A framework and protocols for identification and assessment of key environmental co-benefits from pollinator-friendly land management decisions
Deliverable D3.2

31 August 2023

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Safeguard
Safeguarding European wild pollinators

This project receives funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003476.

Prepared under contract from the European Commission

Grant agreement No. 101003476.
EU Horizon 2020 Research and Innovation action

Project acronym	**Safeguard**
Project full title	**Safeguarding European wild pollinators**
Start of the project	September 2021
Duration	48 months
Project coordinator	Ingolf Steffan-Dewenter Julius-Maximilians-Universität Würzburg https://www.safeguard.biozentrum.uni-wuerzburg.de/
Deliverable title	A framework and protocols for identification and assessment of key environmental co-benefits from pollinator-friendly land management decisions
Deliverable n°	D3.2
Nature of the deliverable	Report
Dissemination level	Public
WP responsible	WP3
Lead beneficiary	SLU
Citation	Lundin O., Breeze T.D., Marini L. and Van der Wal R. (2023). *A framework and protocols for identification and assessment of key environmental co-benefits from pollinator-friendly land management decisions*. Deliverable D3.1 EU Horizon 2020 Safeguard Project, Grant agreement No 101003476.
Due date of deliverable	31/08/23
Actual submission date	31/08/23

Deliverable status:

Version	Status	Date	Author(s)	Reviewer(s)
1.0	Draft	31 August 2023	Ola Lundin - SLU, Tom Breeze – UREAD, Lorenzo Marini – UPAD, Rene van der Wal - SLU	Name Organisation

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1 Summary

Co-benefits of pollinator-targeted interventions are additional positive effects, apart from those on pollinators and pollination, such as pest control or carbon sequestration, resulting from pollinator-friendly land management decisions. The purpose of this framework is to determine the identity and magnitude of co-benefits from pollinator-targeted interventions and how to measure such –largely unintended– co-benefits. To this end, we performed a systematic literature review to identify the types of co-benefits and methodologies for assessing those. We also used expert assessment and Delphi-like methodology to extend our knowledge base, quantify the magnitude of key co-benefits and explore synergies and trade-offs among them. Both the literature review and expert assessment showed that pollinator-targeted interventions are likely to produce several environmental co-benefits such as increased carbon sequestration and storage, nutrient cycling, flood and soil erosion control, and water quality, whereas the effects of these interventions are more mixed for insect pest control and might be negative for weed control. Conservation and management of low-intensity grasslands, woody linear features and crop diversification are pollinator-targeted interventions for which we find evidence of multiple co-benefits, both in the literature and through expert assessment. Reduced pesticide is an example of an intervention for which the evidence of co-benefits is weaker due to low or no effects on ecosystem services such as climate regulation, and soil erosion and mixed, uncertain or partly negative effects on the regulation of pests and weeds. Both our extensive literature review and expert assessment brought to the fore that co-benefits, and notably synergies and trade-offs, remain heavily understudied. As a final component of our framework, therefore, do we provide a detailed protocol for assessing co-benefits of pollinator-targeted interventions for use within and beyond the Safeguard project.

2 Background

Pollinators are under significant pressure from human activities, threatening their biodiversity and the important pollination service they provide to both crops and wild plants (Goulson et al. 2015). Different interventions have been designed and implemented in response to anthropogenic pressures on pollinators (Gill et al. 2016), but a key knowledge gap is the extent to which management for pollinators generates environmental co-benefits, i.e., positive effects on other ecosystem services. In current cropping systems, pollinator-friendly interventions do not always pay off economically in terms of the potential increase in pollination service delivered. This could be because the pollinator species benefitting from the intervention might not visit crops, or that the gains in pollination services accrue outside of the farm or with a time delay (Senapathi et al. 2015). Even with direct gains to e.g., crop pollination from increasing the amount of field margins in a landscape, the increased costs to farmers of managing smaller fields might outweigh the benefits (Kirchweger et al. 2020). Quantifying co-benefits of pollinator-targeted interventions and identifying options that can maximise co-benefits is important as it can make interventions for pollinators more cost-effective (Morandin et al. 2016) or otherwise rewarding.

3 Literature review

3.1 Methods

The literature review focused on studies that measure effects of one or more interventions on pollinators (organisms performing pollination) or pollination (an ecosystem function provided by pollinators)[1] and at least one co-benefit. The scope of the literature review was global and included any land use type including agricultural, forested and urban land. Following the classification of the Millennium Ecosystem Assessment (2005), co-benefits included in our study focused on regulating and supporting ecosystem services (Table 1) and did not include cultural (e.g., aesthetics) or provisioning (e.g. crop yield, timber production) ecosystem services. To include as much literature as possible, we defined interventions liberally as any type of land management decision (common interventions are listed in the results section). The literature review was not limited to interventions primarily targeted at pollinators. Studies needed at least two treatments, such as an intervention compared to a control, or one land management decision compared to another one, to be included. Following the literature we, however, deepened the work on interventions that are pollinator-targeted using Delphi-like methodology (see Chapter 4).

We started with a list of possible co-benefits that might arise from pollinator-targeted interventions (recently published by Cappellari et al. 2023) and used a snow-balling approach where additional co-benefits were added sequentially while scanning publications. Literature was extracted from Web of Science, with the last extraction being done in January to March 2023, depending on co-benefit. We only included peer reviewed articles written in English. Syntheses, meta-analyses, literature reviews, book chapters or conference proceedings were not included. Search terms and number of studies screened are provided in Table 1. For the co-benefit pest control, the largest of all, only the first 1000 articles were screened due to time constraints, whereas for all other co-benefits the literature retrieved in searches was screened in full.

For each publication that met our inclusion criteria, we recorded when (publication year) and where (country or region (e.g. EU)) the study was performed. We recorded the proxies used to represent one or more co-benefits and the types of methods to measure those proxies. Due to the literature being limited in extent and highly dispersed in terms of interventions tested, it was not possible to estimate quantitatively the magnitude of identified co-benefit through e.g. a meta-analysis. Instead, we qualitatively discuss how the identified interventions and land management decisions affect pollinators and the co-benefits.

3.2 Results and discussion

Our search criteria, combining the parallel study of pollinators and one or more co-benefits, retrieved almost 3,000 journal papers. From those, we identified 121 cases where the effect of an intervention was measured on both pollinators and a co-benefit, and thereby meeting our inclusion criteria (Table 1). As some publications measured effects on multiple co-benefits (e.g. Bullock et al. 2011, Tamburini et al. 2022), they contributed to several cases. The total number of identified cases was greatest in two (English-speaking) countries: the USA (26 cases) and the UK (16 cases). Percentage wise, studies were mainly from Europe

[1] For simplicity henceforth the pair will be referred to as pollinators in Chapter 3.

(56%) or North America (26%), with smaller shares from South America (7%), Asia (7%) and Africa (3%, Figure 1).

Of all cases, 73% focused on agricultural land, 8% on forest and 4% on urban land. The remaining 15% of cases covered multiple land use types. Of the cases focused on agricultural land, 52% were on arable land (and their adjacent field edges), 19% on grasslands, 15% on orchards/vineyards and 15% on multiple habitats within agricultural land.

The cases were distributed across a considerable number of different interventions, making the review material rather heterogeneous (Figure 2). Some common types of interventions were related to (reduced) pesticide use, other forms of crop management such as crop type, tillage or organic farming, grassland conservation and management, and flowering habitats, or the effects of woody habitat such as trees, hedgerows and agroforestry (Figure 2). Larger scale studies that tested effects of different land-use scenarios on pollinators and co-benefits were also common.

Table 1. Co-benefits, search terms, and the number of publications screened and included in the literature review. * For the co-benefit pest control, only the first 1000 out of 4925 articles (starting with the most recent studies) were screened.

Co-benefit	Search term(s)	# screened	# included
Pest control	pollinat* AND “pest control”	1000*	48
Weed control	pollinat* AND "weed control“ pollinat* AND "weed seed predation“	900 8	7 1
Nutrient cycling	pollinat* AND “nutrient cycling” pollinat AND “decomposition”	183 235	5 4
Climate regulation	pollinat* AND "climate regulation“ pollinat* AND "carbon sequestration"	49 178	4 23
Water regulation	pollinat* AND "flood control" pollinat* AND "water regulation“	31 79	3 4
Water quality	pollinat* AND "water quality”	132	12
Soil erosion control	pollinat* AND ”erosion control”	71	8
Air quality	pollinat* AND “air quality"	79	2
Total		2945	121

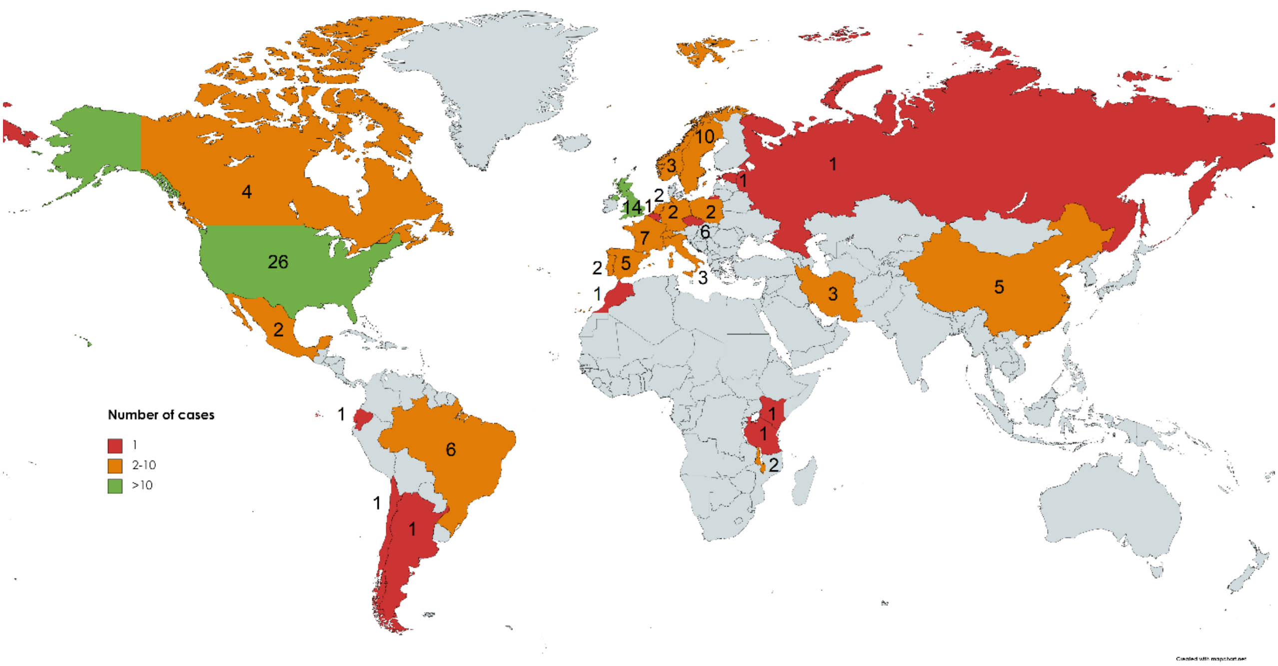


Figure 1. Number of cases per country included in the literature review (some publications measured effects on multiple co-benefits and contributed to several pairwise comparisons of effects on pollinators and a co-benefit). Eight additional cases (not included in the map) were at the EU or European scale.

