Identification of the most effective policy and practice responses to the multiple stressor effects on bees

Deliverable D10.6

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PoshBee

Pan-european assessment, monitoring, and mitigation of stressors on the health of bees

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Preface
Work Package 10 included Task 10.4, which was to identify appropriate response options for multiple stressors on bee health. An expert group would then review the range of possible responses and collectively identify the best matched policy and practice responses at an online workshop, leading to this deliverable D10.6 - a report and policy brief that identifies the most appropriate and effective policy and practice responses for mitigating threats from multiple stressors to managed bee health. Based on the outputs of the workshop, the report includes the current (15/03/2023) draft version of the manuscript being prepared for publication, which presents the most appropriate and effective policy and practice responses for mitigating threats from multiple stressors to managed bee health that were discussed in the workshop. At the time of publishing this deliverable report, the manuscript is in preparation for publication and will undergo a series of reviews by the expert participants in the workshop. We expect several sections will likely undergo edits or alterations. Therefore, the text that appears below represents the final deliverable report, however there will be amendments to the text and formatting that appear in the published manuscript resulting from this task.

Summary
Managed bees, including honey bees, some bumble bees, and some solitary bees, pollinate crops and wildflowers and are essential for the well-being of both humans and biodiversity (Potts et al. 2016). Yet, they face serious threats from anthropogenic disturbances including climate change, landscape modification, agrochemicals, pests, and pathogens (Dicks et al. 2021). While each of these threats, individually, can have negative impacts on bee health, evidence is still being accumulated regarding their relative importance, and the interactions of multiple stressors and their impact (Siviter et al. 2021). Supporting managed pollinators therefore requires a joint effort that couples advancing our understanding of the impacts of multiple stressors with identifying appropriate and effective risk responses to mitigate against threats.

A diverse range of response options, aimed at mitigating threats to pollinators, have been evaluated and reported in assessments including IPBES (2016) 'Pollinators, Pollination and Food Production' and SETAC (2013) MAgPIE: Mitigating the Risks of Plant Protection Products in the Environment, but there has not yet been an effort to match these policy and practice responses to the real-world realities of needing to address multiple stressors. One reason for this may be the complexity of the task, as in addition to multiple stressors, many of the responses outlined in these assessments can be implemented across multiple spatial and temporal scales and will involve numerous avenues of influence (actors, sectors) (Faichnie et al. 2021). To address this, and provide a starting point, we conducted a response screening process, using a well-defined context (outlined in the Methods), to distil the knowledge we have around the most effective and feasible mitigations for multiple stressors and their impact on managed bees.

Furthermore, supporting healthy bee populations, sustainable beekeeping and pollination across Europe are key aspects in the EU Green deal (EC, 2019). For future pollinator and pollination policy to be robust there is a need to identify on-farm risk responses that can be incorporated into CAP Strategic plans, the Nature Restoration Law, EU Pollinators Initiative, and the Biodiversity Strategy 2030.

1. Methods
In this response screening process, we used a modified Delphi technique to identify and reach a consensus on the most appropriate farm level options to manage multiple stressors impacting on managed bees.

1.1. Establishing the expert group

A core group of twenty experts, from across Europe, undertook this response screening process. Experts included members of a wider consortium collaborating on the EU-funded project, PoshBee, and stakeholders representing farmer, beekeeper, NGO, policy and agri-food sectors in Europe. Experts were affiliated with research institutes, universities, government and non-government organisations and industry. In this response screening process, we consider both policy and practice contexts from within the EU and national equivalents in countries including the UK, Switzerland, and Norway.

1.2. Developing response options

Response options were initially drawn from the IPBES (2016) 'Pollinators, Pollinations and Food Production' report and the SETAC (2013) MAgPIE: Mitigating the Risks of Plant Protection Products in the Environment report. Options ranged from small-scale, practical responses (e.g., create uncultivated patches of vegetation) to large-scale, more general responses (e.g., support high-level pollination initiatives). The list was further refined to only include responses that can potentially directly or indirectly reduce the risks from pesticides, pathogens, and poor nutrition on managed bees at the farm level. Further, some of the IPBES options were very broad in scope (e.g., improve managed bee husbandry) and so input was sought from beekeeping experts[1] to split these broad categories into several more specific and relevant response options. The final list comprised 29 response options across three areas of management (Table 1).

