Advancing conservation biological control as a component of IPM of horticultural crops

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Advancing conservation biological control as a component of IPM of horticultural crops

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Abstract

Conservation biological control is commonly considered to be a key component of IPM because it is compatible with and complementary to many other approaches available in the IPM 'toolbox'. However, despite significant study of conservation biological approaches in horticultural systems, uptake has been limited. Furthermore, whilst there are many studies that provide examples of positive implementations, there are as many studies in which the evidence for benefits to pest control is either inconsistent or absent. We suggest that careful consideration needs to be given to the scale at which studies of conservation biological control are conducted (both spatial and temporal) and the metrics that are recorded. To-date there has been a bias towards ecological studies, with relatively scant consideration of the economic impacts of conservation biological control measures. We propose a framework for the future study of conservation biological control approaches, which centres around economic costs and benefits.

Keywords

Natural enemies, invertebrate pests, metrics, spatial scale, temporal scale, economic measures, cost:benefit analysis, co-benefits.

Contents

1. Introduction

What is Conservation Biological Control?

Conservation Biological Control (CBC) of invertebrate pests can be considered as the application or establishment of interventions in an agroecosystem that promote the regulation of pests by enhancing the fitness of their natural enemies (Ehler, 1998). Pest outbreaks occur with much greater frequency in agricultural systems than in nature, and within agroecosystems the frequency of outbreaks has increased with increasing intensification (Singh and Satyanarayana, 2009; Woltz et al., 2012). In natural systems the inherently greater biodiversity results in more interspecific competition for resources and these diverse habitats ensure many different niches exist, facilitating the survival of natural enemies, ensuring no one species dominates and that a dynamic balance is achieved (Gutierrez-Arellano and Mulligan, 2018). The development of intensive commercial agricultural systems and landscapes has created both the perfect environment for crop growth and for pest development, removing competition and limitations on the resources pest species require; furthermore, the decreased diversity and complexity in these systems has removed many habitats which support wider biodiversity, thereby suppressing natural pest control (Altieri, 1999; Woltz et al., 2012). Therefore, the aim of CBC is to use interventions, particularly habitat modification, to support the establishment and maintenance of natural enemy populations, which use pest species as a trophic resource, i.e., facilitating the natural provision of pest regulation services (Power, 2010; Zhang et al., 2007). CBC is differentiated from other forms of biological control in that it aims to promote natural enemies that already occur in the local environment rather than the introduction of novel control agents (Helyer et al., 2014).

As discussed in earlier chapters of this book. there is a clear environmental need, increased political will, increasing need for alternatives to synthetic pesticides, and a strong social argument for a shift in the management of cropping systems towards a more ecologically sustainable approach (Pretty et al., 2018; Sánchez-Bayo and Wyckhuys, 2019; Tilman et al., 2011). It is considered that CBC, as a component of an IPM approach, is a key method with which to address the challenges that face current agricultural production (Birch et al., 2011). One of the key principles of IPM is the reduction in and more targeted use of insecticides (Barzman et al., 2015); therefore, CBC is especially compatible with this approach, in particular because many natural enemies are more susceptible to insecticides and likely to suffer non-target effects (Devine and Furlong, 2007), which would reduce the effectiveness of any CBC measures.

How is Conservation Biological Control Employed in Horticulture?

Measures employed in CBC of arthropod pests focus on the provision of food and shelter for natural enemies. Holland and Ellis (2008) proposed the acronym SAFE (Shelter, Alternative Prey, Floral resources, Environment) as a method of communicating the key resources that are required to promote natural enemies within cropping environments. Shelter or refugia are required because the life cycle of most natural enemies means that they require other habitats, besides the cropping environment, in which to overwinter, forage or reproduce. Alternative Prey are particularly important in systems where the pests are an ephemeral resource and therefore natural enemies require alternative prey or hosts on which to survive during the intervening periods when pests are not present. Floral resources are important for those natural enemies which require either pollen or nectar during at least one part of their life cycles to survive, for example the adult stage of both parasitoid wasps and hoverflies. The term Environment in the SAFE acronym refers to the provision of diverse vegetation untreated by insecticides, which is required by many natural enemies to support different life stages (Holland and Ellis, 2008).

Within this framework, a range of different interventions have been trialled and tested for horticultural crop production, which can be broadly classified as:

1) **In-field approaches** i.e., changes to the management of the cropping system itself to provide a greater diversity and the resources that natural enemies need to persist and survive in the system (e.g. intercropping, companion planting, polycultures, within field flower strips etc.; see figure 1 A and B). Examples of where such approaches have been investigated in horticultural systems include, amongst others, cabbage (Adati et al., 2011; Balmer et al., 2014; Balmer et al., 2013) tomato (Abad et al., 2020), bell pepper (Bickerton and Hamilton, 2012), fennel (Ramalho et al., 2012), citrus (Aguilar-Fenollosa et al., 2011a; Aguilar-Fenollosa et al., 2011b; Aguilar-Fenollosa and Jacas, 2013; Aguilar-Fenollosa et al., 2011c; Kong et al., 2005), apple (Albert et al., 2017; Brown and Mathews, 2007; Brown et al., 2010; Brown and Mathews, 2008) and pear (Song et al., 2010; Song et al., 2011).

2) **Field margins** i.e., changes to the management of the spaces around the edges of fields or cropping areas (e.g., field edge flower or grass strips, uncultivated areas, beetle banks and hedgerows; see figure 1 C). Field margin manipulations have been studied in a range of horticultural crops including, but not limited to, tomato (Balzan and Moonen, 2014), brassica (Geiger et al., 2009), lettuce (Pascual-Villalobos et al., 2006), apples (Santos et al., 2018)

3) **Landscape scale effects** i.e., the management of non-crop vegetation in the wider farming landscape to ensure refugia and food resources, and connectivity of resources are sufficient to promote biodiversity and CBC. Research in this area focuses predominantly on the wider landscape around all agricultural systems (Begg et al., 2017; Bianchi et al., 2006; Chaplin-Kramer et al., 2011; Tscharntke et al., 2016; Tscharntke et al., 2005) although specific examples from horticulture include, amongst other crops, apple (Happe et al., 2019; Happe et al., 2018), grape (Rusch et al., 2016a; Rusch et al., 2017; Thomson and Hoffmann, 2013; Thomson et al., 2010; Wilson et al., 2015; Wilson et al., 2017) and olive (Villa et al., 2020).