Figure 2. Word cloud for the interventions identified in the literature review. Font size is proportional to the frequency of the word occurring in the intervention description (interventions as described by the authors were recorded as free text in our database of identified cases).

Pest control

Forty-eight studies measured effects on pollinators and pest control. Natural enemy and pest abundance were the most common proxies for pest control (Table 2). Pest control proxies were most often obtained by observations of pests or predators, pitfall trapping or transect netting (Table 3).

Table 2. Proxies used for pest control

Proxy	# studies
Natural enemy abundance	30
Pest abundance	23
Natural enemy species richness*	10
Crop damage	6
Predation rate	5
Natural enemy diversity etc.**	5
Parasitism rate	3
Pest species richness	2
Δ pest abundance, caged - open	2
Pest-predator network properties	1
Natural enemy unitless index	1

** number of species, ** E.g., Shannon diversity, functional diversity*

Table 3. Methodologies used for obtaining pest control proxies

Method	# studies
Direct observation*	13
Pitfall trap	13
Transect netting	11
Pan trap	6
Vacuum sampling	5
Predation card	5
Sticky card	4
Rearing from plants	3
Vegetation/ land use proxy**	3
Exclusion cage	2
Crop damage obs.	2
Trap nest	1
Hand capture	1
Beating	1
Parasitism	1
Video recording	1
Emergence cage	1
Window trap	1

Delta trap	1
Other baited trap	1

** of pests or predators; crop damage observations are listed separately.*
*** studies used e.g., vegetation or land use data as proxies for pest control*

Mixed or neutral relationships between pollinators and pest control were the most common outcomes, where interventions showed positive/negative effects on either one of the two and no effect on the other, or mixed effects where the outcome for pollinators or pest control was measured with multiple proxies and depended on the proxy used. There was especially several publications on flower strips showing positive effects for either pollinators or natural enemies but not both, perhaps due to preferences for different types of flower strips for these two organism groups (Nilsson et al. 2021, Scheper et al. 2021, Raderschall et al. 2022).

Synergies between pollinators and pest control were also rather common, especially when natural enemy rather than pest proxies were used to represent pest control. For example, semi-natural habitats/grassland restoration (Redhead et al. 2022), reduced insecticide use (Bakker et al. 2022)), reduced ground cover disturbance in crop fields (Appenfeller et al. 2022, Griffiths-Lee et al. 2023), intercropping (Christmann et al. 2021), plant diversity in field margins (Arnold et al. 2021), organic farming (Rosas-Ramos et al. 2022) and flower strips (Kujawa et al. 2022) benefitted both pollinators and natural enemies in some (but not all) case studies on these interventions.

Only two studies were found where pollinators and pest control directly traded off against each other. Both were related to pesticide use and employed pest abundance as pest control proxy, showing that insecticide use positively affects pest control but negatively affects pollinators (Pecenka et al. 2021, Du et al. 2022). However, by also measuring crop yield, Pecenka et al. (2021) could conclude that the increase in crop pollination benefit from lessened use of insecticides heavily outweighed the decrease in pest control service.

Weed control

Eight studies measured effects of pollinators and weed control. The weed control proxies used were weed cover (n=6), weed species richness (n=5), weed seed predation rate n=2), weed biomass (n=1) and weed community composition (n=1). Weeds were most often assessed through field observations in plots, transects, quadrats or points. Weed seed predation was assessed using weed seed cards.

Mixed outcomes between pollinators and weed control were found across the studies. Interventions like organic farming increased both pollinators and weeds (Sidemo-Holm et al. 2021). An inherent trade-off between pollinators and weed control is to some degree expected, given that common weed species have been found to sustain twice as high pollinator abundance and diversity compared to plant species recommended for pollinator-targeted agri-environmental options (Balfour and Ratnieks 2022).

Possible avenues to mitigate the trade-off between pollinators and weed control is to manage agroecosystems for multifunctional weed communities rather than weed eradication (MacLaren et al. 2020). For example, there is some evidence that more diverse weed communities limit the outbreak of individual weed species and thereby crop yield losses (Adeux et al. 2019), while also being beneficial for biodiversity. Another, related, option for overcoming the trade-off between pollinators and weed control was pointed out in our literature review: adding flowering service crops (sometimes also called cover crops) to agroecosystems tend to suppress weeds and benefit pollinators (Las Casas et al. 2022, Boetzl et al. 2023).

Nutrient cycling

Nine studies measured effects on nutrient cycling and pollinators. Nutrient cycling was measured as weight loss of organic material, such as tea bags (n=4); as soil organic carbon (n=2) in soil samples; or as N, P and/or K concentrations in soil (n=2) or plant samples (n=2). A single study each used soil enzymatic activity, vegetation traits from surveys (e.g. leaf area and biomass) or dung beetle abundance measured with pitfall traps as proxies for nutrient cycling.

Measures of pollinators and nutrient cycling were in most cases unrelated, that is, there was neither a positive nor a negative correlation between them. For example, decomposition rate was unrelated to pollinator abundance in pan traps in Polish forests (Kowalska et al. 2021). While pollinator abundance was negatively related with shrub cover and tree biomass, decomposition was negatively related with tree diameter (Kowalska et al. 2021). In Spanish almond orchards, compost and no-tillage treatments increased soil enzymatic activity and soil and plant nutrient levels, but did not affect pollinator abundance or seed set (de Leijster et al. 2019).

Climate regulation

Twenty eight studies measured effects of pollinators and climate regulation. Climate regulation was most often modelled based on land use and/or vegetation data (n=23). The most common proxies were carbon storage and sequestration. In a few cases proxies were obtained with soil samples (n=2), vegetation surveys (n=2), plant samples (n=1) or gas chambers measuring CO_2, CH_4 and N_2O (n=1).

The relationship between pollinators and water regulation was neutral to positive. Grassland intensification or converting grasslands or protected areas to cropland decreased both pollinator and climate regulation proxies (Le Clec'h et al. 2019, Audia et al. 2022, Mushet et al. 2022). Switching from annual to perennial cropping was estimated to be beneficial for both pollinators and climate regulation (Meehan et al. 2013, Tayyebi et al. 2016). There were also examples of studies showing that different land uses benefitted pollinators versus climate regulation, with cropland and grassland being related to pollinators and forest to climate regulation (Martinez et al. 2009, Bai et al. 2011, Karimi et al. 2021).

Only one study was found where pollinators and climate regulation traded off directly. Tree density reduction in coffee production landscapes promoted pollinators but decreased carbon sequestration. Yet, by economically valuating both ecosystem services the authors could show that the increase in crop pollination value was greater than the reduction in carbon sequestration value (Olschewski et al. 2010). In summary, the literature on pollinators and climate regulation shows multiple potentials for synergies, especially when interventions entail establishing woody vegetation interspersed in agricultural landscapes (e.g. woody linear features with flowers) rather than dense forest stands which can lead to trade-offs between pollinators and climate regulation (see also Sãrdinas et al. 2023).

Water regulation

Eight studies measured effects of pollinators and water regulation. Water regulation was most often modelled based on land use, vegetation and/or soil type data (n=5), yielding different and mostly dimensionless indices of water or flood regulation. In one case water regulation was modelled as water surplus (precipitation minus evapotranspiration). In a few studies water regulation was empirically measured as water holding capacity or plant available water in soil samples (n=2), or as water infiltration rate (n=1).

The relationship between pollinators and water regulation was neutral to positive. For example, grasslands scored higher than arable land for both pollination and water regulation (Tamburini et al. 2022); deforestation led to lower pollinator richness and water infiltration rates (Le Clec'h et al. 2018); and pollination and water regulation were positively correlated across land use types in Darvishi et al. (2022) but not across landscape planning scenarios in Chan et al. (2006).

Shrarafatmandrad and Mashizi (2020) used expert assessment of plant functional traits to establish whether and how vegetation might link to pollination and water regulation services. Water regulation was attributed to rooting depth and specific leaf area, whereas pollination was attributed to floral resources. As pollination and water regulation both are linked to vegetation, but possibly through different plant traits, interventions that add or replace certain types of vegetation might therefore benefit either or both of the services, with the vegetation characteristics determining the outcome (neutral to positive for either one or both of pollinators and water regulation).

Water quality

Twelve studies measured effects on pollinators and water quality. Water quality was most often modelled based on land use and/or topography, soil type and climate data (n=7). Two studies each measured water quality proxies in soil samples and drainage water, respectively, and one study measured a water quality proxy directly in a water body. The proxies for water quality were related to sediment export (n=4) and nitrate/nitrogen (n=5) or phosphorous (n=8) export or presence in soil. Single studies also measured surface water runoff volume, water chlorophyll content and the land area providing water quality regulation as proxies for water quality.