[1] Eleanor Attridge, Pam Hunter, Pilar de la Rua

Table 1: List of 29 potential response options that can be used to reduce the risks from interactions between pesticides, pathogens and poor nutrition on managed pollinators. Full definitions are also provided.

Abbreviation	RESPONSE	Full definition
Options for managed bee management (including honey, bumble and solitary bees)		
Beekeeper training	Beekeepers trained to a high level to recognise and treat pests and diseases	Trained advisors to provide standardised in best practice, general bee husbandry, identification, sampling and treatment of bee diseases to beekeepers. Training through apicultural programs of Member states (EU) or national equivalents (BeeBase, UK).
Colony selection	Beekeepers using colonies selected for reduced parasite loads	A strong market for resistant or reduced parasite load colonies is established and beekeepers prioritise this market.
Reproduction stocks	Beekeepers following best practice for the selection of reproduction stocks	Beekeepers follow best practice guidelines set out under Member State (EU) or national (UK) policies. Undertaking national certification in skills required to improve stocks of bees.
Healthy queens	Beekeepers using healthy local queens to help conserve native bee diversity	Beekeepers prioritise the use of local healthy queens to maintain and conserve native bee diversity.
Varroa resistant	Beekeepers using Varroa resistant drones/queens	Beekeepers prioritise use of queens/drones from naturally surviving populations, or select them for varroa resistance, using characters including SMR (suppression of mite reproduction), VSH (varroa sensitive hygiene) and REC (recapping of infested brood cells).

Native breeds	Beekeepers using native bee breeds or subspecies from breeding programmes	Beekeepers prioritise the use of native bee breeds or subspecies from local breeding programmes.
Quarantine	Beekeepers using inspection and quarantine treatments to reduce pathogen introductions into apiaries	Beekeepers adhere to all necessary precautions, including routine inspections and quarantine conducted by well-trained personnel, to reduce the introduction of pathogens.
Colony certification	Colonies tested and certified as proof they do not carry notifiable diseases	Colonies inspected and required to carry health certificates as proof they do not carry notifiable diseases in accordance with EU and national standards (UK).
Control trade	Beekeepers following legislation/guidance on the sale/trade of colonies	Beekeepers follow EU and/or national regulations on the sale of bee colonies. Regulations may specify what can be imported/exported, what certification is required.
Hive closure	Beekeeper closing or removing hives/colonies during the application of pesticide posing a high risk	Beekeepers and farmers work closely together to ensure hives/colonies are closed, or temporarily removed, during high-risk pesticide (EU Pesticide Database) applications.
Monitor pollinator health	Beekeepers monitoring managed pollinator numbers and health	Beekeepers regularly monitor and keep record of managed hives/colonies on farms to track colony size and health.
Monitor pollination	Monitoring managed bee pollination services	Beekeepers/farmers monitor pollination services through activities such as flower visit counts, or fruit set/yield measures.
Payment for services	A contract for pollination services between the beekeeper and farmer is in place	A contract between beekeeper and farmer is in place to cover costs of beekeeper such as transport costs, resources available to bees (fewer resources may mean more feeding costs), hive/colony maintenance throughout a season and the potential risks to bees (pesticides).
Product certification	Food and hive products are certified as bee friendly with a premium paid to beekeepers and farmers	Beekeepers and farmers participate in certification programs such as an EU equivalent of “Bee Friendly Farming” (example scheme from US - https://www.pollinator.org/bff) that provide labelling and premiums to be paid for products that meet a set of criteria such as guaranteed traceability, establishment of biodiversity zones and strict framework for use of pesticides.
Diversify pollinators	A variety of different managed bee species are used across the farm	Farmers use two or more managed bee species (honey bees, bumble bees, or solitary bees) across their farm.