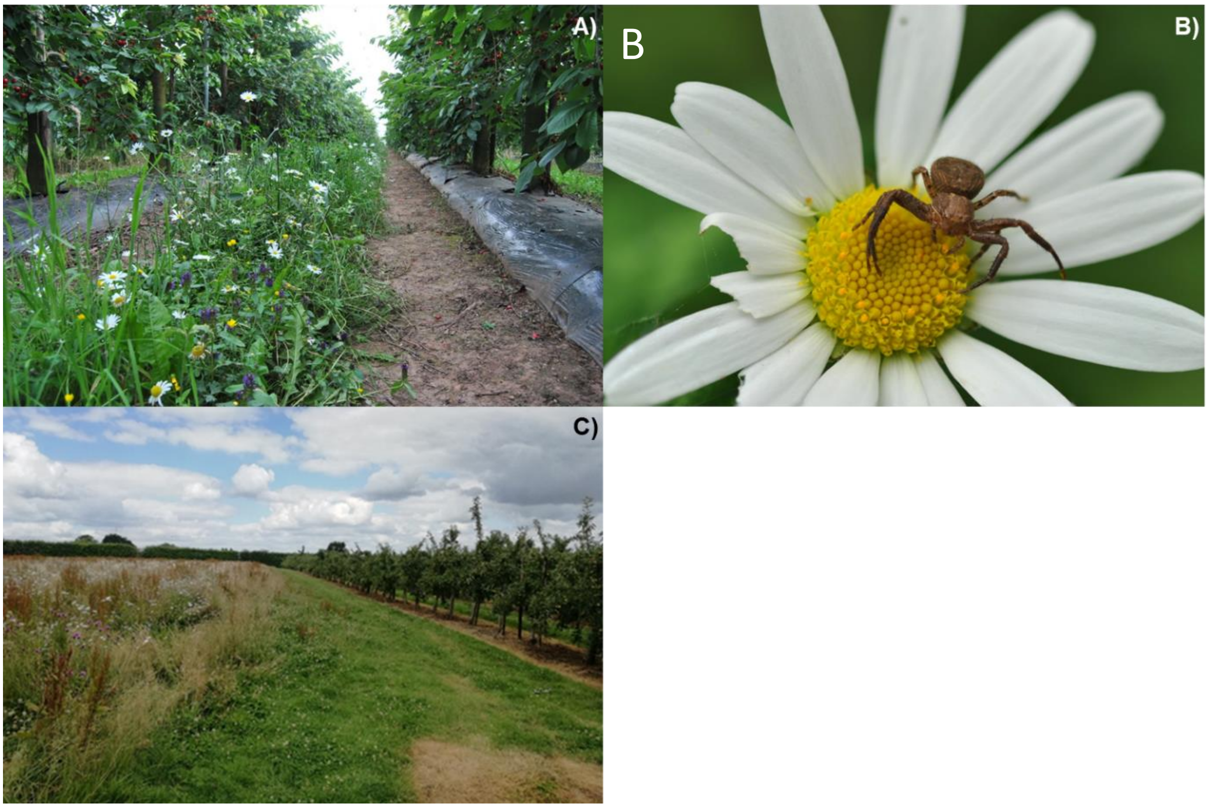

Figure 1. **A:** A flower strip between the rows of trees in a cherry orchard, grown under protected cropping in the UK (Image: Zeus Mateos-Fierro); **B:** A crab spider on an oxeye daisy, one of the natural enemy species promoted by, and found in, the flower strip shown in A (Image: Zeus Mateos-Fierro); **C:** A Floristic margin next to an apple orchard in the UK (Image: Michael Garratt).

Why is uptake of CBC in horticultural production systems still limited and what are some of the broader knowledge gaps?

As highlighted above, there has been significant research to date on many varied CBC approaches in different horticultural cropping systems, and there is evidence of a clear need for such sustainable approaches to be adopted in these cropping systems. However, despite the potential benefits of CBC, its uptake on a commercial scale remains limited (Johnson et al., 2021) and more widely there is strong evidence to suggest that uptake of CBC and other forms of ecological intensification is not as widespread as it could be (Kleijn et al., 2019). Therefore, given the potential benefits of CBC and the clear need and political will to move towards more sustainable approaches to farming, what are the barriers that have stopped the more widespread adoption of CBC measures as part of horticultural IPM?

A recent comprehensive study by Johnson et al (2021), identified 150 primary research papers (comprising 247 separate experiments) from all types of agricultural crop, which have investigated the application of CBC approaches using replicated field experiments, with the aim of understanding why the uptake of CBC in all farming systems globally is currently low. Their key conclusions were that the scope of CBC research to date is too limited, lacking detailed consideration of economic benefits (only 10 of the 247 experiments investigated profitability) and overall, it is focused too heavily upon metrics of pest and natural enemy abundance.

To better understand whether the findings of the Johnson et al (2021) study were also representative for horticultural production we used their published database, but removed all non-horticultural crops and re-ran their analysis following the same methods, which investigated the metrics measured and success of CBC studies. This resulted in a subset of 100 papers and 167 experiments, which were dominated by studies of Brassica (22%), apple (22%) and grape (11%). No other single crop features in more than 8% of studies. Of these studies, 37% were from Europe, although 84% were from temperate locations.

The most common metric measured in papers was the abundance of both natural enemies and pests, both of which were measured in approximately 80% of all experiments conducted (Figure 2). For all metrics used, a high proportion of the studies demonstrated ‘uncertain’ results. Surprisingly, very few studies investigated the impacts of the CBC interventions on the crops themselves and only a handful displayed a clear positive outcome for crop damage or crop yield, and of the two studies that investigated an economic effect, only one showed a positive economic impact from the intervention (the crop was clementine mandarin).