The relationship between pollinators and water quality was mostly positive. In particular, switching from annual cropping of e.g. corn and soybean to less disturbed habitats such as perennial bioenergy crops or grassland favoured both services in series of studies from the USA (Meehan et al. 2013, Tayyebi et al. 2016, Audia et al. 2022, Baral et al. 2022). Diverse perennial prairie vegetation strips in corn-soybean landscapes reduced sediment run-off by 95% while increasing pollinator abundance 3.5 times (Schulte et al. 2021). Spatial context (topography, soil type, climate, type of drainage) might, however, matter as no benefits to water quality of vegetated buffer strips was found in a study from the UK (Bullock et al. 2011).

The presence of trade-offs seemed to be related to the type of proxy used for pollination, as trade-offs were only found when the economic value of crop pollination was used as proxy but not when this was pollinator abundance. Wider riparian buffer strips tended to be more beneficial for water quality but decreased crop pollination service simply because the area for production of insect-pollinated crops decreases with wider buffer strips (Semmens and Ancona 2019). Similarly, converting grassland to annual crops was beneficial for pollination up to a threshold point due to increased cropping area of canola that benefitted from pollination, whereas water quality was negatively affected by the conversion (Habib et al. 2016).

In conclusion, interventions that added more diverse and perennial vegetation most often benefitted pollinators and water quality but did not necessarily increase the value of crop pollination. Although diverse perennial vegetation seemed to benefit both pollinator and water quality proxies, plant identity likely matters. Plant traits related to flowers, such as large floral display size and high nectar content, predict pollinator abundance, whereas traits related mainly to roots, such as rooting depth, root length and density, and percentage of fine roots, predict common proxies of water quality such as reduced soil loss and N and P uptake by plants (Cresswell et al. 2019).

Soil erosion control

Eight studies measured effects of pollinators and soil erosion control. Soil erosion control was most often modelled based on vegetation, land use and/or topography data (n=4), using e.g. variants of the universal soil loss equation to estimate amounts of soil loss (n=2) or indices (n=2) as soil erosion control proxies. Other methods employed were empirical assessments of vegetation density and cover that were used as proxies for soil erosion control (n=2), infiltration tests generating a water infiltration rate (n=1; see also use of the water infiltration rate as proxy for another co-benefit in water regulation section) and the replacement cost method (n=1) estimating the costs of replanting vegetation that was deemed to provide soil erosion control.

The relationship between pollinators and soil erosion control was neutral to positive. Meissen et al. (2020) and Glidden et al. (2023) trialled different seed mixes for grassland restoration. They found that a mix with a grass to forb ratio of 1:3 scored highest for pollinator values due to having the highest floral abundance and richness, whereas a mix with a reversed ratio of 3:1 scored highest for soil erosion control, due to having the highest vegetation density and cover stabilising the soil. A diverse seed mix with a grass to forb ratio of 1:1 showed only marginally lower values for pollinators and soil erosion control compared to the ‘ideal’ mix for each ecosystem service and thereby was the most multi-functional. These studies suggest that mixing ‘ideal’ vegetation for pollinators such as resource-rich forbs, with other type of vegetation that deliver other ecosystem services, such as grasses that prevent soil erosion, can be done with only small penalties to the value of the habitat for pollinators, and thereby increasing habitat multi-functionality.

Air quality

Only two studies measured effects on pollinators and air quality. Links between interventions and air quality proxies were obtained using expert opinion (n=1) or modelling (n=1). Proxies used were land area providing air quality service (n=1) and air cleansing of NO_2, O_3, PM10 and CO (n=1). No strong conclusions regarding air quality as co-benefit from interventions for pollinators could thus be drawn. None of the studies assessed any direct links between pollinators and air quality. Schlaepfer et al. 2022 used a model where the air cleansing ability of trees in cities are determined by leaf and tree crown area, whereas their value to pollinators are determined by nectar and pollen production. Using this approach they compared native and non-native trees in Geneva, Switzerland and found that they produced roughly similar levels of air cleaning and pollination values on a per-tree basis.

Conclusions

Overall, the literature review indicates that interventions which promote pollinators are likely to produce several environmental co-benefits such as pest control, nutrient cycling and climate and water regulation. For most co-benefits resulting from interventions that promoted pollinators the effect on the co-benefit was positive or neutral. Weed control was the only co-benefit with a more mixed outcome of positive, neutral and negative relations with pollinators, indicating that interventions favouring pollinators also can lead to disservices (somewhat challenging the term co-‘benefit’).

The literature review indicated that whether an intervention that promoted pollinators also produced a certain co-benefit was highly context-specific. Many types of interventions alter the vegetation (Figure 2), which forms the food base for pollinators, and several studies indicated that plant identity and traits are important factors for maximising co-benefits of pollinator-targeted interventions. Therefore, it seems that more diverse vegetation can maximise the benefits of pollinator-targeted interventions. For example, while floral resources are a key vegetation property for pollinators, leaf area is more important for air quality and water regulation, vegetation cover for soil erosion control, root architecture for water quality and regulation, and perennial woody vegetation for carbon sequestration. Several of the reviewed studies show substantial increases in co-benefits from land management decision that promote pollinators are possible with no or marginal loss of habitat value for pollinators. Slight alterations to pollinator-targeted interventions, such as including grasses in flower strips or woody plants in field margins, can thus greatly increase their multi-functionality

4 Delphi panel

4.1 Methods

Reviewing the literature brought out seven co-benefits that were sufficiently frequently considered in the context of pollinator interventions. Providing information on the direction and magnitude of such co-benefits is important to understanding the full impacts of the pollinator management, but the limited and highly heterogeneous literature on the topic did not allow for this to be done comprehensively solely through literature review. To address this, we used a structured expert elicitation approach, following Dicks et al (2021), that follows the principles of Delphi-panel methods. For each of six pollinator management interventions this was used to estimated 1) the magnitude and 2) the spatial variation in the production of seven co-benefits (Table 4). We selected the pollinator management interventions based on existing syntheses of pollinator interventions (Cole et al. 2020, Blaydes et al. 2021, Glenny et al. 2022) and so that they overlapped with common interventions tested in studies compiled in the literature review (Figure 2).

Table 4. Definitions of interventions and co-benefits

Item	Definition
Interventions	
Crop diversification	The interventions consist of increasing the diversity of flowering crops that provide resources for pollinators grown across temporal and spatial scales in agricultural landscapes, and includes practices such as intercropping, smaller field sizes and higher crop diversity at the landscape scale. This does not include agroforestry.
Flower rich field margins	The intervention consists of creating linear flowering habitats (a few metres wide) along the cropped part of field margins of a crop field. Sown species are a mix of annual or perennial pollinator-attractive herbs that provide continuous floral resources across the season. The habitats are re-established every 3-5 years and treated with minimal or no synthetic fertiliser or pesticide.
Organic agriculture	The intervention consists of farming land according to an organic certification scheme. Certified organic farming systems typically “promote soil quality, crop rotations, animal and plant diversity, biological processes, and animal welfare, while generally prohibiting irradiation, sewage sludge, genetic engineering, the prophylactic use of antibiotics, and virtually all synthetic pesticides and fertilizers.” (Reganold and Wachter 2016).
Reduced pesticide use	The intervention consists of reducing the use and risk of pesticides (herbicides, fungicides and insecticides) and eliminating the use of more hazardous pesticides, as defined by the EU's Farm2Fork strategy.
Low-intensity grasslands	The intervention consists of managing natural and semi-natural grasslands* under a low-intensity grazing or hay-cutting regime to promote creation of floral resources for pollinators. * Grassland definitions (Bengtsson et al. 2016)

	Natural grasslands: "forming the grassland biomes are natural areas mainly created by processes related to climate, fire, and wildlife grazing, but are also used by livestock". Semi-natural grasslands "are the product of human management, require livestock grazing or hay-cutting for their maintenance, and will generally be encroached by shrubs and trees if taken out of production". Improved grassland (not included in our 'low intensity grassland management intervention) "are pastures resulting from plowing and sowing agricultural varieties or non-native grasses with high production potential. They are usually artificially fertilized and maintained by intensive management.
Woody linear features	The intervention consists of retaining and adding trees and shrubs in field margins along or around crop fields and managing them with minimal pesticides, fertilizers and, at most, a single cut per year.
Co-Benefits	
Insect pest control	Reduction in the abundance of insects that are detrimental to crop productivity
Weed control	Reduction in the abundance of plants that are detrimental to crop productivity
Soil nutrient cycling	The cycling of key nutrients within the soil such as nitrogen, phosphorous and potassium
Greenhouse gas sequestration	The storage and fixing of greenhouse gases
Flood control	Reduction in the risk and severity of flooding in the immediate and surrounding area
Water quality	The drinkable quality of local water bodies
Soil erosion control	The reduction of productive soil lost due to wind or water erosion

Through personal networks, the Safeguard consortium and the literature review, we identified 25 researchers with broad experience regarding the focal co-benefits, ensuring coverage from across Europe and taking heed of gender and age as important factors when it comes to the provision and discussion of expert knowledge. The final panel consisted of eight experts, although others were willing to participate but could not do so in the time available. We asked participants to self-report their experience with each intervention and co-benefit and present this to inform the interpretation of our findings. All participants self-identified as experts in multiple ecosystem services, but none were experts in all seven co-benefits. We attempted to balance participants by geographic region and gender but due to the limited availability of qualifying experts were not able to do so fully.

Following Dicks et al., (2021), the exercise, had two stages[2]. First, all participating experts were sent a spreadsheet-based questionnaire with six questions (Table 5). Among these were two matrix questions that asked participants to score the magnitude of co-benefits on a -3 to 3 scale (-3: very negative, -2: negative, -1: slightly negative, 0: mixed/no effect, 1:

[2] All steps were subject to ethical approval by the University of Reading.

slightly positive, 2: positive, 3: very positive effect of the intervention on the co-benefit) scale[3] (Q3) and the spatial sensitivity of co-benefits on a 1-5 scale (Q4) for each intervention, scoring each co-benefit separately (i.e. a total of 42 combinations). For each score, participants were asked to indicate their confidence in their answers on a 1-5 scale (1: None, 2: Not very confident, 3: Fairly confident, 4: Confident, 5: Very confident). The median and interquartile ranges (IQR – the difference between the first and third quartiles of a dataset) were then calculated for the magnitude and spatial sensitivity scores for each co-benefit arising from each intervention across all participants.