Options for pesticide and farm management		
IPM	Farmer adopting full IPM practices on farm	Integrated pest management means careful consideration of all available plant protection methods. When intervention against a pest is necessary, sustainable biological, physical, and other non-chemical methods must be preferred to chemical methods if they provide satisfactory pest control. The products applied shall be as specific as possible for the target and shall have the least side effects on human health, non-target organisms and the environment https://food.ec.europa.eu/plants/pesticides/sustainable-use-pesticides/integrated-pest-management-ipm_en
Organic	Farmer adopts full organic practices on farm	Farmers follow EU regulations for organic production where there is: *prohibition of the use of GMOs; *forbidding the use of ionising radiation; and *limiting the use of artificial fertilisers, herbicides and pesticides. Instead, farmers use practices including: • crop rotation; • cultivation of nitrogen fixing plants and other green manure crops to restore the fertility of the soil; • prohibition of use of mineral nitrogen fertilisers; • farmers choose weed/pest resistant varieties and breeds and techniques encouraging natural pest control https://agriculture.ec.europa.eu/farming/organic-farming/organic-production-and-products_en
Diversified farming	Farmer adopts diversified farming practices across the farm	Farmers utilise practices that promote agro-biodiversity within the farm and reduce the need for off-farm inputs. Practices include mixed crop types, crop-livestock mixtures, intercropping, cover crops, reducing field sizes and polyculture (IPBES Pollinators, Pollination and Food Production Report, 2016, p52) https://ipbes.net/
Hive placement	Farmer following guidance on placing hives to reduce pesticide risks and increase access to floral resources	Working with beekeepers to identify sheltered, high floral resource areas for hive placement on farms. Communication about pesticide application programs.
Lower toxicity PPP	Farmer uses less toxic plant protection products wherever possible	Farmers prioritise use of lower toxicity PPP as outlined in EU and national regulations. (EU Pesticide Database) (National Action Plans) https://food.ec.europa.eu/plants/pesticides/sustainable-use-pesticides/national-action-plans_en
Reduced application	Farmer reduces the frequency/area/rate of pesticide application wherever possible	The farmer reduces the frequency/area/rate of synthetic pesticide application, but unlike in IPM or organic management, this is not in combination with any other alternative pest regulation practices.

Reduce drift	Farmer adopts practices to reduce pesticide drift and exposure	Farmers adopt practices such as using the coarsest appropriate spray quality at all times, low drift spray nozzles, dust collectors and keeping spray boom as low as possible (HSE UK, 2012).
Mass flowering blooming	Farmers manage blooming of mass-flowering crops to increase the continuity of flowering across the farm	Farmers choose crops and/or varieties that have consecutive blooming periods, e.g., multiple varieties of apples, pears, oilseed etc. that have different but overlapping blooming periods
Reward farmers	Reward farmers for pollinator-friendly practices	Farmers are rewarded through schemes such as Eco-schemes under the CAP (EU) for using environmentally sustainable approaches in their land management, which includes a package of measures benefitting pollinators.
Options for uncultivated farm habitat management		
Flower patches	Farmers create uncultivated patches of vegetation (providing forage resources and refuges)	Uncultivated flower margins, strips or patches are added to the farmland-type matrix and are managed to provide forage and refuge resources.
Grassland management	Farmers change the management of grasslands to provide a wider variety of floral resources	Farmers change the management of grasslands to provide a wider variety of floral resources e.g., altering mowing times.
Road verge management	Farmers manage on-farm road verges through sowing and mowing to enhance floral resources	Road verges are managed as uncultivated floral habitats and managed to enhance the resources available e.g., specific sowing and mowing times to allow floral resources to be of most benefit.
Restore habitats	Farmers restore grassland, forest, scrub habitats	Farmers restore grassland, forest, scrub habitats within farm boundaries and manage this as uncultivated land.
Increase connectivity	Farmers increase the connectivity of habitat patches on the farm	Farmers increase the connectivity of habitat patches on the farm through the creation of habitat corridors or links.

1.3. Farm context for assessment

To assess each case study, experts were asked to consider a single representative type of farm, where most land is used for arable crops with smaller areas of permanent pasture and/or horticulture and where the arable and horticulture land use includes crops that depend to some extent on pollination services (e.g., oilseed rape, apples). Other general characteristics of this representative farm were also defined (Table 2).

Table 2: General farm characteristics as defined for the representative farm used in this process.

