tanzania found greater natural enemy diversity in fields surrounded by intercropped fields, suggesting spatial flow of potential biocontrol services across landscapes (Tripathi et al. 2022), but the established relationship between landscape composition, natural enemies and pest regulation is almost entirely based on studies carried out in the global north, and very seldom in sub-Saharan regions where farmers are most exposed to food insecurity caused by crop pests (Steward *et al.* 2014). This represents a key knowledge gap; more clarity is needed about the environmental factors affecting biocontrol performance in sub-Saharan Africa 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 (Stiling & Cornelissen 2005), on the impact of landscape context on augmentative biocontrol (Perez-alvarez *et al.* 2019) and pest and natural enemy responses (Chaplin-Kramen *et al.* 2011). However, none of these approaches have focussed specifically on the sub-Saharan region, nor have they evaluated the efficacy of different biocontrol interventions on crop 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. Specifically, we posed the following questions:

(1) What are the effects of biocontrol interventions on the management of insect crop pests in sub-Saharan Africa? (2) Are these effects consistent across biocontrol techniques, crop types, target pests and farming systems? (3) How does the effectiveness and impact of biocontrol interventions on crop pests and non-target insects compare to synthetic pesticides? (4) Does the surrounding landscape composition affect the efficacy of biocontrol interventions?

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

MATERIALS and METHODS

Literature search strategy and data collection

To identify candidate studies, we screened a dataset included in a mapping review carried out by Ratto *et al* . (2022) that described the existing literature on biocontrol interventions for insect pests of crops in SSA. Ratto *et al.* (2022) 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*”, “armyworm”), agricultural settings (e.g., “agri*”, “farm*”) and the target geographical location (e.g., “sub-Saharan Africa”, “Southern Africa”)(Table S1). Grey literature was captured by conducting additional searches on Google and Google Scholar and by searching websites of relevant institutions. This mapping review covered a period between 2005 and April 2021 and was summarised narratively, with no quantitative analysis performed.

We integrated this initial dataset (149 articles) (Ratto et al. 2022) with a follow up search of relevant papers published between April 2021 and December 2021. Overall, we found 146 eligible articles. 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 crop damage that threatens their food security.

We included in the definition of biocontrol interventions any practice that utilises 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 natural enemy abundance and diversity (Amoabeng *et al.* 2020) and included push-pull, intercropping and 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 to all articles in Ratto *et al.* (2022). 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 pest abundance (PA), crop damage (CD), crop yield (Y) or natural enemy abundance (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 crop damage 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. Crop yield was reported as either kg/ha or tonne/ha, which was standardised to the latter for analysis.

We categorised 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 (SD) 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 (Schneider *et al.* 2012). We contacted the lead authors of the studies that had incomplete data and abandoned these studies if we could not obtain the missing statistics.

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 (Gurevitch & Hedges 1993). 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, 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 (Supplementary information S2).

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 (Hedges *et al.* 1999):

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

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 +). The use of the natural logarithm linearizes the metric, treating changes in nominator and denominator equally, and produces a normalised sampling distribution (Hedges *et al.* 1999).

All outcome measures were analysed separately (pest abundance, crop damage, crop yield, natural enemy abundance). Fitted random effects models were used to calculate the overall means and 95% confidence intervals 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 confidence intervals (C.I.) of the effect size did not overlap zero (Koricheva *et al.*2013).

Meta-regression was used to explore sources of heterogeneity across each dataset. Our analysis focussed on the following ecological, environmental, and experimental parameters: (1) biocontrol technique; (2) crop type; (3) target pest taxon; (4) 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, cocoa) and nuts due 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% confidence intervals around the mean were back-transformed with the formula ($e^{\ln R}$-1) *100 and expressed as percent change relative to the controls to facilitate interpretation.