Table 5. Questionnaire questions for the expert elicitation exercise.

Question		Response type
1	Your name	Open text
2	Please indicate your level of experience and regions where you have primary experience (i.e. field experience) and secondary experience (i.e. experience with data, models or other projects) with each of the interventions and co-benefits.	Experience: fixed answers (none at all, a little, some, moderate, a lot). Primary and secondary regions: free text
3	For each of the following interventions, based on your experience and your knowledge of research literature - What do you believe would be the magnitude and direction of its effects on each of the following co-benefits (when this intervention is managed according to best management practices for pollinators in the local landscape context). Please indicate your confidence for each co-benefit.	Magnitude: fixed answers (-3: the intervention has a strong negative effect on the co-benefit. 3: the intervention has a strong positive effect on the co-benefit. 0: the intervention has no effect on the co-benefit). Confidence: fixed answers (1: none – 5: very confident)
4	Based on your experience and your knowledge of research literature - How sensitive[4] are the magnitudes of these co-benefit across variations in climate, geography and topography	Sensitivity: fixed answers (1: the magnitude of these co-benefits is not sensitive to these factors, 5: the magnitude of these co-benefits is extremely sensitive to all of these factors) Confidence: fixed answers (1: none – 5: very confident)
5	Are there any additional intervention types, apart from the ones above that you believe will provide both benefits to pollinators and one or more of the co-benefits above.	Free text
6	Do you believe that there are any additional co-benefits, not listed in this survey, that will arise from any of the interventions listed above? If so, please use this space to discuss them.	Free text

[3] For the purpose of analysis we used a 1-7 scale to capture both direction and overall scale of effects as a -3 to 3 scale can complicate the calculation and interpretation of IQRs. We present the results in their intended scale

[4] In the original text, this was framed as "consistency". However participants found this framing confusing based on the text used in the scale description. This was clarified and scores were adjusted during the workshop. We have amended it to "sensitivity" in this deliverable for the sake of clarity.

Importantly, when scoring, participants were asked to consider these interventions as if they were managed a) according to best management practices for pollinators in the local landscape context and b) at the scale of a farm and its immediate surrounding landscape but with appropriate levels of uptake in the surrounding area.

The second stage involved a three-hour long online workshop on June 20th 2023, hosted by The University of Reading. Where the magnitude or sensitivity of an intervention on a co-benefit had an IQR greater than 2 we considered there to be a lack of consensus. An IQR less than two indicates that most responses fell into one of two points on the response scale that were adjacent to each other e.g. slightly positive or positive while and IQR of 2 or more indicates that sufficient numbers of participants gave values that were more relatively polarised, e.g. as many may have responded “slightly negative” as responded “slightly positive”. Participants were asked to discuss these differences and argue for any divergent opinions they may have. Much of the discussion focused on more precisely defining certain co-benefits. In this discursive process deep insight and nuance was generated, which assisted group members to reflect on their own scores. Participants were also invited to discuss the relative importance of other interventions and collectively proposed expanding the scoring exercise to include four additional co-benefits (Appendix A) and discussing several others that were highlighted from the survey phase (Appendix B). Following this workshop, participants were asked to revise their scores, which were then re-compiled and form the basis of the results section, and to score the additional co-benefits (Appendix A).

4.2 Results

Respondents self-reported expertise (1-5 scale, from none at all to very experienced) tended to be greater for interventions than for co-benefits, in particular, respondents had substantial experience with flower rich field margins (average: 4.13) but much lower experience with water quality , flood control and soil erosion control (Table 6).

Table 6. Respondents average self-reported expertise for interventions and co-benefits (1= no experience at all, 5= a lot of experience).

Intervention	Average expertise score
Crop diversification	3.9
Flower rich field margins	4.1
Organic agriculture	3.8
Reduced pesticide use	3.8
Low-intensity grasslands	3.8
Woody linear features	3.9
Co-Benefit	**Average expertise score**
Insect pest control	3.9
Weed control	3.6
Soil nutrient cycling	3.0
Greenhouse gas sequestration	3.1
Flood control	2.4
Water quality	2.3
Soil erosion control	2.9

Following the first round of scoring, six combinations of co-benefits and interventions had an IQR greater than 2 for the magnitude question and seven had an IQR greater than 2 for the severity question. Following rescoring, no combination of co-benefit and intervention had an IQR greater than 2.

Magnitude of effects on co-benefits

Most interventions were thought to have a minor to moderate positive influence on most co-benefits, with 77% (34 of 44) of the intervention/co-benefit combinations having a median score of 1 (slight positive) or more (Table 7, Figure 3). Weed control was the co-benefit thought to be least positively affected by the interventions (average median score = 0, no effect), with only crop diversification having any positive effect while both organic agriculture and reduced pesticide use were both considered to negatively affect this co-benefit. It should be noted that this represents the overall control of weeds, not the biological control of weeds, which participants scored separately (Appendix A). Water quality had, on average, the highest median score for co-benefit delivery across all interventions (average median score = 1.6, positive benefit). Participants were most confident in their responses for insect pest control (average confidence: 3.5), which is well studied (again, the biological control aspects were considered separately - Appendix A), and were least confident when scoring flood control (average confidence: 2.8). This could reflect the bias towards field ecology and modelling within our sample but participants noted a general shortcoming of studies considering the impacts of these interventions on hydrological flow. This was because the interventions are usually deployed at relatively small scales, compared to the larger spatial scales over which flood management typically occurs (Schulp et al. 2016).

Of the interventions, low intensity grasslands were assessed to have the strongest positive impacts on the co-benefits (average median score = 1.6). This intervention encompasses several related practices, including reduced grazing and inputs, that can have significant positive impacts on plant diversity and growth, in turn influencing soil health (Byrnes et al., 2018) and structure (Mayel et al., 2021), and by reducing the amount of fertiliser applied, improve local water quality (Audia et al. 2022). By contrast, reduced pesticide use had the lowest magnitude across all co-benefits (average median score = 0.3). This arises because many of the co-benefits result from physical properties of the landscape that are not thought to be substantially affected by the use or non-use of chemicals alone (flood control, soil erosion control, greenhouse gas sequestration[5]). Insect pest control was viewed as a more neutral impact, as reducing pesticide use may increase the abundance and diversity of natural enemies but may also increase pest prevalence. As such, further habitat restoration efforts would be required to ensure that natural enemy populations are sufficient to suppress pests consistently. Participants confidence was, on average, highest for low intensity grasslands (average confidence: 3.3) and lowest for flower rich field margins (average confidence: 3). The latter is surprising given participants high self-reported experience with this intervention and, although confidence was higher for insect pest control, confidence was middling for most.

The single greatest magnitude was thought to be woody linear features on soil erosion control, with a median score of 2.5 (average confidence: 3.9), which is in line with findings from the literature review that woody vegetation is important for soil erosion control (Le

[5] Note that greenhouse gas sequestration refers to the sequestering of gases, not the carbon footprint of land use activities. If this was the case, a reduction in pesticide use could have a positive impact.

Clec'h et all. 2018, Silvestro et al. 2021). Crop diversification and insect pest control (median score: 2) was the combination with the highest confidence (average confidence: 4) which is consistent with studies into this intervention (e.g. Jaworski et al., 2023).
Four combinations of intervention and co-benefit had an IQR of zero, indicating that there was near complete agreement among participants. These were:

1) Woody linear features effects on nutrient cycling (median score: 1, average confidence: 2.9), where participants highlighted considerable evidence that such features have positive effects on soil nutrients, particularly when managed in a relatively low intense fashion.
2) Reduced pesticide use effects on flood control (median score: 0, average confidence: 2.6) where participants agreed that the co-benefit was unlikely to be influenced by changes in chemical application.
3) Flower-rich field margins effects on soil erosion control (median score: 1, average confidence: 3), because participants agreed that the measure had the capacity to intercept movement of soils from fields but only to a limited extent.
4) Low intensity grassland effects on soil erosion control (median score: 2, average confidence: 3.3), as it was generally agreed that the reduced soil disturbance from these practices would have a substantive effect on soil structure and vegetation keeping soil in place (yet, confidence was generally low).