Defined characteristic	Representative farm	Justification
Farm size	The farm is around 15ha in area	The mean farm area in the EU in 2016 (EC 2021)
Farm composition	About 70% of cultivated land is used for arable, 25% for permanent grassland and 5% for permanent crops such as olives, nuts, grapes, top fruit.	Mean land use composition in EU 2016 (EC 2021)
Production methods	The farm focuses primarily on high yield production through conventional production methods.	91.5% of farms were not organic in 2019 (EC 2021)
Input management	Conventional use of synthetic pesticides (including insecticides, herbicides, fungicides), and inorganic fertilizers allowed under current EU regulations, are applied at manufacturer recommended rates. Full IPM is not practiced on the farm, but some general IPM principles have been adopted (e.g., in some cases targeted pesticide applications are used for specific pests rather than broad-spectrum pesticides).	
CAP Greening obligations	There is modest investment in the environment in cultivated areas; always meeting minimum legal requirements (e.g., Cross Compliance and Greening under CAP Pillar 1) and with some agri-environmental and climate measures being implemented to deliver public goods and services (CAP Pillar 2).	In 2018, 80% of EU farm land was subject to at least one of the CAP greening obligations (https://copa-cogeca.eu/europeanfarming)
Uncultivated land management	There are small areas of uncultivated land spared for nature on the farm (e.g., semi-natural habitats and high nature value woodlands, grasslands, and wetlands), which account for no more than 5-10% of the farm area.	

1.4. Case studies

Four case studies were chosen based on a set of eligibility criteria (Appendices A-D). Individual experimental papers were assessed against the following criteria: 1) need to investigate the impact of an interaction between stressors (agrochemicals, parasites, pathogens or nutrition) on managed bee species; 2) stressors need to be relevant to Europe (i.e., not include things such as neonicotinoid pesticides that have been banned in the EU); and 3) the focal bee species of the study needs to be relevant to Europe (e.g., *Apis mellifera*, *Bombus* spp. or *Osmia* spp.). Overall, we aimed to have both a balance of managed bee species and a diversity of stressor interactions represented across all the chosen case studies (Table 3). The final selection included three studies that looked at pesticide and nutrition interactions (Barascou et al. 2021; Knauer et al. 2022; Wintermantel et al. 2022) and one study that assessed pesticide and pathogen interactions (Siviter et al. 2020).

Table 3: Final selected case study details

First Author	Title	Focal Bee Species	Stressors
Barascou	Pollen nutrition fosters honeybee tolerance to pesticides.	*Apis mellifera*	Pesticide x nutrition
Knauer	Nutritional stress exacerbates impact of a novel insecticide (flupyradifurone) on solitary bees' behaviour, reproduction and survival.	*Osmia bicornis*	Pesticide x nutrition
Siviter	Individual and combined impacts of sulfoxaflor and *Nosema bombi* on bumblebee (Bombus terrestris) larval growth and mortality.	*Bombus terrestris*	Pesticide x pathogen
Wintermantel	Flowering resources modulate the sensitivity of bumblebees (*Bombus terrestris*) to a common fungicide (azoxystrobin).	*Bombus terrestris*	Pesticide x nutrition

1.5. Scoring procedure

Each response option was scored for effectiveness for each of the four case studies (116 scores per expert), where effectiveness was defined as the ability to reduce the effect of threat or risk to managed pollinators in the context of the case study. Each response option was also scored for feasibility, defined as the ease of implementation of the specific response option, both with external support and without external support from an overall perspective i.e., across all case study contexts (58 scores per expert). For feasibility with external support, experts were asked to consider 'external support' to mean being inclusive of but not limited to, things like agri-environmental type scheme (AES) payments, industry or government sponsored training or provision of equipment or consumables (e.g., seeds). For feasibility without external support, experts were asked to consider the ease of implementation of each response option with no additional support from AES, industry or government sponsored training or provision of equipment or consumables. Scoring was on a scale of 0-10, where a score of 0 meant the response option was entirely ineffective or entirely unfeasible and a score of 10 meant the response option was entirely effective or entirely feasible. Two scoring rounds were conducted with the first conducted prior to the workshop in January 2023 and the second either during or shortly after the workshop had taken place.

During their two scoring rounds we asked experts to keep these five points in mind:

1. Scoring needs to be done from a balanced systems perspective rather than as an individual with a specific agenda (e.g., individuals focused solely on managed bee well-being, or an individual focused solely on maximising productivity outcomes).