Publication bias

We assessed publication bias in three ways. We first visually assessed funnel plots for strong asymmetries (Fig S1). Visual inspection of the funnel plots revealed symmetrical distribution of effect size around the meta-analytical mean of all outcome measures apart from pest abundance. We then ran Egger's regression test (Egger *et al.* 1997; Nakagawa & Santos 2012) and the trim-and-fill test (Duval & Tweedie 2000). Egger's test indicated that publication bias was significant for the pest abundance (z= -2.1065, p=0.0352), crop damage (z= -2.3886, p=0.0169), and NEA datasets (z=-2.4708, p=0.0135), but not significant for the crop yield dataset (CY: z= 0.0362, p=0.9711). This was inconsistent with the trim-and-fill tests showing no missing studies for all datasets. All statistical analysis was performed using the "metaphor" package in R (version 4.1.2) (Viechtbauer 2010).

Results

Comparison with no pest control

Overall, relative to farms without any pest control method, biocontrol interventions had a strong negative effect on pest abundance and crop damage, which were reduced by 55% (95% Confidence intervals (C.I.) = -64.62 to -44.21, p< 0.0001) and 60% (C.I. = -71.44 to -45.38, p< 0.0001), respectively (Fig. 1). Crops subject to biocontrol exhibited a 62% increase in yield (C.I. = 38.58 to 91.57, p< 0.0001). However, we found no significant overall effect of biocontrol on natural enemy abundance (-19%, C.I. = 38.58 to 91.57) (Fig. 1). There was substantial heterogeneity for all outcome measures, suggesting unexplained variation (Pest abundance,I^2 = 54,98%; Crop damage, I^2 = 51.35; Yield, I^2= 69,20%, Natural enemy abundance, I^2 = 92.35) (Fig.1). Hence, we used meta-regression to elucidate the effect of potential moderators.

Factors affecting biocontrol effectives

Biocontrol intervention technique

Overall, the most tested biocontrol approaches were botanical pesticides (n = 244), followed by intercropping (n = 163) and push-pull (n = 46), followed by both field margins (n = 38) and augmentation/introduction (n = 38). We found that crop yield was significantly affected by the nature of the biocontrol intervention (p=0.0001), with botanical pesticides and push-pull increasing yield by 92% (C.I. = 50.48 to 147) and 80% (C.I. = 52.13 to 114), respectively (Fig. 2c). In contrast, the specific biocontrol technique adopted had no significant effect on pest abundance (p=0.21), crop damage (p=0.30), or contrasting effects on natural enemy abundance (p=0.35).

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 pest abundance across all crop types, with cereal pests showing a 61% reduction (C.I. = -77.84to -34.66), followed by vegetable pests with a 54% reduction (C.I. = -63.47 to -35.31) (Fig.3a). Pest abundance in pulses and fruits showed a 52% and 39% decrease in pests respectively (pulses: C.I. = -71.80 to -20.29; fruits: C.I. = -62.79 to -2.59) (Fig.3a).

We found that biocontrol had a strong negative effect on crop damage in all crop types tested (cereal: 60%, C.I. = -71.37 to -45.01; vegetables: 46%, C.I. = -62.05 to -24.55; pulses: 44%, C.I. = -60.72 to -20.29; fruits:

38%, C.I. = -58.69 to -7.27) (Fig3b). Yield was positively affected by biocontrol, but this varied according to crop type; yields in vegetables increased by 57% (C.I. = 16.08 to 135) and pulses by 61% (C.I. = 5.91 to 145), while cereals and fibres showed an increase of 36% and 29% respectively (cereal: C.I. = 18.13 to 58.75; fibres: C.I. = 25.55 to 33.26) (Fig.3c). The specific crop type in which biocontrol interventions were tested did not influence the abundance of natural enemies (NEA, p = 0.06, Fig.3d).

Target pest taxon

Biocontrol interventions had a significant negative effect on the abundance of all pest taxa ($p<0.0001$), with lepidopteran pests showing the greatest decline (-63%, C.I. =-73.47 to -49.30) (Fig.4a). The crop damage of all taxa was strongly negatively affected by biocontrol interventions (p=0.012), with damage caused by Blattodea showing a 79% reduction (C.I. = -95.45 to -7.49) with biocontrol implementation (Fig.4b). We found that exposure to biocontrol interventions had a significant positive effect on yield where Coleoptera, Lepidoptera and Blattodea were the targeted pests (Fig.4c, Coleoptera: 157%, C.I.= 11.28 to 316; Lepidoptera: 65%, C.I. = 32.49 to 106.51; Blattodea 51%, C.I. = 17.62 to 94.37). There was no detectable effect of pest taxon on NEA response to biocontrol (p = 0.60; Fig.4d).