Spatial sensitivity of co-benefit delivery

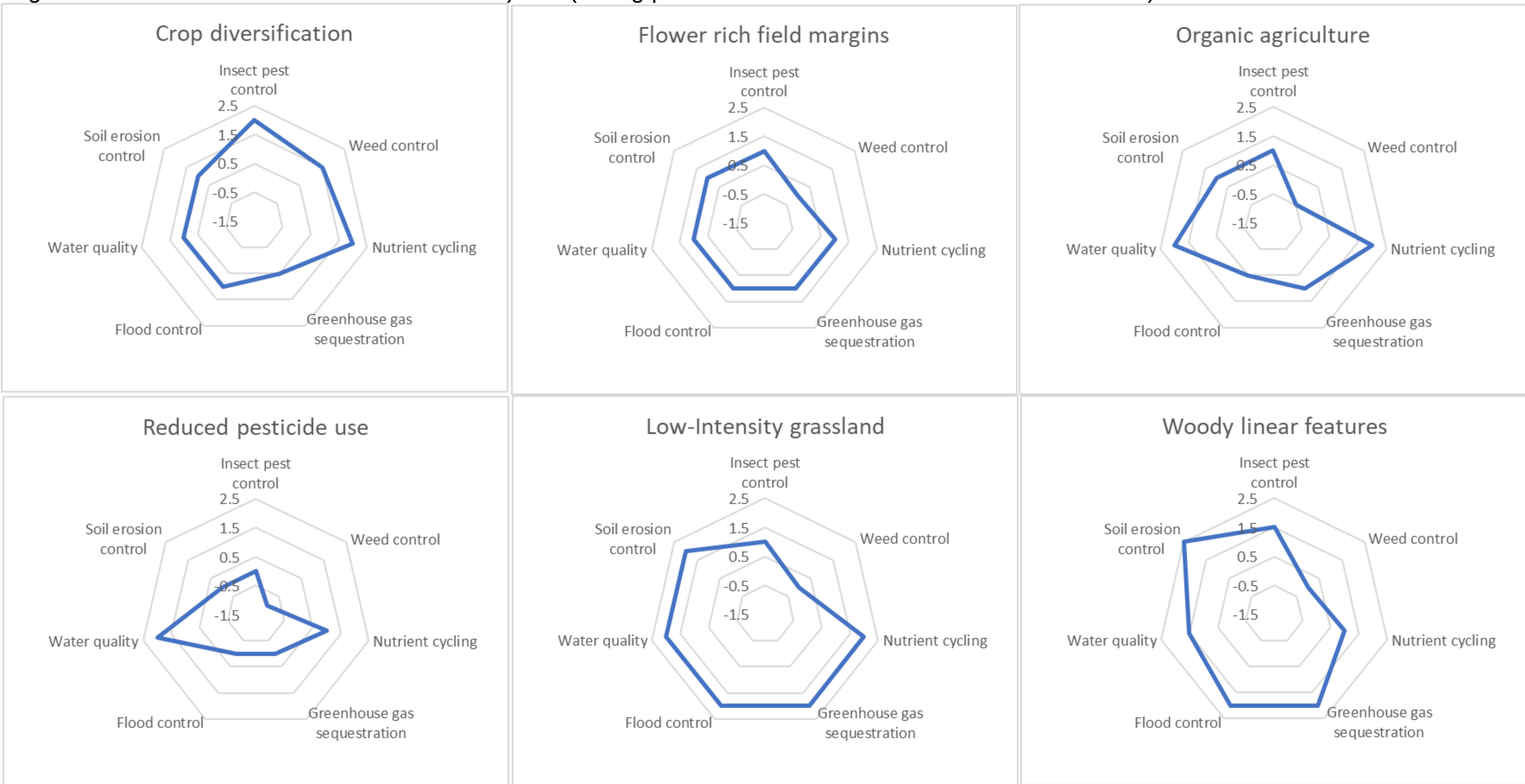
Spatial sensitivity was assessed in terms of the impact that "variations in climate, geography and topography" would have on the magnitude of the co-benefits generated. This framing was chosen so that sensitivity could be captured in a purely environmental perspective, rather than having to factor in variations in land use policy across Europe.

In general, the pest control co-benefits were considered more spatially variable (average median scores: 3.1) than co-benefits that relating to physical or hydrological processes (all medians ≤2.8, table 8, Figure 4). Insect and weed control co-benefits are heavily influenced by a wide range of different pest and predator species, each of which can be independently affected by local conditions (Karp et al. 2018). However, even after the second round of scoring, respondents had strong disagreements on the sensitivity of pest control from several interventions (IQR: 2), particularly crop diversification, organic agriculture and low-intensity grassland due to conflicting information in the literature and from the personal experiences of participants. Despite this, confidence in scores for pest regulation were the highest of all the co-benefits (average confidence: 3.4).

By contrast the co-benefit that the panel considered least sensitive to spatial variation was water quality (average median score: 2.5). This result was because landscape features were felt to be less important to these co-benefits than changing levels of agrochemical inputs (pesticides, fertilizers etc.) applied. This perspective is reflected in the particularly low sensitivity score of this co-benefit for reduced pesticide use (median score: 1.5) and the higher confidence for interventions that affect the level of inputs applied (organic agriculture, reduced pesticide use and low-intensity grasslands) compared with other interventions. Following discussions about this co-benefit, the participants decided to separately score wider water quality, affecting the suitability of water for supporting biodiversity (Appendix A).

Of the interventions, the panel expected the greatest spatial sensitivity in co-benefit delivery to be from crop diversification (average median score: 3) as spatial factors will significantly affect what crops can be grown where and in what sort of systems (e.g. mixed cropping, trap cropping etc.). In particular, the single highest sensitivity was thought to be in the benefits of crop diversification on greenhouse gas sequestration (median score: 3.5), a combination which also did not establish a consensus among participants even after the workshop (IQR: 2). This was unexpected as there was little discussion on this in the workshop and the co-benefit has a lower magnitude score (median score: 0.5), indicating that the effects are small and participants had relatively low confidence (average: 2.9). Participants emphasised that this intervention was unavoidably influenced by economic factors in each country. Reduced pesticide use was also thought to have the least spatial sensitivity across co-benefits (average median score: 2.5).

Figure 3. Radar diagrams of median scores of the magnitude of co-benefits associated with each intervention. Scores range from -3 (strong negative effect of intervention on the co-benefit) to 3 (strong positive effect of intervention on the co-benefit).



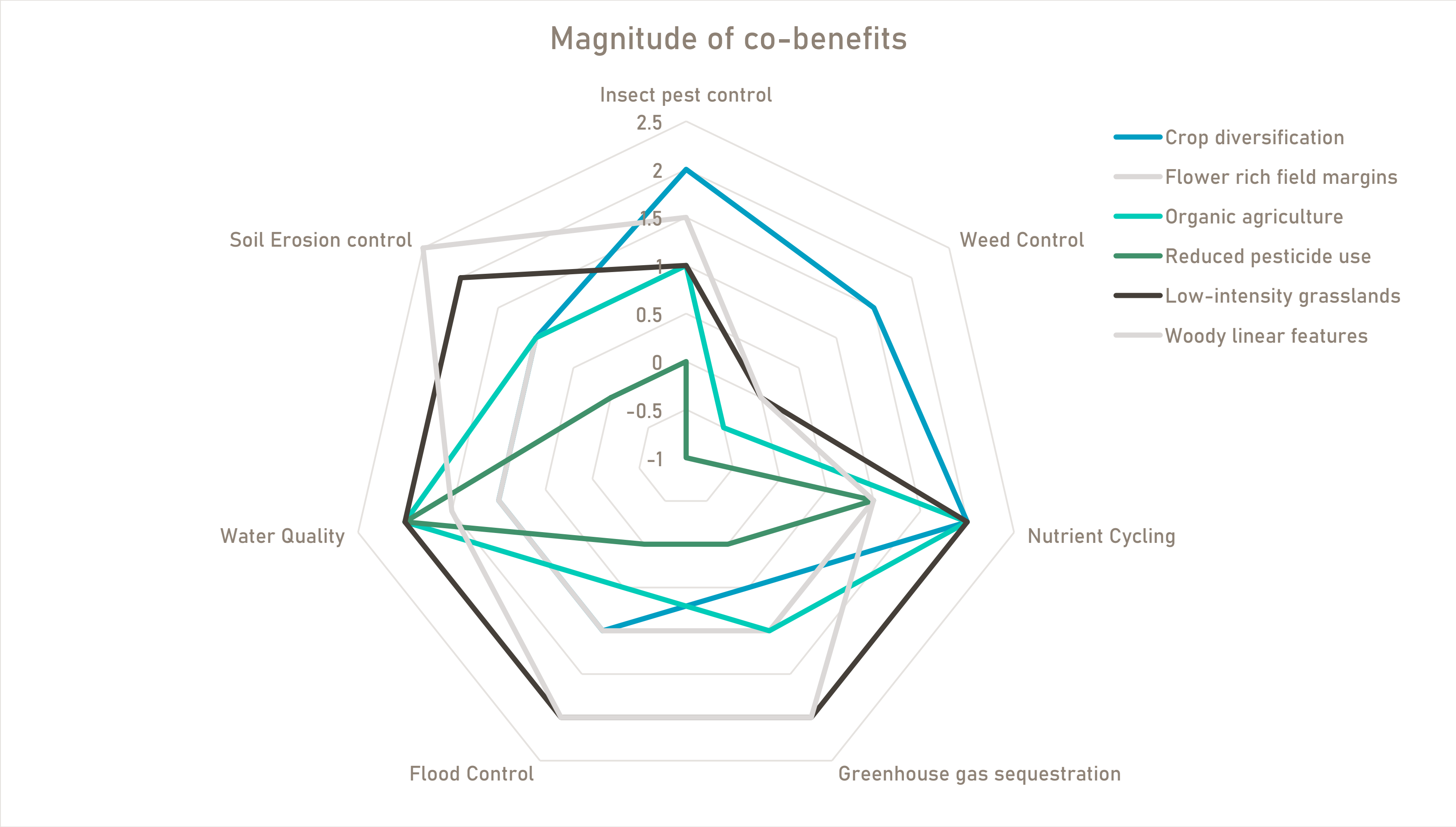

Magnitude of co-benefits
Insect pest control
Weed Control
Nutrient Cycling
Greenhouse gas sequestration
Flood Control
Water Quality
Soil Erosion control
2.5
2
1.5
1
0.5
0
-0.5
-1
Crop diversification
Flower rich field margins
Organic agriculture
Reduced pesticide use
Low-intensity grasslands
Woody linear features

Figure 4. Radar diagrams of median scores of the spatial sensitivity of co-benefits (the sensitivity of the co-benefit across variations in climate, geography and topography). Scores scale from 1 (not sensitive) to 5 (extremely sensitive).