2. Each case study must be assessed in the context of the defined representative European farm.

3. Each case study scenario must be scored from the perspective of the system's goals, which are: to mainly focus on food production but with some investment in environmental quality.

4. Each response option needs to be scored solely for the stressor or combination of stressors posed within each case study.

5. All responses need to be considered at the scale they would typically be applied.

1.6. Score analysis

For the first round of scores (20 experts returned scores), we calculated both the median score and the interquartile range (IQR) for each response option x case study or feasibility scenario. The IQR was used to assess the level of consensus among the group for each response option, where higher IQRs represented less consensus among the experts scores.

Following the second round of scores (19 experts re-scored), we repeated our calculations as above to determine the final scores for effectiveness and feasibility.

We classified scores along our scale of 0 to 10 into five categories - very low (0-2), low (2.01-4), medium (4.01-6), high (6.01-8) and very high (8.01-10) and used these categories to summarise both the feasibility and the most effective response options.

1.7. Workshop

An online workshop, with 19 experts in attendance, was held in January 2023. Response options were ranked by decreasing level of consensus (i.e., least consensus at top of list) and discussed in this order for both feasibility scenarios and each of the four case studies. To start the discussion for each response option we asked that one expert who scored high and one expert who scored low volunteered their reasoning behind these scores. Due to time constraints not all response options for each case study or feasibility scenario could be discussed, so we set a limit to at least discuss all response options that had an IQR of 6 or more and if time allowed options with IQRs below this were also discussed. Experts privately re-scored all response options (including those not discussed) as previously described.

2. Results

2.1. Feasibility Scenarios

On average, scores for feasibility between the first and second rounds showed an increase in consensus across both scenarios. Consensus for the scenario involving additional support increased by 20% and for the without additional support scenario consensus increased by 16%. All response options were determined to be more feasible in the scenario involving additional support, with median scores ranging from 6 to 9 (Figure 1a). Without additional support, the feasibility of response options dropped to scores ranging between 2 and 6 (Figure 1b).

For bee management, a wide range of options were deemed to be equally easy to implement if additional support was available, these included beekeeper training, colony certification, controlling trade, hive closure, monitoring pollinator health, payments to beekeepers for services and certifying products as ‘bee friendly’ (scores of 8). Monitoring pollination and prioritizing the use of native breeds were the least feasible in this scenario (scores of 6), with all remaining options scoring 7. Without additional support, hive closure was retained as a most feasible option along with healthy queens (scores of 6), followed by beekeeper training and best practice reproduction stock approaches (scores of 5). Monitoring pollination was again the least feasible option in this scenario (score of 2) with the remaining options split evenly across scores of 3 (product certification, quarantine, colony certification, control trade and diversify pollinators) or 4 (colony selection, varroa resistant, native breeds, payment for services and monitoring pollinator health).

For habitat management, the creation of flower patches in both scenarios (with or without support) was considered the most feasible response, with a score of 9 when additional support was available and 4 without the support. For the ‘with support’ scenario, flower patches was followed by restoring habitats and increasing connectivity between habitat patches (scores of 8) and grassland management and road verge management (scores of 7). In the ‘without support’ scenario, grassland management was deemed equally as feasible as flower patches followed by the last three options, each with a score of 3.

For farm management, rewarding farmers was the most feasible response in the ‘with support’ scenario (score of 9), this was followed by reducing spray drift and IPM practices (scores of 8) then all remaining options (scores of 7). In the ‘without support’ scenario, reducing spray drift was the most feasible option (score of 6), while both rewarding farmers and IPM practices were deemed the least feasible (scores of 3). Without additional support, reducing spray drift was followed by hive placement (score of 5), mass flower blooming (score of 4) and then all remaining options (scores of 3).