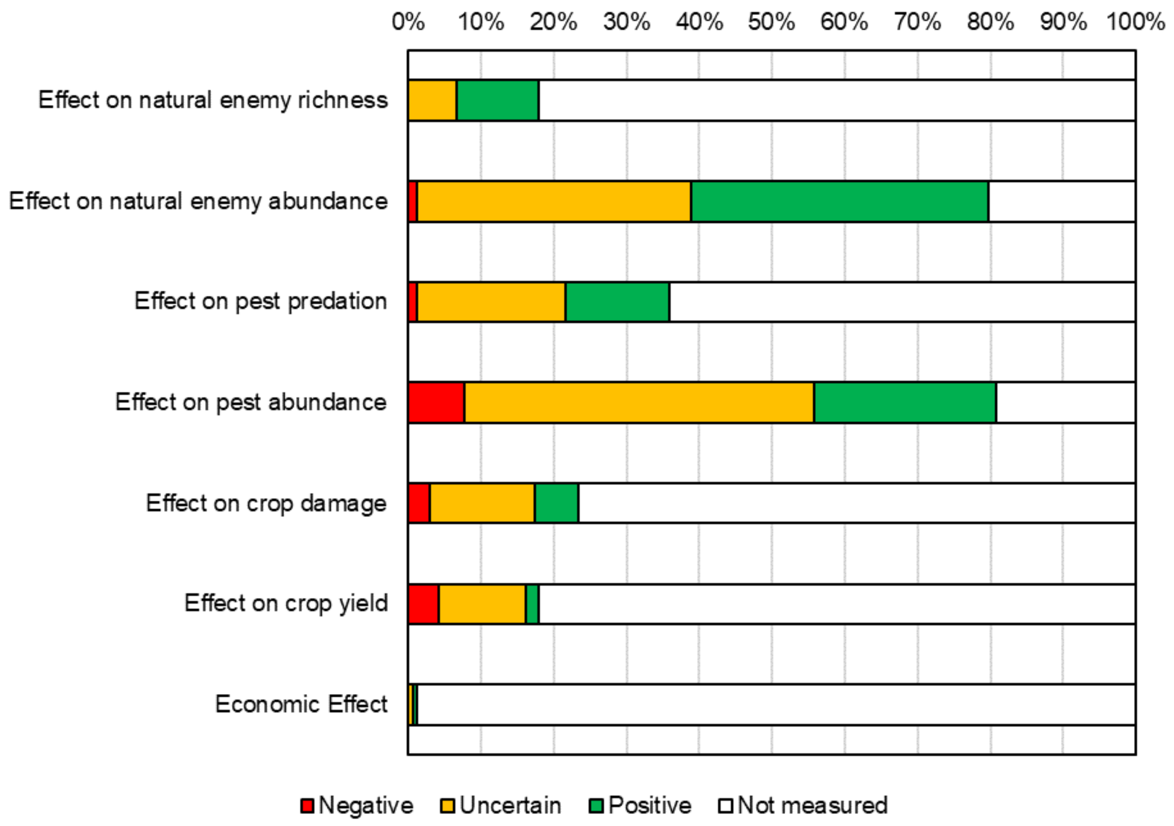

Figure 2. The percentage of positive, negative, uncertain and unmeasured outcomes for different metrics measured to monitor the effects of conservation biological control amendments in 100 field trial studies (including a total of 167 separate experiments) of horticultural crops. Based on a dataset by (Johnson et al., 2021)

From their broader data set, Johnson et al (2021) demonstrated similar outcomes and concluded that the potential barriers to wider adoption of CBC included the fact that levels of 'inconsistent' or 'no' effect were high for many response variables. As a result, they proposed that more research should be conducted to provide a broader body of data from which to understand such inconsistent or negative effects. However, there are already many studies, with some crops, for example those on the brassicaceous crops and apple in this dataset (a total of 37 experiments on each), yet inconsistent effects were still common (61% of all recorded effects for brassica were "uncertain" and 54% for apple). We propose that the inconsistency of effects may not simply be a result of a limited number of studies but that there may be other factors that contribute.

Thus, these results pose two clear questions that researchers in the field must investigate in an attempt to enhance both the efficacy and uptake of CBC in commercial horticulture:

1. The benefits of CBC on response metrics appear to be varied and uncertain, which factors could be the primary causes of this variation?
2. Given the low number of studies looking at the impacts of CBC measures on the crops themselves, are researchers measuring the appropriate metrics to promote the uptake of CBC amongst practitioners?

2. Effects of scale on the efficacy of Conservation Biological Control

Evidence of the potential benefits of CBC to reduce crop pest damage in horticultural systems have been reported by many studies (Aguilar-Fenollosa et al., 2011c; Balzan, 2017; Balzan and Moonen, 2014; Brown et al., 2010; Cahenzli et al., 2017; Gómez-Marco et al., 2016; Irvin et al., 2006; Salamanca et al., 2018), but as explained above, outcomes can often be mixed and there are many examples where the results of CBC through habitat management are unclear or even have a negative impact on crop damage (Aguilar-Fenollosa et al., 2011c; Brown and Mathews, 2007; Irvin et al., 2016; Schellhorn and Sork, 1997; Tscharntke et al., 2016).

Such examples could be due to specific factors that prevent CBC action delivering the benefits intended, such as the impacts of pesticides not allowing natural enemy populations to increase (McKerchar et al., 2020), intra guild predation (Finke and Denno, 2003; Müller and Brodeur, 2002), or that the target natural enemy population is not increased (Larentzaki et al., 2008). Fundamental to CBC is that viable populations of the natural enemies that deliver pest control must exist in the agroecosystem, which, as we state above, requires provision of the necessary habitat elements that provide supplemental food resources, nesting locations, and/or overwintering sites, supporting every life stage of natural enemies (Gurr et al., 2017). Therefore, habitat interventions to promote CBC as a pest control strategy are likely operate at a different spatial and temporal scales to more conventional pest control approaches. This concerns both the application of a CBC intervention, but also how the impacts of the intervention are assessed.

Spatial considerations

With regard to active management to improve CBC, such as through the provision of habitats in the form of hedgerows, field margins or beetle banks, it is critical that habitats are both large enough, and close enough to farm fields, to provide a sufficient increase in natural enemy abundance to deliver pest control services. The abundance of natural enemies is known to decline away from source habitats and depends on habitat quality (Albrecht et al., 2020; Garratt et al., 2017; Woodcock et al., 2016). Furthermore the density, diversity, and function of natural enemies are sensitive to the size of suitable habitats, such as wildflower plantings (Blaauw and Isaacs, 2012), and interventions employed without sufficient coverage may not deliver pest control services effectively (Tscharntke et al., 2016). Introducing in-field habitat interventions (i.e., within the crop itself), such as in the alleyways of fruit orchards, is one way of mitigating these spatial limitations and ensuring uplifts in populations of beneficials, even with only limited spill over of natural enemies. This was shown to improve pest control in apple orchards (Campbell et al., 2017). Similarly companion cropping alongside cucurbit crops increased the populations of beneficial insects and spiders with the potential to control key pest insects (Qureshi et al., 2009) although impacts on yield were not measured in this case.

Landscape context surrounding crops in terms of the cover of non-cropped land (Chaplin-Kramer et al., 2011; Dainese et al., 2019; Rusch et al., 2016b), and the arrangement and distribution of these elements (Martin et al., 2019) are an important determinant of invertebrate communities and resulting pest control. Therefore, the protection or restoration of these landscape elements are recommended as a solution to improve CBC in agricultural systems (Garibaldi et al., 2019). However, despite generally positive effects of less intensively managed landscapes being detected across systems as a whole (Dainese et al., 2019), positive responses of natural enemies are not universal and are highly context dependent (Karp et al., 2018). More research is needed to understand to what extent non-crop areas effect CBC in horticultural crops and at what spatial scale this operates, particularly in protected or semi-protected contexts.

Furthermore, landscape context and local CBC interventions, such as floral habitat creation, can interact to determine the relative success of these interventions. Interventions often prove most effective in intermediate landscapes compared to either very simple landscapes, where there are no source populations of natural enemies, or in highly complex landscapes where the response potential is already saturated (Tscharntke et al., 2005). For example, when floral strips of buckwheat were established next to Kale fields in New Zealand, parasitism rates were enhanced, the abundance of pests reduced and crop yield increased in fields in moderately simple landscapes, but not in those in highly complex landscapes (Jonsson et al., 2015).

Ultimately the spatial scale at which CBC management is undertaken (e.g., habitat protection) or interventions implemented (e.g., flowery field margins) depends on the crop system, and importantly those species which have a role to play in CBC, either as protagonists or antagonists. The traits of these different actors can be used to anticipate which approaches are likely to deliver better pest control. For example, in a large scale meta-analysis, which included data on a number of horticultural crops, it was found that natural enemies that can fly benefitted more from a high density of field edges, which promoted spill-over into crop fields, in contrast to less mobile ground-dispersing natural enemies which are better able to persist in crop fields and were most abundant in landscapes with few edges (Martin et al., 2019).