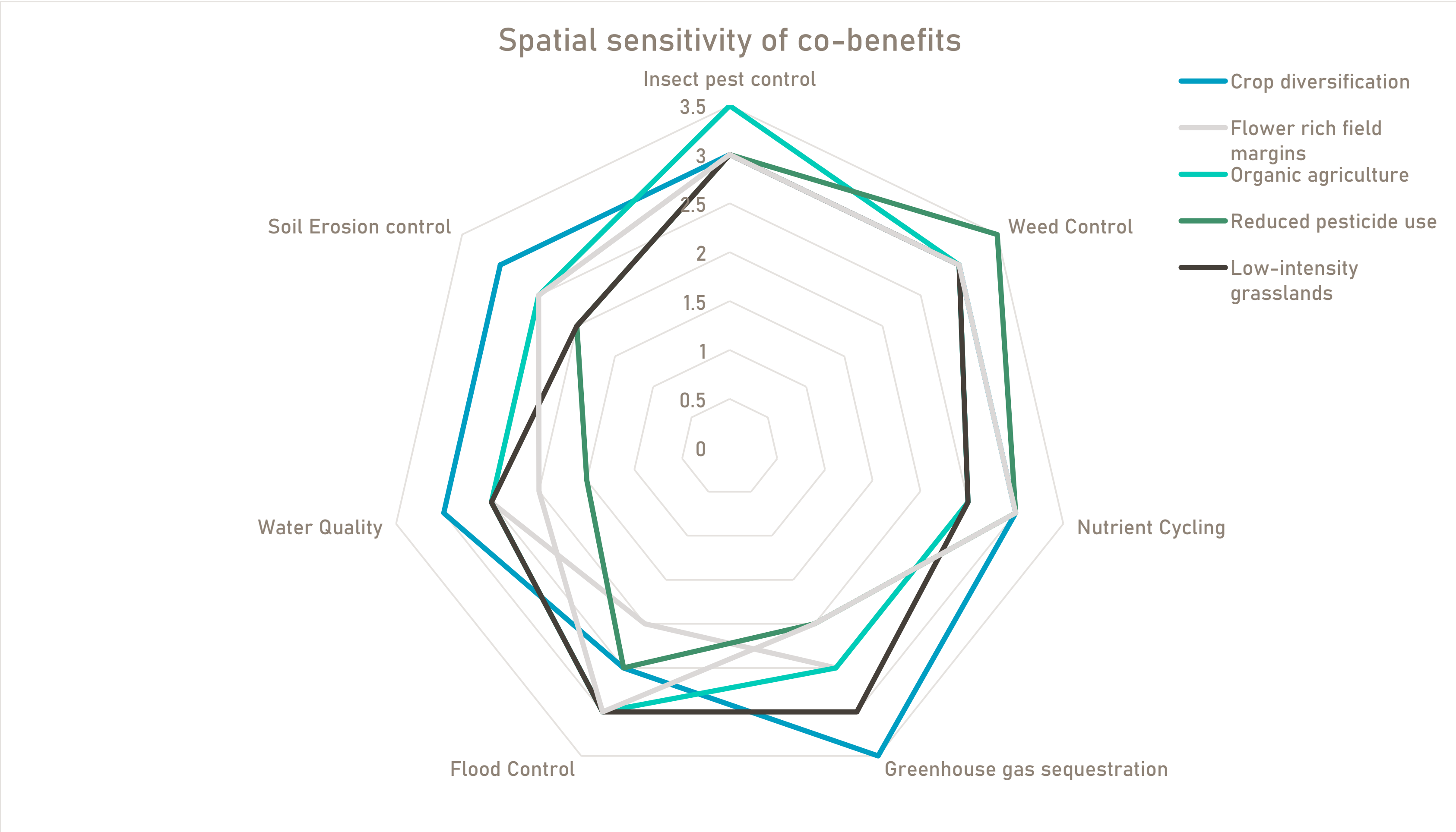

Spatial sensitivity of co-benefits
Insect pest control
Weed Control
Nutrient Cycling
Greenhouse gas sequestration
Flood Control
Water Quality
Soil Erosion control
3.5
3
2.5
2
1.5
1
0.5
0
Crop diversification
Flower rich field margins
Organic agriculture
Reduced pesticide use
Low-intensity grasslands

Table 7. Median scores for the magnitude (Scores scale from -3 (strong negative effect of intervention on the co-benefit) to 3 (strong positive effect of co-benefit on the co-benefit)) of co-benefits (average confidence in brackets)

	Insect pest control	Weed control	Nutrient cycling	Greenhouse gas sequestration	Flood control	Water quality	Soil erosion control	Average
Crop diversification	2 (4.0)	1.5 (3.6)	2 (3.3)	0.5 (3.0)	1 (2.6)	1 (2.9)	1 (3.0)	1.3 (3.2)
Flower-rich field margins	1 (3.8)	0 (3.0)	1 (3.0)	1 (3.0)	1 (2.5)	1 (2.8)	1 (3.0)	0.9 (3.0)
Organic agriculture	1 (3.3)	-1.5 (3.4)	2 (3.0)	1 (2.9)	0.5 (2.6)	2 (3.4)	1 (2.9)	1.0 (3.1)
Reduced pesticide use	0 (3.4)	-1 (3.6)	1 (3.0)	0 (2.5)	0 (2.6)	2 (3.5)	0 (2.6)	0.3 (3.0)
Low-intensity grasslands	1 (3.0)	0 (3.1)	2 (3.0)	2 (3.6)	2 (3.5)	2 (3.4)	2 (3.3)	1.6 (3.3)
Woody linear features	1.5 (3.4)	0 (3.0)	1 (2.9)	2 (3.4)	2 (3.0)	1.5 (3.3)	2.5 (3.9)	1.5 (3.3)
Average (co-benefit)	1.1 (3.5)	0 (3.3)	1.5 (3.0)	1.1 (3.1)	1.1 (2.8)	1.6 (3.2)	1.2 (3.1)	

Table 8. Median scores for Spatial sensitivity (scores ranging from 1: not sensitive to spatial factors to 5: highly sensitive) of co-benefits (average confidence in brackets)

	Insect pest control	Weed control	Nutrient cycling	Greenhouse gas sequestration	Flood control	Water quality	Soil erosion control	Average
Crop diversification	3 (3.5)	3 (3.5)	3 (3.0)	3.5 (2.9)	2.5 (2.4)	3 (3.0)	3 (3.0)	3 (3.0)
Flower rich field margins	3 (3.5)	3 (3.1)	2.5 (2.8)	2.5 (3.0)	2 (2.6)	2.5 (2.8)	2.5 (3.1)	2.6 (3.0)
Organic agriculture	3.5 (3.5)	3 (3.1)	2.5 (3.0)	2.5 (3.3)	3 (2.4)	2.5 (3.1)	2.5 (2.9)	2.8 (3.0)
Reduced pesticide use	3 (3.3)	3.5 (3.6)	3 (2.8)	2 (2.5)	2.5 (2.3)	1.5 (3.8)	2 (2.8)	2.5 (3.0)
Low-intensity grasslands	3 (3.0)	3 (3.1)	2.5 (2.9)	3 (3.8)	3 (2.9)	2.5 (3.1)	2 (3.3)	2.7 (3.1)
Woody linear features	3 (3.4)	3 (3.1)	3 (2.8)	2 (3.5)	3 (3.2)	2 (3.4)	2.5 (3.8)	2.6 (3.3)
Average (co-benefit)	3.1 (3.4)	3.1 (3.3)	2.8 (2.9)	2.6 (3.2)	2.7 (2.6)	2.3 (3.2)	2.4 (3.1)	

Other interventions and co-benefits

In addition to the main panel exercise, participants were asked to suggest other interventions that could support pollinators and co-benefits, and to identify further co-benefits that may arise from the original six interventions listed. These are summarised in Appendix B. When asking participants to rank these from high to low priority for future research, fallow land, woodland patches, agroforestry and diversification of non-crop habitats emerged as the highest priority interventions and soil structure, water storage and human health as the highest priority co-benefits.

Key outcomes

The results of the panel exercise indicate that low input grassland, woody linear features and crop diversification can provide multiple positive co-benefits to the surrounding landscape. By contrast, reduced pesticide use and organic agriculture are thought to provide much fewer co-benefits while also potentially being detrimental to overall pest control (Table 7). In general, co-benefits relating to the more ecological processes (e.g. insect and weed pest regulation) are more sensitive to variations in climate, geography and topography, than the more physical processes such as water quality and soil erosion control (Table 8). However, there was considerable uncertainty among the panel about these sensitivity estimates, even for interventions for which the panel generally had strong expertise, such as flower rich field margins and low-intensity grassland.

Building upon this exercise, we identify the following key priorities for further research into co-benefits:

1. Although their benefits for pollinators are well studied, there is considerable uncertainty around the capacity of **flower-rich field margins** to deliver ecosystem co-benefits. This intervention can be very specifically tailored by sowing mixes of different plants and thus could be tailored to deliver different co-benefits while still providing significant floral resources.
2. **Crop diversification** is thought to be able to deliver significant co-benefits but these are highly sensitive to spatial context and there is considerable uncertainty around them.
3. There is a lot of uncertainty around the capacity of interventions to generate **flood control** benefits. Further research into the delivery of this co-benefit should consider the quantity and location of different interventions throughout the landscape and how they interact to regulate flood impacts.
4. **Nutrient cycling** was also highlighted as a potentially significant co-benefit across all interventions, but one where sensitivity to spatial factors was lower. As such, it would potentially require relatively less effort to develop a strong understanding of this co-benefit.
5. As some habitat interventions that benefit pollinators can have a negative effect on **weed control**, future studies should explore the scale of these effects and the potential economic trade-offs it may cause if not addressed.

5 Protocols

5.1 Background and rationale

Here we provide protocols for empirically assessing environmental co-benefits of pollinator-targeted interventions. The experimental unit in the protocols is referred to as 'site' but could also be a plot etc. depending on the scale of the study. The protocols assumes that the sites selected either have been assigned to different treatments of interest (e.g., flower strip or no flower strip) or are situated along gradients of interest (e.g., amount of floral resources in field edges). Many of the studies identified in the literature review are interested in assessing multiple co-benefits at regional or even continental scales and therefore often used modelling (e.g., InVEST modules https://naturalcapitalproject.stanford.edu/software/invest) based on land use and other widely available digitised geographical data, to inform on the research question. Such studies are beyond scope of the protocols provided here, where we instead assume that the interest is to empirically determine co-benefits in case studies.