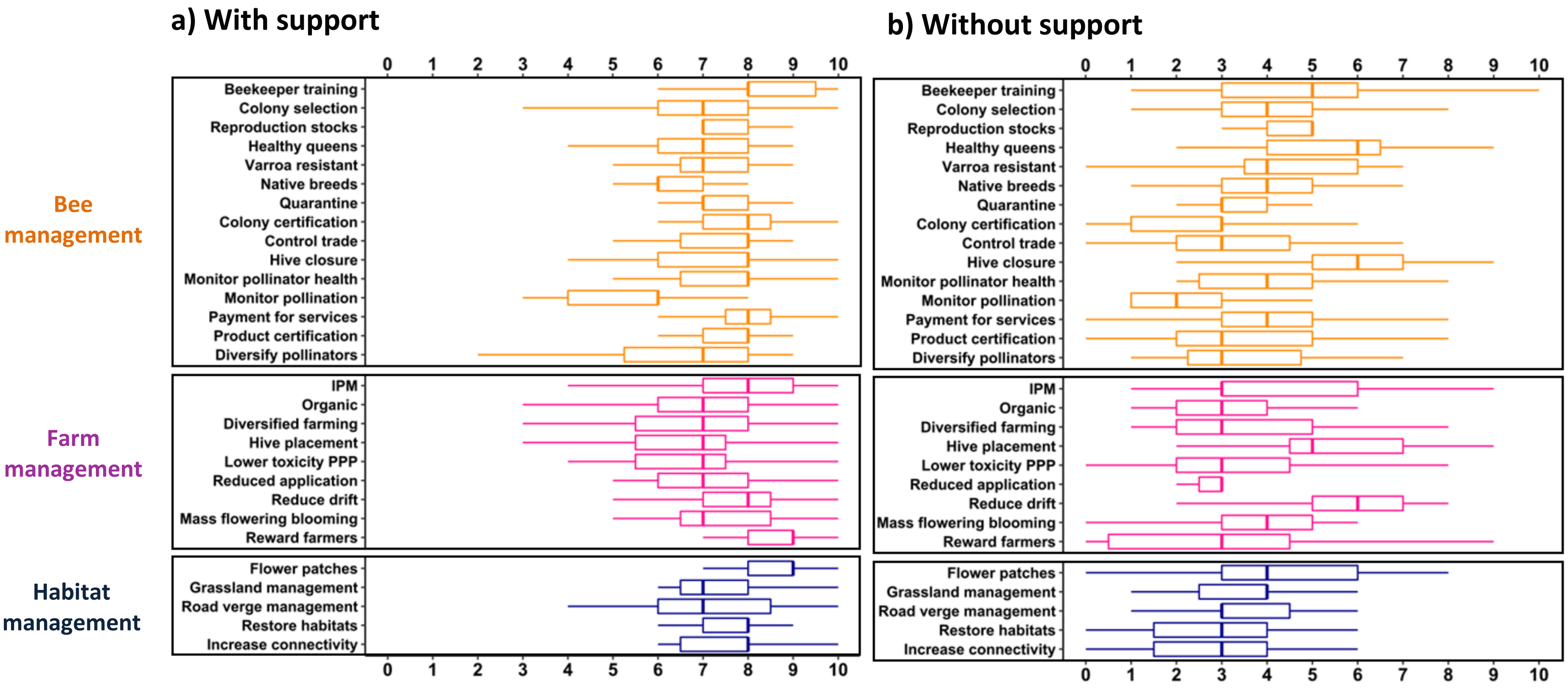

Figure 1: Results from the second round of scoring all response options for their overall feasibility under two scenarios, that is a) with additional support and b) without additional support.

2.2. Case Study Scenarios

Average overall consensus, for each of the four case studies, also increased between the first and second round of scoring. The Siviter case study showed the biggest change with consensus increasing by 31%, followed by increases to Wintermantel (23%), Knauer (22%) and Barascou (19%).

2.2.1. Barascou Case Study

The Barascou study was one of three that looked at the interaction between a pesticide (Sulfoxaflor) and nutrition in managed bees, specifically *Apis mellifera* in this study (Appendix I). Several response options under farm and habitat management were deemed to be the most effective in this scenario, with options under bee management being least effective (Figure 2). The creation of flower patches, under habitat management options, was the most effective response in this scenario (score of 8). This was followed by nine options, under farm and habitat management, that were equally effective responses including restoring habitats, road verge and grassland management (habitat) and rewarding farmers, reducing spray drift, reducing the application of pesticides, using lower toxicity plant protection products, diversifying farming, and incorporating IPM practices (farm) (scores of 7). Of the bee management options, the most effective was hive closure (score of 6) followed by monitoring pollinator health and healthy queens (scores of 5), with the least effective being colony certification (score of 0).