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 pest abundance was marginally higher in smallholder farms (66%, C.I.: -78.14 to -47.21) than in research farms (48%, C.I.= -59.62 to -33.64) (Fig.5a). Crop damage showed a similar pattern, where reduction in small holder farms (-69%, C.I.: -81.83 to -47.87) marginally exceeded that of research farms (45%, C.I.= -55.53 to -34.04) (Fig. 5b). With regards to yield, the proportional increase was almost equal in the two cropping types (small farm: 59%, research farm 67%). in neither case was NEA affected by biocontrol interventions.

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 pest abundance and damage, and reduced yield compared to synthetic pesticides, we found no significant difference between the two treatments (Fig.6, pest abundance: 23%, C.I. = -10.30 to 69.04; crop damage: 87%, -2.06 to 246; yield: -7%, C.I. -24.04 to 11.48). NEA: 43%, C.I. = 5.26 to 116.62). Conversely, the abundance of natural enemies was significantly greater following biocontrol implementation compared to the application of synthetic pesticides (43%, C.I. = 5.26 to 116.62) (Fig.6).

Landscape composition

Our search yielded seven studies that explored the effect of landscape composition 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) (Henri *et al.* 2015; Milligan *et al.* 2016; Kebede *et al.* 2018; Soti *et al.* 2019). Only three studies explored the interactive effects of landscape complexity and farm management on pest control effectiveness (Tsafack *et al.*2013; Midega *et al.* 2014; Kebede *et al.* 2019). All studies found an interactive effect of management and landscape composition, though the low sample size did not allow for quantitative analysis here.

Discussion

In this study we identified the overall effectiveness of biocontrol techniques in controlling insect pests of crops in sub-Saharan Africa, and identified patterns across biocontrol interventions, pest taxa, crop types and experimental design. Using a meta-analytical approach, we found that biocontrol interventions effectively reduced pest abundance and crop damage by over 50%, while increasing crop yield 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 (Oerke 2006; Savary *et al.* 2019). 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 pest abundance, crop damage and crop yield, and a significant reduction in the loss of natural enemies, particularly following botanical pesticides application.

Biocontrol effectiveness across biocontrol intervention techniques

Pest abundance and crop damage were negatively affected by biocontrol across all interventions. Push-pull and botanical pesticides had the greatest effect on crop yield, increasing production by 92% and 80% respectively. This may be due to the highly effective companion crops utilised 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 (Khan *et al.* 2014). The large yield increase observed in our synthesis may be due to a combination of the pest repellent and weed suppression abilities of push-pull implementation. Our findings indicate 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*) (Norgaard 1988). Conceivably these interventions may be hampered by the high costs involved in their research and production, such as insect rearing facilities (Neuenschwander 2004), and the growing concerns on the environmental risks of releasing exotic species (Van Lenteren *et al.* 2006). Therefore, they may only be implemented for highly widespread and devastating pests such as the Cassava mealybug or the Tomato leaf miner (*Tuta absoluta*).

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 (Robinson *et al.* 2015). 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 crop damage by 60% is encouraging given the devastating damage caused, particularly on maize, by caterpillars including fall armyworm (*Spodoptera frugiperda*), Diamondback moth (*Plutella xylostella*), Crambid cereal stemborer (*Chilo partellus*) and Maize stemborer (*Busseola fusca*).