Temporal Considerations

Spatial components are not the only considerations when implementing management to exploit CBC in horticultural crop systems. Considering the temporal availability of key resources is also critically important. Very often the natural enemies that are relied upon to deliver CBC services are longer lived than many pest species, living over several seasons and requiring different resources at different times depending on their life stage. Therefore, it is not just about how much and where resources are available, but also when they are available. Targeted measures that secure the continuity of resources throughout the life cycle of service-providing organisms are therefore needed (Schellhorn et al., 2015). For example, non-crop areas provided critical overwintering habitats for natural enemies in Brussels sprout production systems with herbaceous non-crop habitats, in particular, providing important refugia for predators important for CBC (Geiger et al., 2009).

Another temporal consideration when establishing habitat management approaches to increase populations of locally abundant natural enemies is that interventions such as wildflower strips can take time to establish and deliver benefits. It can take several generations for local populations of beneficial organisms to respond with an increase in local abundance. A classic example concerns not insect natural enemies but insect pollinators, where it has been shown that it takes several seasons for wild bee populations to increase in abundance following the establishment of flower plots adjacent to blueberry crops (Blaauw and Isaacs, 2014). The same lag effect would be expected for habitat effects on natural enemies, although a recent meta-analysis, incorporating data from many different crop systems, demonstrated that while the age since establishment of flower strips affected pollinators and pollination, no such effect was seen for pest regulation services (Albrecht et al., 2020). This suggests that perhaps natural enemies are better able to respond to such interventions in the short term, although more targeted research is required to establish this effect and how broadly it applies to different groups of natural enemies. For example, the increased abundance of natural enemies in apple trees in response to alleyway plantings of flowers were seen after just one year post establishment in cider apple orchards, although benefits to yield and crop quality were not observed (Campbell et al., 2017), but it is unclear whether these benefits would be observed over a greater time period. Furthermore, CBC interventions, including hedgerows and floral plantings, were employed in another study on orchard systems where they increased the abundance of spiders, an important natural enemy in this system. However, the benefits of this were not observed until the subsequent season after abundant spider populations in the previous autumn had reduced the number of aphid fundatrices the following spring, a clear example of a lag effect of an intervention (Cahenzli et al., 2017).

Successfully implementing CBC using habitat management, either through the protection of non-cropped areas or the establishment of new resource rich habitats, is knowledge intensive in terms of knowing which approaches will work and where. Importantly, it requires a specific recognition of the spatial and temporal factors which will ultimately determine whether an approach is successful or not. This includes the extent to which effects spill over from different habitats and whether these habitats, in combination with other landscape elements, provide a continuous supply of the necessary resources for beneficials. Both factors are likely to be determined by the ecological and physical traits of natural enemies within the crop system (Martin et al., 2019) and can be used to help target management approaches and floral species selection for horticultural crops (van Rijn and Wäckers, 2016; Wäckers and van Rijn). The time it may take to realise benefits from natural enemy abundance or crop production in response to CBC interventions must also be considered, particularly when being compared with direct approaches with more immediate effects such as pesticide use (Wilson and Tisdell, 2001).

3. Evaluating the effectiveness of Conservation Biological Control management in multiple dimensions

Research to-date has therefore developed our understanding of the biological and ecological factors that must be considered when designing CBC management options, but which other factors may contribute to low uptake of CBC in many parts of the world? Several authors have suggested that low uptake is largely due to the focus of much research on the strictly ecological aspects of CBC interventions: changes in pest and predator density, alterations of species community compositions or binary evaluations of changes in pest damage (Chaplin-Kramer et al., 2019; Johnson et al., 2021). Farmers are often highly risk averse and ultimately require a strong economic incentive to undertake such major management changes, particularly if they do not perceive them to be effective (Zhang et al., 2018b). As such, there are growing calls for greater study into the full economic impacts of CBC methods, including formal cost:benefit analyses, to demonstrate the full benefits of CBC measures (Chaplin-Kramer et al., 2019; Johnson et al., 2021; Shields et al., 2019).

A number of studies have undertaken some economic appraisal of the yield impacts observed following CBC interventions in horticultural cropping systems (e.g. Colloff et al. (2013)), but many lack an assessment of the intervention costs, and almost all are based on simple 'before vs after' comparisons of interventions, without an assessment of the baseline levels of pest control (but see Rodríguez-San Pedro et al. (2020)). Furthermore, unlike some other ecosystem services that arise due to natural ecological processes (e.g., carbon storage) or simple trophic interactions (e.g., pollination), pest regulation by natural enemies is often dependent on a more complex trophic system, involving a wide number of pests and their associated predators. Each of these is likely to have different responses to the environment and to interact with one another at different times of the year. As such, even if other factors can be controlled for, it can be very difficult to link interventions to economic metrics of yield because links between interventions and predator populations, predators and pests, and pests and damage all need to be accounted for separately.

Here, we present a simple best practice guideline for researchers to assess the economic costs and benefits of CBC interventions (Figure 3). Steps are marked as either ***Critical*** or ***Recommended***. Crucial steps will give the researcher the data they need to assess costs and benefits without any intensive economic background. Recommended steps allow for a deeper appraisal of these values but may be resource limited.

1. *Determine appropriate spatial scales:* As highlighted in Section 2, the CBC treatment site should account for i) proximity to the CBC intervention and ii) the overall landscape context although the specific details of this are likely to vary between crops, systems, and regions. Within sites, sampling should be undertaken using a stratified random design to ensure that surveys of pest damage are representative of the whole field/orchard. The sites must be commercial, or have the aim of becoming commercial, in order to ensure relatively representative management. (***Critical***)
2. *Calculate costs of CBC management:* Ideally these costs should be based on actual management costs experienced in situ over the lifespan of the intervention. However, if this is not possible then it is important to estimate these costs over time – specifically the initial establishment costs (e.g. planting) and maintenance costs (e.g. cutting, re-sowing) of the measures, including all relevant materials and labour. Cost assessment should also include any cost reductions from the CBC method, such as reduced pesticide usage. Farming handbooks (e.g. Redman (2020)) can provide this information, but direct discussion with land owners is preferable. (***Critical***)
3. *Record counts of pests and predators:* If it is possible, ecological surveys of the abundance and diversity of known crop pests and their predators should be undertaken throughout the study and compared with suitable control sites. Unlike simple observations of pest presence/absence, direct counts of pest and predator populations allow quantifiable links to be drawn between the CBC measures and changes in pest damage (see point 4) arising from altered natural pest regulation services. Although species level assessments are ideal, responses may only be apparent when considering functional guilds (Gardarin et al., 2018; Staton et al., 2021), which may be more practical for some researchers. (***Recommended***)
4. *Evaluate pest damage:* Levels of pest damage to the crop (e.g., fruit loss/damage or occurrence of disease vectored by pests) should be monitored throughout the growing period of the crop and either compared with damage in untreated fields or from past years of that field as appropriate. Distinction should be drawn between this observed loss and natural losses due to e.g. fruit abortion. Where possible, researchers should look for opportunities to separate out the impacts of specific pests, in case their responses differ (e.g., are either suppressed less or increase) as a result of the CBC measures. (***Crucial***)
5. *Evaluate final crop yield:* Evaluating final harvested crop yield should consider both the total weight of marketable crop and any quality parameters (e.g. shape) that may affect the final sale price. (***Critical***)