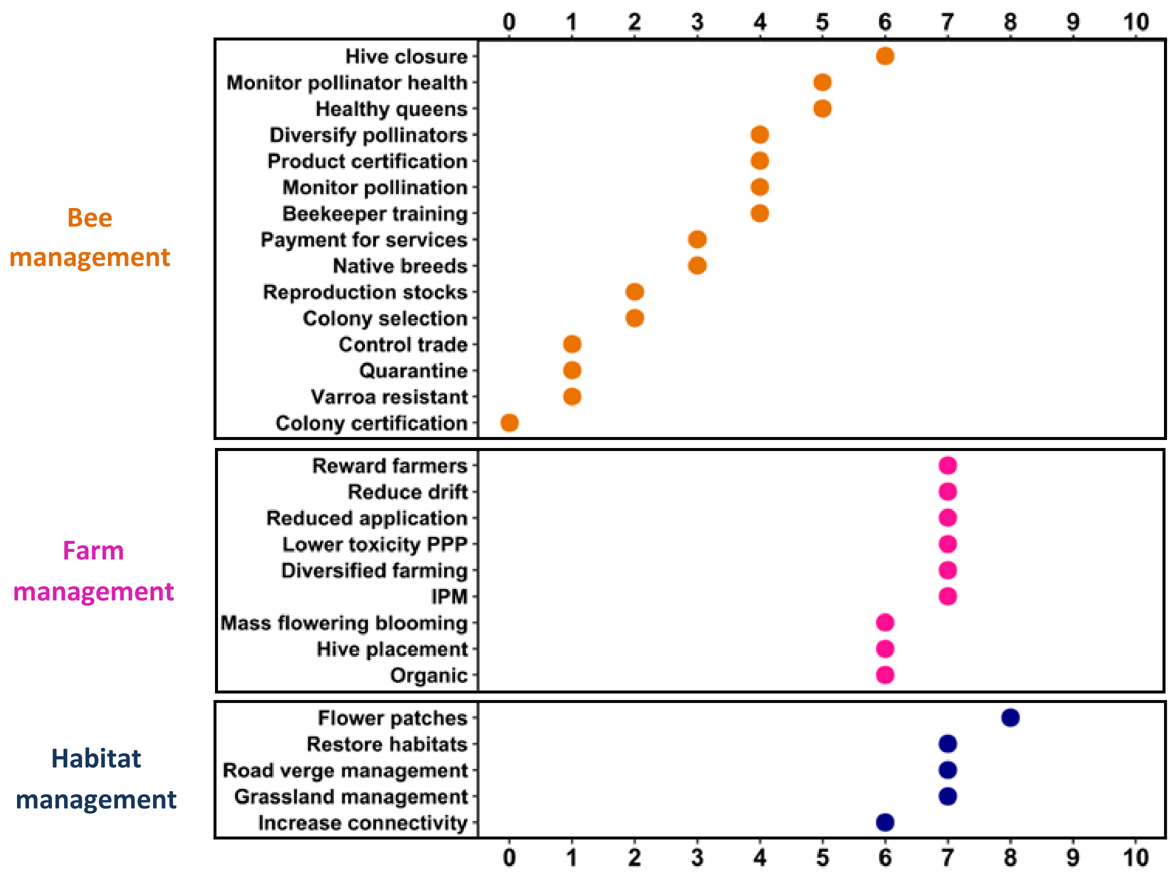

Figure 2: Final median scores for each response option in the Barascou case study scenario (pesticide x nutrition).

2.2.2. Knauer Case Study

The Knauer case study also looked at the impact of an interaction between a pesticide (Flupyradifurone) and nutritional stress on the solitary bee species, *Osmia bicornis* (Appendix B). The most effective responses to this stressor interaction were similar to those in the Barascou case study, that is, the most effective options were from habitat and farm management responses with bee management responses being the least effective (Figure 3). The creation of flower patches was again the most effective response (score of 8), followed by restoring habitats and road verge management (habitat) and rewarding farmers, reducing spray drift, reducing the application of pesticides, using lower toxicity plant protection products and diversifying farming (farm) (scores of 7). There were two points of difference to the previous case study, with both grassland management (score of 6) and IPM practices (score of 5) being less effective for this particular stressor combination. For the bee management options, the most effective was diversifying pollinators (score of 5) and both colony certification and the use of varroa resistant queens/drones were the least effective (scores of 0).