Methodologies and proxies were selected to be relatively easy and quick to measure. With this limitation in proxies that more close approximated the ecosystem function, such as predation rather than abundance of natural enemies for pest control´, was given priority. The protocol was also tailored to be widely applicable across different land use types (Cappellari et al. 2023). We include measurement protocols for the co-benefits covered in Chapter 4, with the exceptions of soil erosion control, as no methodologies that fulfilled these selection criteria could be identified on basis of the literature review.

5.2 Pest control

When: 2 sampling rounds. Choose three days during summer with no wind and no rain.

How many: 16 dummy caterpillars per site per sampling round. Place them in two spots at each site.

Time needed in the lab: one day to prepare the dummy caterpillars (x2), one day to examine the predation marks (x2).

References: Howe et al. (2009); Low et al. (2014)

What you need:

- Green plasticine: 1 bag
- Wood skewer, c. 25 cm long: c. 300;
- Loctite™ Control Superglue or Bostik: 3 tubes;
- Magnifying glass: 1;
- Paper box: 8;
- Pin: c. 400.

1. Prepare the dummy caterpillars. You will need 16 dummy caterpillars per site (240 caterpillars per round). Caterpillars should be 2.5 mm x 30 mm in size and moulded into the characteristic looping position of a geometrid (Fig. 5a). Pay attention not to leave any mark on your caterpillars.

2. Prepare the wood skewers. You will need 4 skewers per site (120 skewers per round). For each site, break in half 2 skewers, so they should be c. 12 cm long (Fig. 5a, left skewer). For the remaining 2 skewers, fold the ends over, but be careful not to break them off completely, so that they remain attached to the skewer (Fig. 5a, right skewer).

3. Glue the dummy caterpillars to the wood skewers. For each site, 4 caterpillars should be glued on one skewer each (the ones c. 12 cm long) toward one of the ends (Fig. 5a, left skewer). The remaining 4 caterpillars should be glued in pairs toward the centre of the 2 “double-folded” skewers (Fig. 5a, right skewer). Always pay attention not to leave any mark

on the caterpillars. Place your caterpillars into some boxes, *e.g.*, paper boxes with a polystyrene basis (as in Fig. 5a).

4. On field, place the dummy caterpillars at least 50 cm apart. Single caterpillars should be c. 5-10 cm above the ground, while paired caterpillars should touch the ground (Fig. 5b). Write down the date, time, and any additional notes.

5. Wait for 3 days.

6. After 3 days, collect the dummy caterpillars and place them back in the boxes with polystyrene, next to a label with the side code and sampling round (R1 or R2). Write down the date, time, and any additional notes.

7. In the lab, look for predation marks on your caterpillars. Use the guides to assess the predator group. If you can, take pictures of all marks on each caterpillar using the magnifying glass, the stereoscope, or a magnifying lens for the phone (Fig. 5c). Each picture should be renamed with the site name, number of caterpillar (from 1 to 8), H or L (high or low, for single caterpillars or paired caterpillars respectively), and the sampling round, *e.g.*, "DE1GER01_1_L_R1", "DE1GER01_2_L_R1", "DE1GER01_3_H_R1".

8. Place the dummy caterpillars back into the boxes and fix them using pins (Fig. 5d).

9. For each site estimate pest control as the proportion of caterpillars with bite marks.

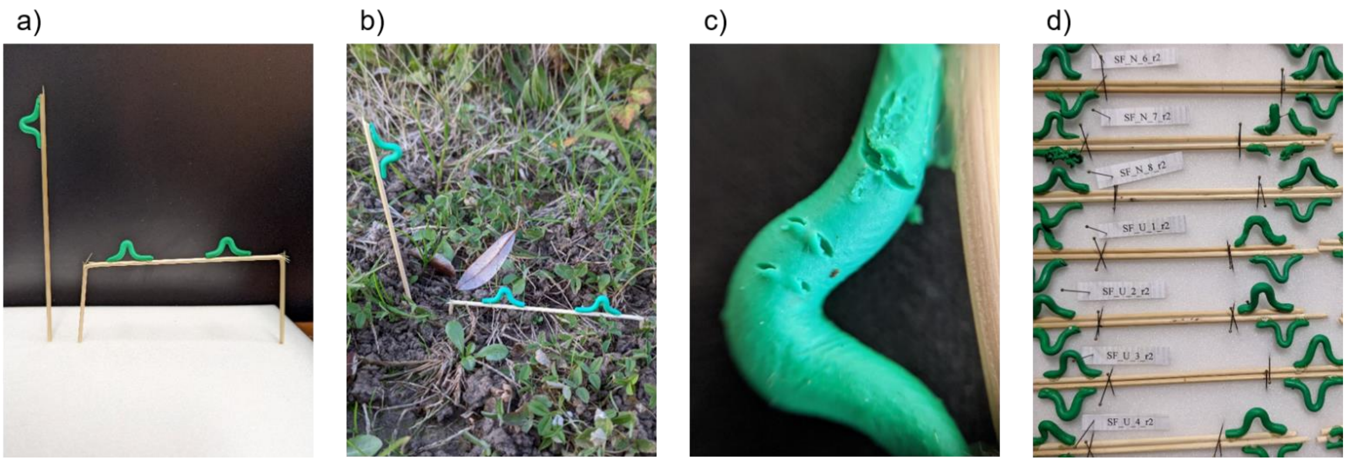


Figure 5 a) Dummy caterpillars in lab, with a single high caterpillar (left) and one low pair of caterpillars (right); **b)** The same three dummy caterpillars on field; **c)** Predation marks on a dummy caterpillar; **d)** Dummy caterpillars in the box.

5.3 Weed control

When: 2 sampling rounds. Choose three days during summer with no wind and no rain, so the seeds will not come off the sandpaper.

How many: 3 seed cards per site per sampling round.

Time needed in the lab: one day to count the seeds and prepare the seed cards (x2), one day to count the seeds after the collection of seed cards (x2).

References: Westerman et al. (2003)

What you need:

- Sandpaper, P80 grit, c. 10 cm wide: 1 roll (10 m length);
- *Taraxacum officinale* seeds: c. 100 gr;
- *Lolium perenne* seeds: c. 100 gr; if this species is not available in your country, choose another grass species, *e.g., Festuca* sp.;
- 3M Spray Mount repositionable glue: 2 cans;
- Small nails, c. 5 cm long: c. 500;
- Plastic bags, c. 12 x 5 cm: c. 400.

1. Prepare the sandpaper. Cut 3 pieces of sandpaper per site (90 pieces per round) c. 10 cm x 5 cm in size. Mark each piece of sandpaper on the back with a permanent black marker, writing the site code, number of the seed card (from 1 to 3), and sampling round (R1 or R2), *e.g.*, "DE1GER01_1_R1", "DE1GER01_2_R1", "DE1GER01_3_R1".

2. Prepare the plastic bags. You will need one bag per seed card. Mark each plastic bag with a permanent black marker, writing on it the correspondent seed card code, *e.g.*, "DE1GER01_1_R1", "DE1GER01_2_R1", "DE1GER01_3_R1".

3. Prepare the seeds. Take off the pappus from *Taraxacum* seeds by rubbing the seeds between your hands. Count 40 seeds of each species per seed card. On each seed card, you will therefore have 80 seeds in total. Put the seeds in small tubes.

4. Assemble the seed cards (Fig. 6a). Spray a thin layer of repositionable glue on each piece of sandpaper, then tip the seeds on the sandpaper and spread them a bit using your fingers. Wait for about 30 seconds, then press the seeds onto the sandpaper (*e.g.*, using the cap of a tube). Leave the seed cards to dry for at least 24 hours, then place them in their respective plastic bags.

5. On field, if possible choose a spot with short grass. Remove the seed cards from their plastic bags with extreme caution, and place them on the ground at least 50 cm apart. Fix the seed cards using small nails, so that they adhere to the ground (Fig. 6b). Pay attention not to lose any seed.

6. Write down the date, time, number of fallen seeds for each seed card (*i.e.*, still inside the plastic bag, if any), and any additional notes. Then, empty the plastic bags from the fallen seeds.

7. Wait for 3 days.

8. After 3 days, collect the seed cards. Take off the nails with extreme caution, and place each seed card in its plastic bag. Write down the date, time, and any additional notes.

9. In the lab, count the remaining seeds of the two species using the stereoscope. Consider half-eaten seeds as eaten.

10. For each site estimate weed control as the proportion of predated seeds.

a) b)

Figure 6: a) Seed cards preparation in the lab; **b)** Seed card on field, fixed with small nails.

5.4 Nutrient cycling

The stepwise protocol, together with some tips, is available at http://www.teatime4science.org/method/stepwise-protocol/. For additional suggestions, see http://www.teatime4science.org/method/availability-of-tea/.

When: in spring/summer.

How many: 3 pairs of tea bags per site, *i.e.*, 3 green tea bags and 3 rooibos bags per site.

Time needed in the lab: half a day to mark and weigh the tea bags, half a day to put the tea bags to dry and to weigh them again.

References: Keuskamp et al. (2013)

What you need:

- Lipton Indonesian tea Sencha tradition (EAN 87 22700 05552 5): 5 boxes, 100 bags in total; you will only need 90 tea bags, but it is better to have some in stock;
- Lipton Rooibos tea (EAN 87 11327 5143 48, https://www.dutchsupermarket.com/en/lipton-rooibos-tea.html): 5 boxes, 100 bags in total;
- Small shovel: 2;
- Plastic bag: c. 100;
- Scale with at least two digits (0.01): 1;
- Permanent black marker: 1.

1. Mark the tea bags on the white side of the label with the permanent black marker. Use “G” for green tea and “R” for rooibos tea, then add subsequent numbers, *e.g.*, G1, G2, …, G99, G100. The coloured side of the label is made up of paper and will disappear over time.

2. Weigh each tea bag (Fig. 7a).

3. On field, at each site bury three pairs of bags, each consisting of one green tea bag and one rooibos tea bag. Bury each pair in a 8 cm-deep hole, keeping the three holes c. 15 cm apart. Keep the labels visible above the soil (Fig. 7b). Mark the burial site somehow, *e.g.*,

using a stick. This is a crucial step, as if you don’t mark the site clearly it will be very difficult to locate the tea bags after three months. Write down the code of the bags in each hole at each site, date, shading of the soil (1-5, from none to completely), and impact by humans (1-5, no impact to completely impacted).