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 natural enemy abundance following botanical pesticides 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, but the direct negative impact of some interventions, such as some broad-spectrum botanical pesticides, cannot be excluded (Ndakidemi *et al.* 2016). 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 (Simmonds *et al.*2002; Maia & Moore 2011), while other studies found no detrimental effect of pepper and garlic extract on natural enemies populations (Fening *et al.* 2013; Amoabeng *et al.* 2020). More research is needed to draw robust inferences on the repercussion 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 (Koji *et al.* 2007; Midega *et al.* 2008), which is in line with evidence from the global north on the benefits of habitat enhancement on natural enemy density and diversity (Blaauw & Isaacs 2012; Holland *et al.* 2017). However, we found that only 14% of the studies measured NE abundance following biocontrol application in sub-Saharan Africa. Natural enemy abundance 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 outcomes measures reported in the studies focussed on the abundance of pests and/or natural enemies, while we did not find studies measuring their species diversity or functional group diversity. However, it has been shown that biocontrol is strengthened by increased natural enemy richness (Griffin *et al.* 2013; Katano*et al.* 2015) and this is consistent across temperate and tropical regions (Letourneau *et al.* 2009). Ecosystem functioning can be stabilised by functional redundancy, by enabling functional groups to compensate for individual species fluctuations and increase the resilience of ecosystem against species loss (Rosenfeld 2002; Hooper*et al.* 2005). 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.

Biocontrol effectiveness compared to synthetic pesticides

When compared to synthetic pesticides, biocontrol interventions had a similar impact on pest abundance and crop damage, which is a critical finding for farmers who cannot access or afford chemicals. Crucially, natural enemy abundance was significantly reduced after synthetic pesticides application even over the short time scales 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 overrepresentation 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 suggest there is a big opportunity to raise yields with biocontrol interventions.

Landscape composition and biocontrol

Our study set out to answer the question, "does the surrounding landscape composition affect the effectiveness of biocontrol interventions?". However, we found a paucity of studies investigating either the effect of landscape composition on biocontrol effectiveness, or the relationship between landscape composition and natural enemy abundance. The research we found indicated a significant decrease of natural enemy density and predation/parasitism activity with isolation from natural habitat (e.g., Henri *et al.* 2015; Soti *et al.*2019). This is in line with recent research showing a similar effect of landscape complexity on pollinators and natural enemies in sub-Saharan regions (Ratto *et al.* 2021; Jordon *et al.* 2022) and a larger body of research particularly in the global north (Bianchi*et al.* 2006; Chaplin-Kramen *et al.* 2011; Shackelford*et al.* 2013).

Furthermore, the sparse evidence we found focusing on the effect of landscape composition on biocontrol effectiveness showed inconsistent results. Midega *et al.* (2014) found that semi-natural habitat acted as a source of lepidopteran pests to the maize crop fields in Kenya, while Kebede *et al* . (2019) 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. Furthermore, recent evidence from SSA showed that natural enemy diversity in crop fields is dependent on the land management of neighbouring fields (Tripathi *et al.* 2022). This highlights the need for further multi-scale studies to identify potential variation in biocontrol effectiveness across different land management contexts.

In conclusion, our findings provide the first quantitative synthesis of biocontrol effectiveness in SSA, indicating that biocontrol interventions have the potential to substantially reduce crop damage, increase crop yield 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. Our results suggest that biocontrol represents an effective intervention for farmers who do not have access to pesticides, while it can maintain crop yields without associated negative pesticide effects.

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Data Availability statement

Data used in these analyses will be published on upon acceptance of the manuscript.

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Figure captions

Figure 1 . Changes in pest abundance, crop damage, yield, and 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. Results that cross zero indicate no significant difference between control and treatment groups. K = number of articles, n = number of effect sizes

Figure 2 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 categorised as Botanical Pesticides (BP), Field margins (FM), Intercropping (Int), Push-Pull (PP). Results that cross zero indicate no significant difference between control and treatment groups, n = number of effect sizes