6. *Determine crop price:* The market sale price of the crop should be as current as possible and account for any difference in prices due to crop quality. Ideally, this should draw from industry data, however national statistical agencies and FAO data (FAOSTAT, 2021) can be used if necessary. If the research is relatively short term, an average of the past 3-5 years prices can be used to account for price fluctuations. (***Critical***)
7. *Conduct a farmer Cost:Benefit analysis:* Benefits are simply calculated as the total output (yield x quality x price) of the CBC system compared with an untreated control. From then, it is possible to subtract the costs of the CBC measures from the difference to give an initial estimate of net benefits. If projecting costs and benefits into the future, it is important to include a measure of variance in these values over time and apply a discounting rate (a projection of inflation in the future, representing the decreasing value of currency over time) to future years. (***Critical***)
8. *Determine the appropriate temporal scale:* Many CBC measures are unlikely to have an immediate effect, as populations of predators may take some time to grow and habitat modification measures often take time to establish (see Section 2 above). It is preferable for a study to be undertaken over multiple years, ideally over the lifespan of the CBC measure; monitoring the change in cost:benefit each year can identify: i) when, if at all, the measure will become profitable; and ii) how the CBC measure affects the stability of economic output over time. (***Recommended***)
9. *Evaluate consumer impacts:* If the researcher is interested in upscaling the results to a national or regional scale then they may wish to consider evaluating the impacts on consumers as well as producers. This can be achieved using partial equilibrium modelling (see e.g. Zhang et al. (2018a)) wherein the change in total crop output resulting from the mass implementation of the CBC measure is translated to a change in consumer price. This requires more advanced economic modelling but can give a measure of the net societal benefits of the CBC measures, which may incentivise policy support. (***Recommended***)

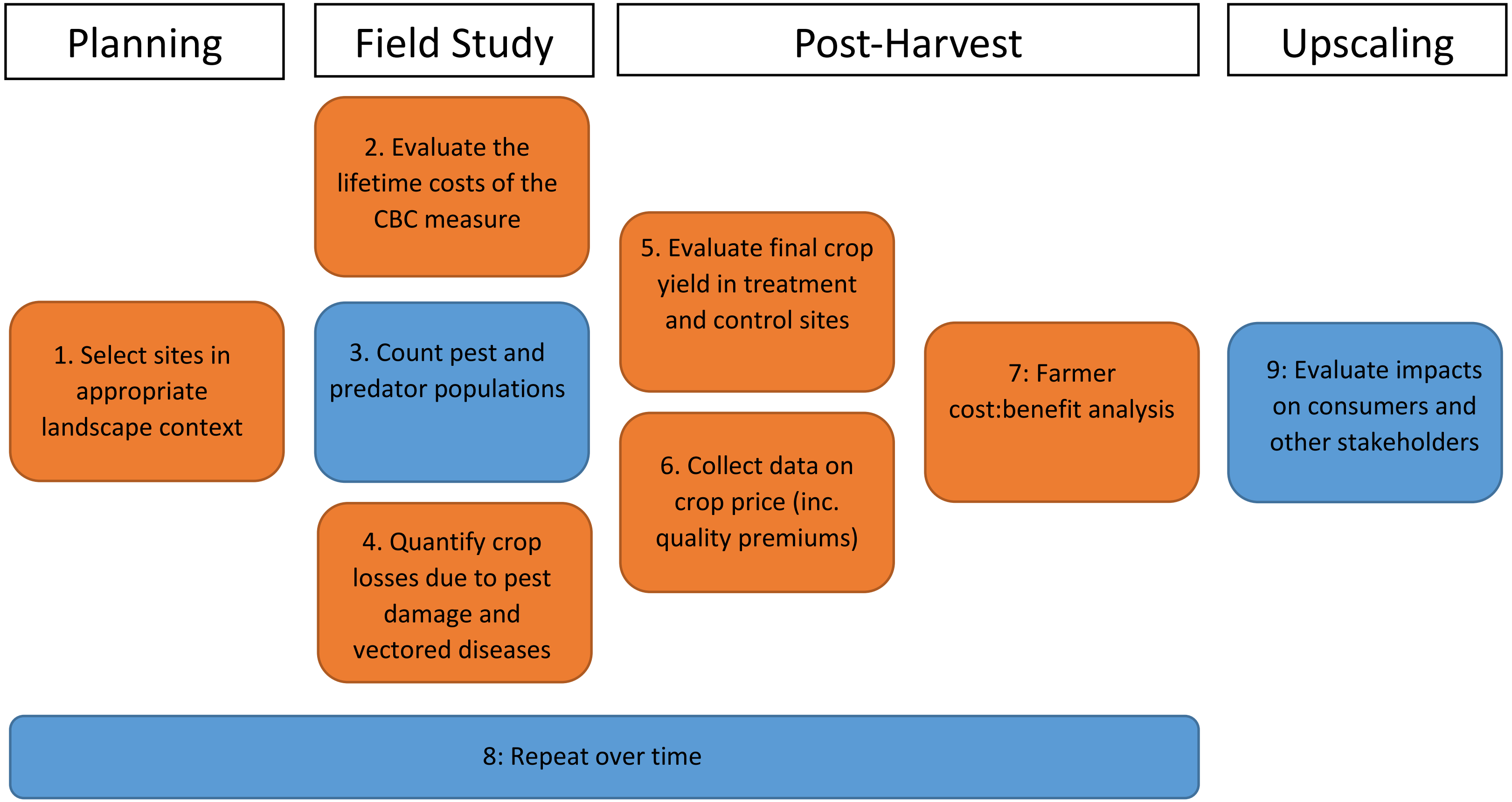

Figure 3. Process diagram for assessing economic benefits of CBC. Cells in orange are critical, while cells in blue are recommended but optional.

Although income is a major concern for many farmers, economic arguments alone may not be enough to fully promote CBC methods. A number of sociological factors have been identified as potential barriers to alternative pest management in general. Farmers may be reluctant to deviate too strongly from their neighbours for fear of becoming a pest reservoir (Wilson and Tisdell, 2001). At the same time however, landscape scale management may not be beneficial to all participants, particularly in mixed landscapes where some landowners, such as pasture or arable farmers, may face little or very different pest pressures compared to horticultural growers. Landowners may also find certain CBC measures, such as flower rich field margins, unsightly and poorly reflective upon their abilities as farmers (Burton et al., 2008) or lack the knowledge to properly implement them (Mankad et al., 2017).