4. Wait for approximately 90 days (±5 days).

5. After 90 days, recover the tea bags. Do not pull the label hard, as it might break. Write down the date and any additional information (*e.g.*, pierced bags). Place each pair in a single plastic bag, writing on each plastic bag the site and pair code.

6. Remove adhering soil particles and dry the tea bags in a stove for 48 hours at 70 °C.

7. Take the tea out of each bag and weigh it.

8. For each site calculate the decomposition rate and stabilisation factor (Keuskamp et al. 2013) as proxies for nutrient cycling.

a) b)

Figure 7 a) Weighing of tea bags; **b)** One pair of tea bags (rooibos tea on the left, green tea on the right). Note the labels above the soil.

5.5 Climate regulation

When: in spring/summer.

How many: five soil samples per site.

Time needed in the lab: one day to prepare the soil samples for the analysis.

References: Pizzeghello et al. (2011); Tamburini et al. (2016)

What you need:

- Small shovel: 2;
- Plastic bag: c. 50;
- Permanent black marker: 1.

1. On field, collect five soil samples of c. 0.1 kg each and pool them for each site. The five samples should be collected around the vegetation plots/pollinator transects. Place the soil into a plastic bag and write the site code on the bag using a permanent black marker.

2. In the lab, dry the soil in a stove at 70 °C. Then, analyse the soil organic matter content

5.6 Water regulation

When: it is easier to do this activity after at least a couple of days of rain.

Time needed in the lab: /

What you need:

- PVC or metal tube, c. 15 cm in diameter and 30 cm in height: 2;
- Water canister, c. 5 L: 1;
- Scissors: 1;
- Plastic bag/sheet/wrap: 2;
- Ruler: 2;
- Stopwatch: 1;
- Small wooden board: 1;
- Mallet: 1;
- Water.

1. On field, select two spots within the vegetation plots/pollinator transects at each site. If it is necessary, shorten the grass a bit using scissors.

2. The soil should be saturated with water before each test. Check if the soil is already saturated (*e.g.*, if it rained), otherwise add some water. Write down how many litres of water are needed to saturate the soil.

3. Insert the PVC/metal tube into the soil, 5-10 cm deep. If the soil is too hard, place the wooden board on top of the tube and tap it with the mallet. Place the plastic bag in the tube, so the water is not absorbed as you pour it in the tube, and the ruler on one side of the tube (Fig. 8).

4. Pour 1 L of water into the tube and write down the water level.

5. Remove the plastic bag and immediately start the stopwatch.

6. Mark the water level at every minute for six minutes. Each test thus lasts a maximum of 6 minutes, even if the water has not been fully absorbed.

7. If the water is completely absorbed within six minutes, write down the complete absorption time.

8. Repeat the test at each spot two times.

Figure 8. Water is poured into the plastic-lined tube.

5.7 Water quality

When: in spring/summer.

How many: five soil samples per site.

Time needed in the lab: one day to prepare the soil samples for the analysis.

References: Pizzeghello et al. (2011); Tamburini et al. (2016).

What you need:

- Small shovel: 2;
- Plastic bag: c. 50;

- Permanent black marker: 1.

1. On field, collect five soil samples of c. 0.1 kg each and pool them for each site. The five samples should be collected around the vegetation plots/pollinator transects. Place the soil into a plastic bag and write the site code on the bag using a permanent black marker.

2. In the lab, dry the soil in a stove at 70 °C. Then, analyse phosphorus saturation as the the ratio between soil P and the sum of aluminium (Al), iron (Fe), calcium (Ca), and magnesium (Mg). Extractable P, Al, Fe, Ca, and Mg is determined by Mehlich-3 solutions. P concentration is determined calorimetrically whether Al, Fe, Ca, and Mg concentrations spectrophotometrically.

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Appendix A. Scoring of additional co-benefits

During the panel discussions, four additional co-benefits were identified and discussed by the participants. These are defined (Table A1) and scored (Tables A2 and A3) below. The IQRs for these are all below the threshold value of 2 and would be considered consistent. However as they were extra to the original process, they are not included in the main text.

Table A1. Definitions

Co-Benefits	
Biocontrol of insect pests	The suppression of insect crop pests by biological control agents, such as predators, parasitoids, diseases etc.
Biocontrol of weeds	The suppression of pest plants by biological control agents, such as predators, parasitoids, diseases etc
Soil nutrient retention	The retention of nutrients such as phosphorous, nitrogen and potassium within the soil
Environmental water quality	The general environmental quality of nearby water bodies (excluding water quality for human consumption)

Of the additional co-benefits, low intensity grasslands and woody linear features had the strongest overall benefits (average benefits for both: 1.75), while flower rich field margins had the lowest (average median: 0.75). Confidence was notably strong (average confidence: 3.52) for biocontrol of insect pests, which has a strong score across interventions. Confidence was lower for soil nutrient retention, despite the strong consensus of interventions having lower impacts.

In terms of spatial sensitivity, participants score most extra co-benefits are being of medium sensitivity to variations in topography, geography and climate. Biocontrol of both insects and weeds was scored at 3 (medium effects) universally, while Environmental water quality was generally less sensitive (average median 2.33). Biocontrol of insect pests and soil nutrient retention were again the highest and lowest confidence scores respectively (average confidence 3.24 and 2.71 respectively).

Table A2. Median scores for the magnitude (scores scale from -3 (strong negative effect of intervention on the co-benefit) to 3 (strong positive effect of co-benefit on the co-benefit)) of co-benefits (average confidence in brackets)

	Biocontrol of Insect pests	Biocontrol of weeds	Soil nutrient retention	Environmental water quality	Average
Crop diversification	2 (4)	1 (3.43)	1 (3)	2 (3)	1.5 (3.36)
Flower-rich field margins	1 (3.57)	1 (3.14)	0 (3.29)	1 (2.43)	0.75 (3.11)
Organic agriculture	2 (3.57)	1 (3.43)	1 (2.86)	2 (3)	1.5 (3.21)
Reduced pesticide use	1 (3.43)	2 (3.43)	0 (2.43)	2 (3.43)	1.25 (3.18)
Low-intensity grasslands	2 (3.14)	1 (3.14)	2 (3.43)	2 (3.43)	1.75 (3.29)
Woody linear features	2 (3.43)	1 (3.14)	2 (2.86)	2 (2.71)	1.75 (3.04)
Average (co-benefit)	1.67 (3.52)	1.17 (3.29)	1 (2.98)	1.83 (3)	

Table A3 – Median scores for spatial sensitivity (scores ranging from 1: not sensitive to spatial factors to 5: highly sensitive) of co-benefits (average confidence in brackets)

	Biocontrol of Insect pests	Biocontrol of weeds	Soil nutrient retention	Environmental water quality	Average
Crop diversification	3 (3.29)	3 (3)	3 (2.71)	3 (2.86)	3 (2.96)
Flower rich field margins	3 (3.14)	3 (3.29)	2 (3.14)	3 (2.43)	2.75 (3)
Organic agriculture	3 (3.29)	3 (3.14)	3 (2.57)	2 (2.86)	2.75 (2.96)
Reduced pesticide use	3 (3.43)	3 (3.14)	3 (2.14)	2 (3.14)	2.75 (2.96)
Low-intensity grasslands	3 (3)	3 (3.14)	3 (3.14)	2 (2.86)	2.75 (3.04)
Woody linear features	3 (3.29)	3 (3)	3 (2.57)	2 (2.86)	2.75 (2.93)
Average (co-benefit)	3 (3.24)	3 (3.12)	2.83 (2.71)	2.33 (2.83)	

Appendix B. Additional interventions and co-benefits

The panel identified 13 other interventions and 11 other co-benefits of interest, as presented below, over the course of the survey (Q5 & 6, Table 5) and from the workshop discussions

Table B1. Additional interventions and co-benefits suggested by participants

Interventions	Description
Woodland patches	Patches of managed woodland
Individual trees	Maintenance of individual trees within boundary features
Creating/maintaining ponds	Creating and maintaining small standing water bodies
Small shrublands	Maintaining patches of perennial woody plants (scrub, tall shrubs, dwarf shrubs)
Rotational grazing	Rotation of livestock between grazing habitats across the season
Fallow land	Taking utilized agricultural land out of use for a short time
Natural regeneration of plant communities	Allowing natural regeneration of local plant communities in and around fields, without artificial seeding.
Herbal leys	Sowing and maintaining leys of flowering herbaceous plants
In field flower strips	Flower strips sown within fields
Beetle banks	Maintaining in-field soil mounds to support the nesting of beetles and other ground-nesting invertebrates
Diversification of non-crop habitat	Deliberate diversification of non-crop habitats through alterations in management
Agroforestry	Planting trees within productive arable or pastoral land
Wetland management	Maintaining wetland habitats such as bogs and fens
Increasing perennial plants and crops in landscapes	Increasing the proportion of landscapes dedicated to perennial plants and crops
Co-benefits	**Description**
Recreation	Benefits to recreational activities
Cultural values of landscapes	Benefits to the cultural value associated with the landscape.
Human health	Positive impacts on human health
Air quality	Benefits to local air quality for human respiratory health and airborne environmental quality
Microclimate regulation	Regulation of local climate conditions (e.g. temperature)
Pathogen control	Regulation of the prevalence of harmful pathogens (to crops, livestock and humans) within the landscape
Water storage	The storage of water within the landscape
Soil structure and fertility	The structural characteristics and nutrient availability within soils, which affect it’s accessibility to crop and non-crop plants
Forage for animals & humans	The provision of edible foods for animals and human
Aesthetic values	The impact on the aesthetic value of the landscape.
Biodiversity conservation	Support for wider biodiversity conservation (e.g. rare species)
Water provisioning	The accessibility of useable water

Descriptions are relatively coarse as there was not sufficient time to discuss these in depth during the workshop.