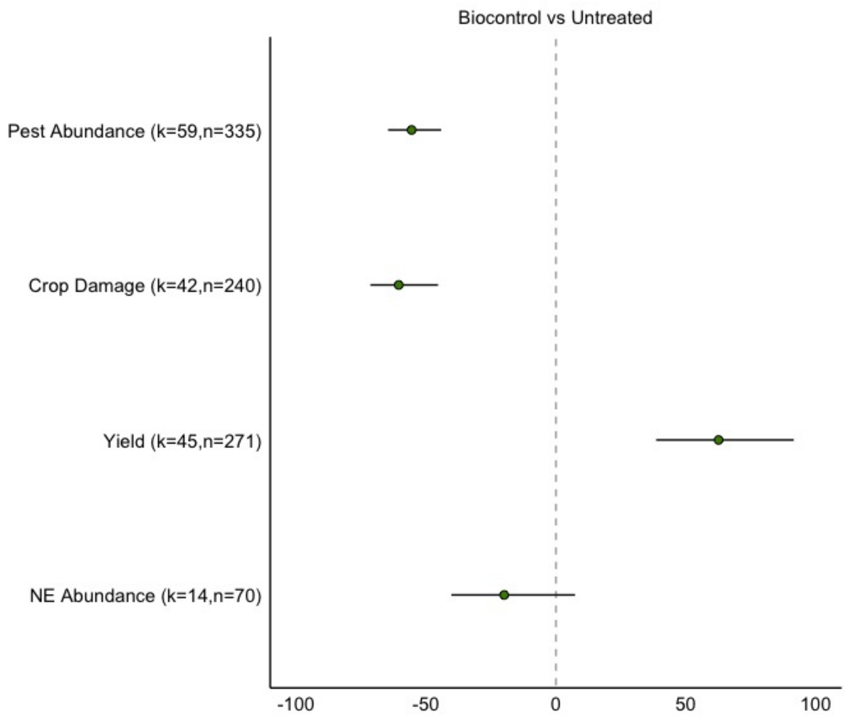
Figure 3 Changes in (a) pest abundance, (b) crop damage, (c) yield, and (d) natural enemy abundance when biocontrol interventions are implemented compared to untreated crops (untreated/monocropping). The values are expressed in percentage with 95% bias-corrected confidence intervals categorised as Cereal, Fibre, Fruit, Pulses and Vegetable (Veg) where available. Results that cross zero indicate no significant difference between control and treatment groups; n = number of effect sizes

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 categorised 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

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 categorised as small farms and research farms. Results that cross zero indicate no significant difference between control and treatment groups; n = number of effect sizes.

Figure 6 Changes in pest abundance, crop damage, yield, and natural enemy 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.

figures



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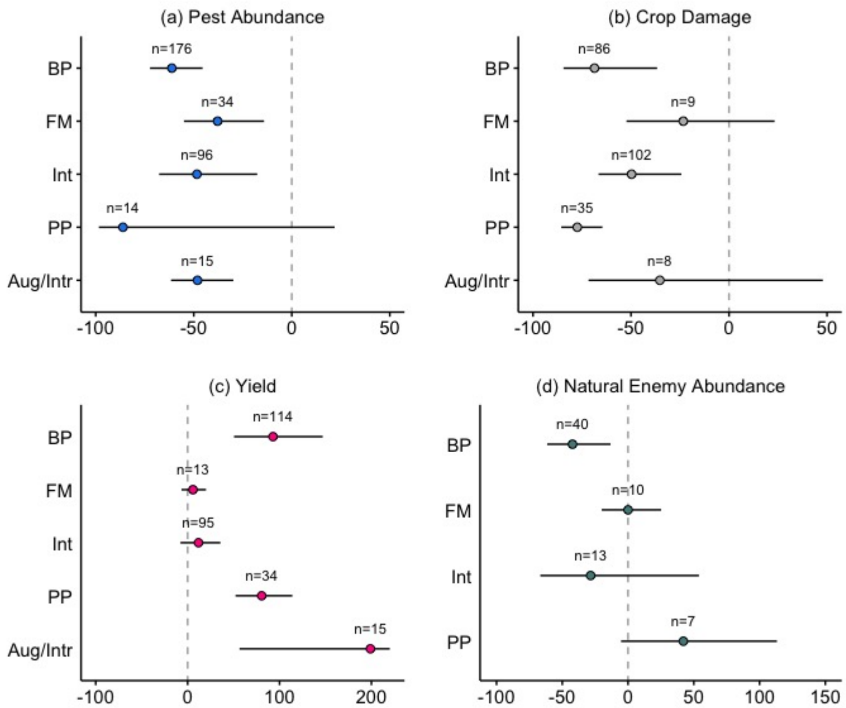