Addressing these barriers requires additional data gathering outside of a standard ecological study. Ideally, before any research is conducted, CBC measures should be co-developed with groups of local stakeholders in order to maximise their collective willingness to take them up and identify barriers (e.g. Giles et al. (2017); Husson et al. (2016)). On a wider scale, farmer surveys, using psychological frameworks such as the theory of planned behaviour (Ajzen, 1991), can also help identify wider perceived and observable barriers to wider uptake (Mankad et al., 2017). Finally, additional economic analysis, drawing from the cost:benefit work outlined above, can also identify the points at which subsidies will make otherwise unprofitable CBC systems more economically viable, particularly in the earlier years when they are initially establishing (Yang et al., 2020).

4. Benefits of Conservation Biological Control beyond IPM

By their very nature CBC management approaches can change the nature of the cropping environment either through adaptive management at the field scale (Larentzaki et al., 2008), habitat creation in and around crop fields (Albrecht et al., 2020; Campbell et al., 2017) or larger scale alteration to landscape context (Jonsson et al., 2015; Martin et al., 2019). These are put in place to manipulate populations of natural enemies and pests to support sustainable crop production through IPM, but can inevitably have impacts beyond this.

One area where there are clear synergies concerns management approaches to increase populations of wild pollinators and the pollination services they provide to crops. Approaches to boost pollinators are often equivalent to those for CBC, including reducing harmful inputs, establishment of floral resources through flower margins, and protection and management of non-cropped habitats such as hedgerows (Kovács-Hostyánszki et al., 2017). Numerous studies have highlighted the co-benefits of such approaches to both pollinators and natural enemies of pests (Albrecht et al., 2020; Garratt et al., 2017; Wratten et al., 2012). In fact by considering these co-benefits and their positive impact on the yield of tomato crops delivered by hedgerows, the economic return on investment and breakeven point for hedgerow establishment was reduced from 16 to 7 years (Morandin et al., 2016). Despite the similarities in the habitat requirements of wild pollinators and many natural enemies, inevitably they are not exactly the same, and features, such as wildflower plots, can be tailored to support different functional groups of beneficial organisms. As a consequence, some compromises or trade-offs are likely when managing for both pest regulation and pollination (Campbell et al., 2012; Campbell et al., 2017). However given the obvious similarities and potential synergies that management of pollination and wider IPM practices offer, they can, and should, be better integrated (Egan et al., 2020).

There are many other potential benefits arising from implementing CBC practices including direct impacts from in-field crop management approaches such as reduced or more targeted pesticide spraying to protect natural enemies (Ruberson et al., 1998) and the associated environmental benefits (Aktar et al., 2009); to reduced tillage to improve biocontrol (Roger-Estrade et al., 2010) benefiting multiple soil physical, chemical and biological properties (Busari et al., 2015). Particularly diverse benefits can be realised through the introduction of non-crop habitats such as flower plots and hedgerows including species conservation (Requier and Leonhardt, 2020), improved soil and water quality (Montgomery et al., 2020) and enhancing the rural aesthetics (Wratten et al., 2012). By the same measure, management approaches implemented for other reasons can deliver CBC benefits, for example field margins to support conservation of birds benefited natural enemies of pests as an unintended side effect (Olson and Wäckers, 2007). When considering implementing CBC actions these multiple benefits should be taken into consideration, particularly when comparing the benefits against more conventional approaches such as pesticide application. Furthermore, these co-benefits should be factored into calculations of any economic analysis of CBC measures.

5. Case studies of conservation biological control in practice

The application of CBC as a component of an IPM approach, is met with a range of challenges that are often specific to the growing system and crop. Therefore, detailed research is often required to provide a clearer understanding of the challenges each system/crop faces and to optimise the different CBC methods, both with respect to their efficacy and cost effectiveness, that can be applied. Here we provide two case study examples of research that have contributed towards the inclusion of CBC in commercial practice. These case studies highlight the application of CBC in an organic field vegetable horticultural production system and in a conventional protected-cropping stone fruit orchard production system.

Case study1: Organic lettuce production in California

Globally, aphids are a key pest of field vegetable production. They can damage their host plants, resulting in yield reductions, in a range of ways, including by depriving the plant of nutrients through feeding on the plants phloem, by the transmission of viruses during feeding (Tomlinson, 1987), and by the honeydew they produce while feeding encouraging the growth of sooty mould (Dedryver et al., 2010). Their presence and the damage they cause can also reduce the marketability of produce for a range of horticultural crops (AHDB, 2021). During the main growing season aphids reproduce parthenogenically, meaning they reproduce asexually, and are viviparous, meaning that the give birth to live young (Hardie, 2017). They therefore have a very fast rate of increase, which means that their control is challenging.

Conventional horticultural production systems have commonly relied upon insecticides to control aphid populations, however their fast rate of increase has meant the development of insecticide resistance in multiple aphid species (Foster et al., 2017). Furthermore, the effectiveness of using insecticides to control the transmission of viruses, through control of the vector, is mixed and often ineffective (Perring et al., 1999). Therefore, there is increasing demand for alternative approaches to controlling aphid pests, which can be adopted as part of an IPM approach (Dedryver et al., 2010).

Organic production has promoted the development of a variety of alternative approaches to pest control, including CBC, although for many of these pest management strategies there is a paucity of rigorous scientific evidence to substantiate their benefits (Zehnder et al., 2007). However, one case study in which the benefits of an organic pest management strategy has been successfully quantified is the application of CBC to control aphid populations in lettuce production on the central coast of California (Brennan, 2013). The predominant aphid pest in lettuce production in central California is the currant-lettuce aphid, *Nasonovia ribisnigri* Mosley (Smith et al., 2008). Controlling this aphid species in lettuce production can be challenging because it aggregates and feed upon the interior leaves of the lettuce plants (Liu, 2004).

In central California it is well established in the organic farming community that by intercropping lettuce plants with sweet alyssum, *Lobularia maritima* (L.) Desv. (Figure 4), it is possible to control *N. ribisnigri* (Gillespie et al., 2011). The mechanism for this control is that the intercropped alyssum acts as an insectary plant, i.e. by having abundant flowers that produce pollen and nectar it attracts beneficial insects, and in particular hoverflies, which feed on these floral resources (Colley and Luna, 2000). The adult hoverflies mate, and subsequently the females forage in the local vicinity of the insectary plants, searching for patches of aphids in which to lay their eggs. The larvae that hatch from these eggs are voracious predators and specialise on feeding on aphids, eating up to 168 currant-lettuce aphids per day (Hopper et al., 2011). Therefore, sweet alyssum has been used as an insectary plant in organic lettuce fields on the Californian Central coast for many years (Bugg et al., 2008).