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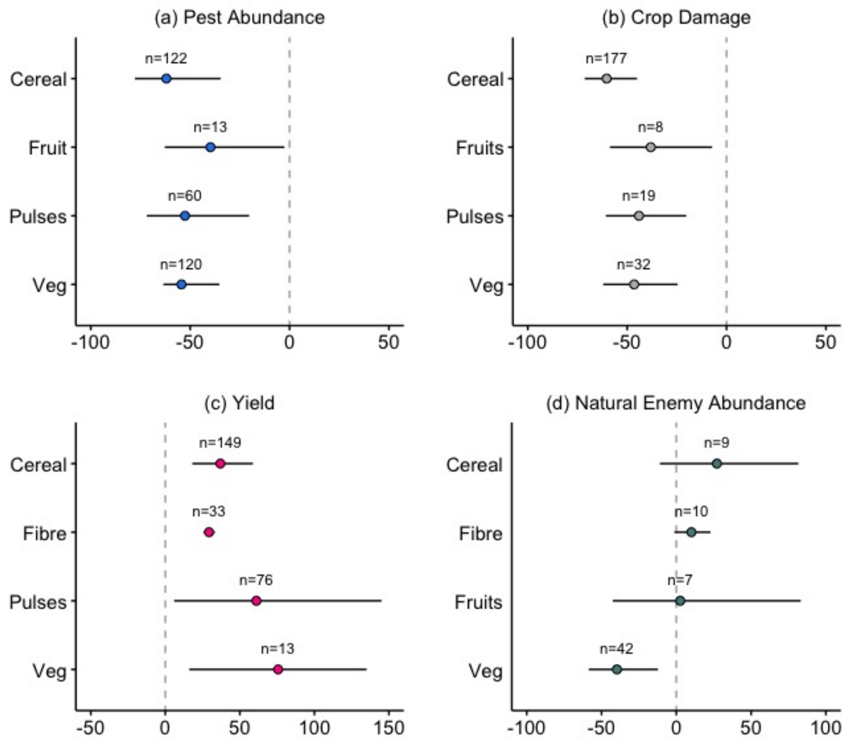

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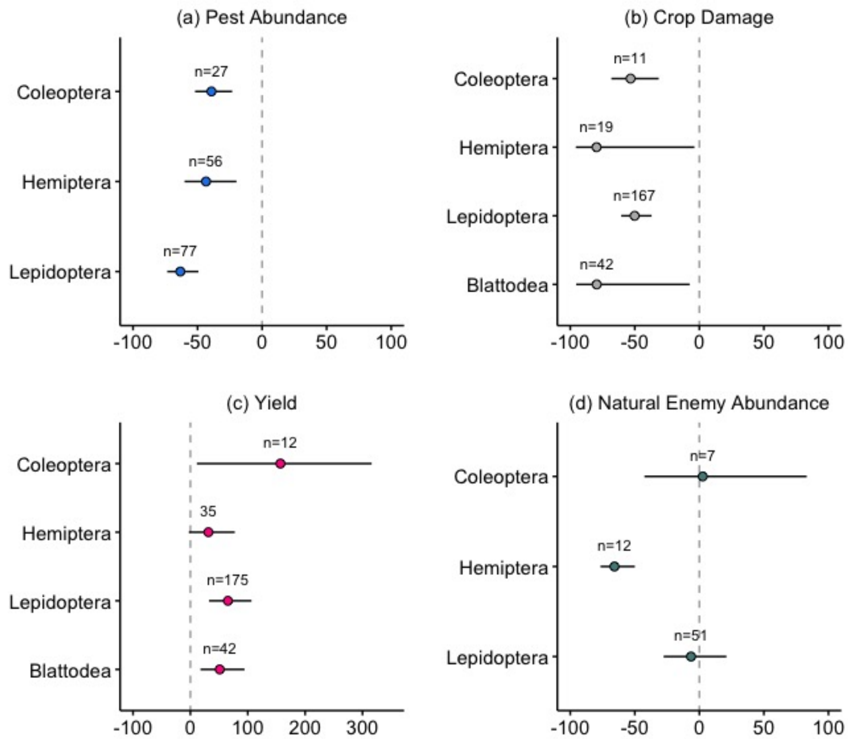

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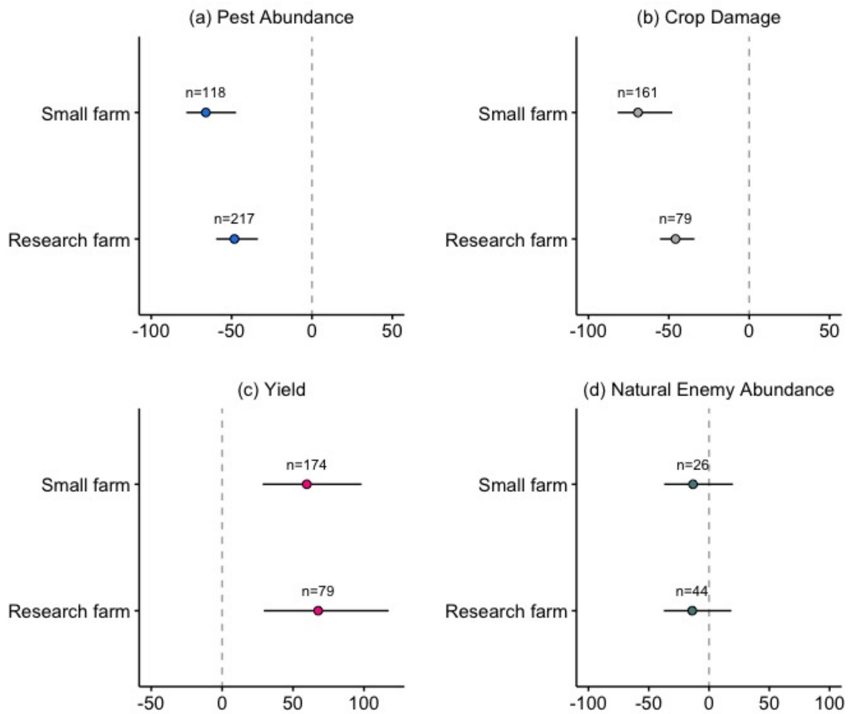

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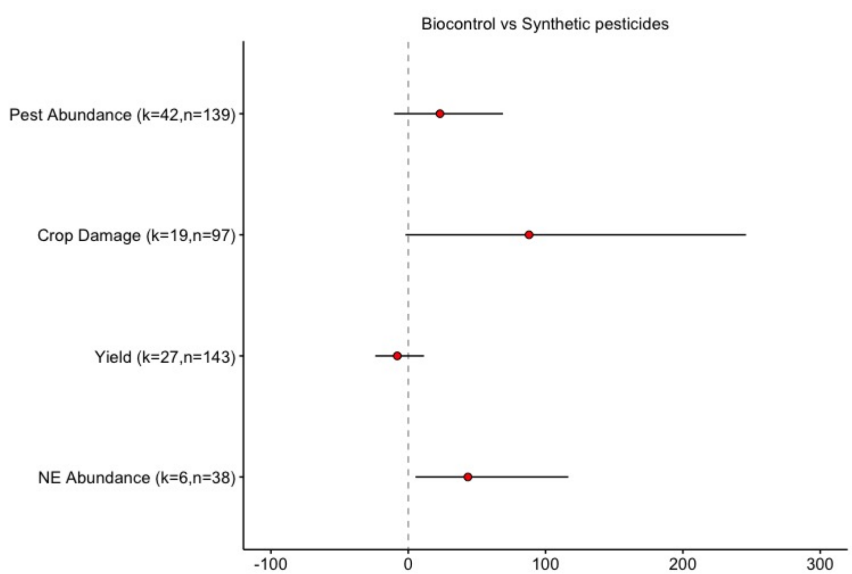

Figure 6 Changes in pest abundance, crop damage, yield, and natural enemy abundance when biocontrol

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.

Tables

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, 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., *Desmodium spp*) to repel (push) pests. A trap crop, a perennial fodder (Napier or *Brachiaria 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