Figure 4. Additive intercropping of the white flowering plant sweet alyssum (*Lobularia maritima* (L.) Desv.) into organic romaine lettuce fields in: A) the USDA-ARS organic research farm in Salinas CA; B) A commercial organic farm in the region (Image: Eric Brennan, USDA-ARS)

A range of different approaches have been used by growers in the region to incorporate these insectary plants, from strip cropping by interplanting full beds of sweet alyssum across the field of lettuce, to interspersing plants within lettuce beds. As a result, the land used to plant these insectary plants displaces lettuce plants, which reduces the cropping area by between 5-10 %. This means that there is an economic cost through crop displacement, in addition to the costs of establishment and maintenance of this CBC measure (Bugg et al., 2008; Colfer, 2004). Therefore, a study was conducted by Brennan (2013) to investigate different methods that could be used to optimise the quantity and arrangement of sweet alyssum and minimise the displacement organic romaine lettuce, by investigating the effect of different methods of incorporating alyssum on plant biomass/yield. Brennan trialled a series of different replacement intercropping approaches, i.e. various numbers of lettuce transplants were replaced by alyssum transplants (replacing between 2-8% of lettuce transplants), and novel additive intercropping approaches, i.e. alyssum transplants were added to lettuce transplants without displacing them, in comparison to a lettuce monoculture (control). Over two growing seasons the biomass of both lettuce and alyssum were recorded, as was the flower production in the alyssum. All but one of the treatments (replacement with 4% of lettuce transplants displaced in a symmetrical pattern) resulted in decreases in romaine lettuce head dry weight biomass relative to those plants in the lettuce monoculture treatment, indicating that inclusion of alyssum came at a yield cost. The additive treatments, where plants were at a greater density per unit area and therefore under greater competition, resulted in a decrease in the dry weight biomass of alyssum plants, however this was countered by an increase in the number of inflorescences per gram (dry weight) of alyssum. The novel additive treatments appeared to offer the best option for growers because there was no effect on the number of heads grown in comparison to the lettuce monoculture control. Whilst there was a reduction in head dry weight of plants grown in the additive compared to the replacement treatments it was proposed that in commercial production this may have little impact after trimming and packing is considered.

Further research by Brennan (pers. comm.) has refined the additive methods (see Figure 4 A) so that alyssum plants are only included in ‘insectary beds’, which are separated by ten lettuce only beds. Alyssum plants are only planted in one line of each insectary bed at a density of one alyssum plant between every five lettuce plants. This method has been shown to recruit sufficient hoverflies to maintain good control of aphid pests, and it has been demonstrated that the insectary beds produce yields of equal marketable weight to lettuce only beds. This suggests that it is possible to gain all the benefits of pest control by using alyssum in a CBC approach, without having any negative effect on yield, and therefore the only cost is in purchasing and maintaining the alyssum transplants. This is a significant advance on the traditional replacement methods where up to 10% of the lettuce plants were being substituted for alyssum and has resulted in adoption by a number of growers in the region (Figure 4 B).

Case study 2: Conventional sweet cherry production in the UK

Sweet cherry (*Prunus avium* L.) presents several challenges for incorporating CBC as part of an effective IPM programme. Firstly, it is a high value crop where little pest damage can be tolerated, secondly it is often intensively produced under protected or semi-protected conditions (Lang, 2014) where the influx of naturally occurring pest enemies may be constrained, and finally chemical pest control options are widely used in cherry production (Daniel and Grunder, 2012), which may not always be compatible with CBC.

As demonstrated in section 1, the introduction of wildflower habitats can increase both the abundance of natural enemies and the pest regulation services they provide, including in apples (Campbell et al., 2017; McKerchar et al., 2020) and blueberry (Blaauw and Isaacs, 2014). However, such habitat interventions have rarely, if ever, been tested in semi-protected cultivation because of additional barriers to their adoption including: i) increased watering and maintenance costs for flower habitats under plastic, ii) changes in microclimate increasing the risk of pathogens, and iii) inconvenience to grower operations including spraying and picking, for which alleyways are usually kept mown short.

Effective CBC tools are needed in such intensive systems if they are to become less reliant on high inputs of pesticide, particularly in the face of increasing limitations due to changing legislation (e.g. thiacloprid for aphid control) (Daniel and Grunder, 2012). These CBC tools need to be compatible with grower operations, suitable in protected cropping systems, and deliver benefits that are important to growers, thus co-development with growers is essential (Cullen et al., 2008; Kleijn et al., 2019; Simon et al., 2017).

Working closely with growers, a recent study looked to address this challenge directly in sweet cherry (Mateos-Fierro et al., 2021). The study investigated the feasibility of establishing wildflower habitats in the alleyways of sweet cherry orchards, measure how cutting of these habitats effected their quality as a CBC resource, and quantified to what extent wildflower habitats delivered, not only increases in natural enemy numbers, but also improved pest regulation. Using relatively standard management approaches, wildflower strips were successfully established in cherry orchards (Mateos-Fierro et al., 2018), achieving good coverage of a variety of sown flower species (Figure 1 A). Growers were engaged in the development of the CBC amendments and suggested modifications for trial, for example in season cutting of the flower strips.

Wildflower treatments almost doubled the abundance of natural enemies in alleyways, and increased abundance in cherry trees by ~15% compared to the standard alleyway management, although importantly benefits were only seen from year two of study (Figure 5 A-D) (Mateos-Fierro et al., 2021). Wildflower strips increased predation of aphids (measured using bait cards) in cherry trees by 25% early in the season (Figure 5 E-F). No difference in natural enemy abundance, richness or pest control was recorded between wildflower strips that were left uncut, and those that were actively managed in a way preferred by growers, specifically involving regular cutting to maintain a sward height of 20cm. Furthermore, these differences in natural enemy abundance and predation rates between wildflower and control treatments were detected despite the continued use of pesticides by growers.

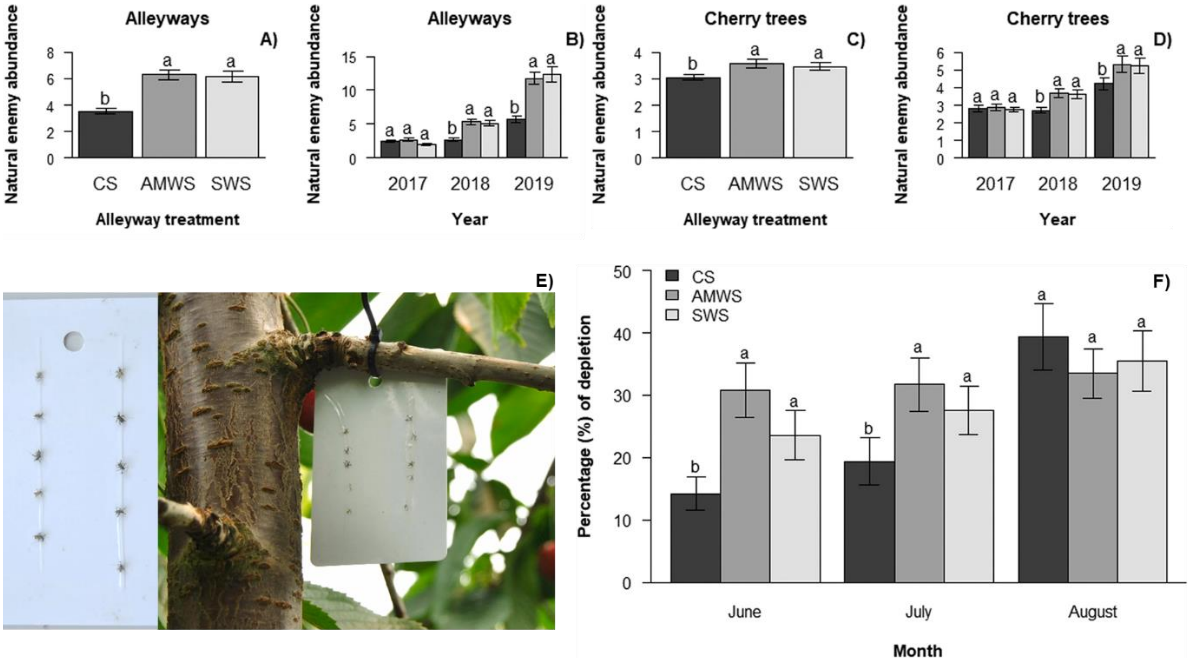

Figure 5. Mean of natural enemy abundance (±SE) recorded throughout the three-year study according to A) and C) alleyway treatment, and B) and D) year, and the effect of alleyway treatment in either the alleyways or the cherry trees. E) Shows bait cards with ten dead aphids glued to the surface to assess predation rate. F) Mean percentage (±SE) of *Acyrthosiphon pisum* aphids (dead) depleted from bait cards. The same superscript letters indicate no significant difference (Tukey test, $P > 0.05$). CS (Control Strips). AMWS (Actively Managed Wildflower Strips), SWS (Standard Wildflower Strips) (adapted from Mateos-Fierro et al., 2021).

This study demonstrated that even in intensive production systems habitat creation for CBC can be effective. Engaging with growers during the development of the CBC amendments aimed to encourage greater uptake of successful measures into commercial production. As with supporting CBC in any production system, identifying the link between ecosystem services and the factors that farmers view as most important may positively influence communication and potential of adoption (Bardenhagen et al., 2020).

6. Summary and proposed future trends in research

Whilst CBC has been shown, by a number of studies, to be an effective method of pest control for a range of horticultural crops, when considered as a whole, the effects measured to-date have been inconsistent and furthermore uptake has been low. Understanding the cause of such inconsistency in results is therefore crucial. It is clear that spatial and temporal scales matter for CBC because it relies on existing biodiversity as opposed to conventional pest control approaches, which often have rapid effects at a local scale (e.g. pesticide application). Habitat interventions for CBC need to be employed with sufficient coverage and sufficiently close to the crop to ensure benefits are delivered, as declining benefits at increasing distances from interventions are common. The local landscape is critical as non-crop areas can provide important habitats for natural enemies in agroecosystems and landscape context can modify the effects of habitat interventions, which often prove most effective in landscapes with an intermediate amount of non-crop area. The effects of local landscape and management interventions on CBC are very context dependent, depending on the cropping system, and are influenced by the traits of the species involved (both pests and natural enemies). Management interventions to improve CBC need to provide resources for all life stages of natural enemies, which are often longer lived and have a more complex life history than pests. The time it takes to realise benefits to natural enemy abundance or crop production from CBC interventions must be taken into account, particularly when being compared to direct approaches with more immediate effects such as pesticides.

We propose that in order to improve uptake of CBC measures, future studies could make use of the framework we set out in our simple best practice guideline (Figure 3), which will assist researchers in assessing the economic costs and benefits of CBC interventions. It is critical that, moving forwards, a clearer economic understanding is developed for all proposed CBC interventions. This is particularly important given the understandably risk averse nature of many farmers, especially with respect to making major system changes. In order to achieve wider uptake, particularly in the light of the many inconsistent studies to date, which in itself is likely to result in farmers questioning the effectiveness of such measures, it is important that evidence of strong and clear economic incentives of system change are provided.

CBC management approaches often involve changing the nature of the cropping environment and so inevitably have impacts beyond CBC alone. One area where there are clear synergies concerns managing for CBC and managing for wild pollinators, and in particular those approaches used to boost pollinator populations (e.g. reducing harmful inputs, establishment of floral resources, protection of non-cropped habitats) often deliver benefits for CBC and vice versa. There are many other benefits that CBC practices can deliver, including reduced negative environmental impacts, improved soil health and positive effects on the rural aesthetic. These multiple benefits should be taken into consideration when deciding whether to implement CBC actions, particularly when compared with more conventional approaches such as pesticide application, and should form a key part of any economic analyses that are conducted to evaluate the cost effectiveness of CBC approaches.

6. Where to look for further information

The following articles provide a good overview of the subject:

- Begg, G.S., Cook, S.M., Dye, R., Ferrante, M., Franck, P., Lavigne, C., Lövei, G.L., Mansion-Vaquie, A., Pell, J.K., Petit, S., Quesada, N., Ricci, B., Wratten, S.D. and Birch, A.N.E. (2017), ‘A functional overview of conservation biological control’, Crop Protection, 97: 145-158.
- Chaplin-Kramer, R., O'rourke, M., Schellhorn, N., Zhang, W., Robinson, B. E., Gratton, C., Rosenheim, J. A., Tscharntke, T. & Karp, D. S. (2019), ‘Measuring What Matters: Actionable Information for Conservation Biocontrol in Multifunctional Landscapes’, Frontiers in Sustainable Food Systems, 3: 60.

- Dainese, M. et al. (2019), ‘A global synthesis reveals biodiversity-mediated benefits for crop production. Science advances’, 5 (10). doi: https://doi.org/10.1126/sciadv.aax0121
- Holland, J. M., Bianchi, F. J., Entling, M. H., Moonen, A.-C., Smith, B. M. & Jeanneret, P. (2016), ‘Structure, function and management of semi-natural habitats for conservation

biological control: a review of European studies’ Pest Management Science, 72: 1638-1651.

- Martin, E.A. et al. (2019), ‘The interplay of landscape composition and configuration: new pathways to manage functional biodiversity and agroecosystem services across Europe’, Ecology Letters, 22 (7): 1083-1094. doi: https://doi.org/10.1111/ele.13265
- Shields, M. W., Johnson, A. C., Pandey, S., Cullen, R., González- Chang, M., Wratten, S. D. & Gurr, G. M. (2019), ‘History, current situation and challenges for conservation biological control’, Biological Control, 131: 25-35.

Key research in this area can be found at the following organisations and sites:

- Agricology (https://www.agricology.co.uk/)
- Centre for Agri-Environment Research (http://www.reading.ac.uk/caer/)
- Centre for Biological Control – SLU (https://www.slu.se/en/Collaborative-Centres-and-Projects/centre-for-biological-control-cbc)
- FAO Agroecology (http://www.fao.org/agroecology)
- FiBL (https://www.fibl.org/en/index.html)

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