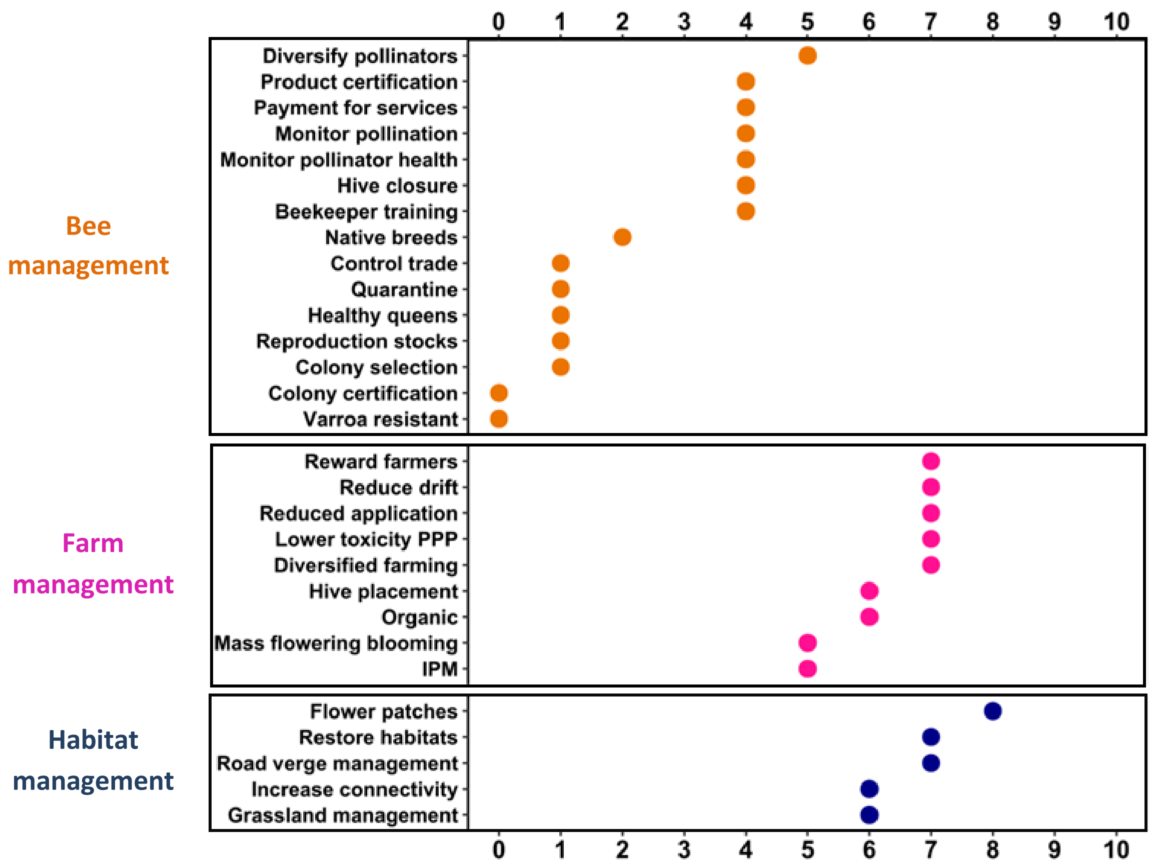

Figure 3: Final median scores for each response option in the Knauer case study scenario (pesticide x nutrition).

2.2.3. Wintermantel Case Study

The Wintermantel case study looked at the impact of an interaction between a fungicide (Azoxystrobin) and nutrition on bumblebees, *Bombus terrestris* (Appendix C). The results were similar to the previous two case studies, in that habitat and farm responses were the most effective options and bee management options were less effective (Figure 4). Flower patch creation was again the most effective response option to mitigate against this stressor interaction (score of 8). Two more habitat management options, road verge and grassland management, were among the next most effective along with several farm management options including rewarding farmers, reducing spray drift, reducing the application of pesticides, hive placement and diversifying farming (scores of 7). For bee management options, the most effective was hive closure (score of 6) and the use of varroa resistant queens/drones was the least effective (score of 0).

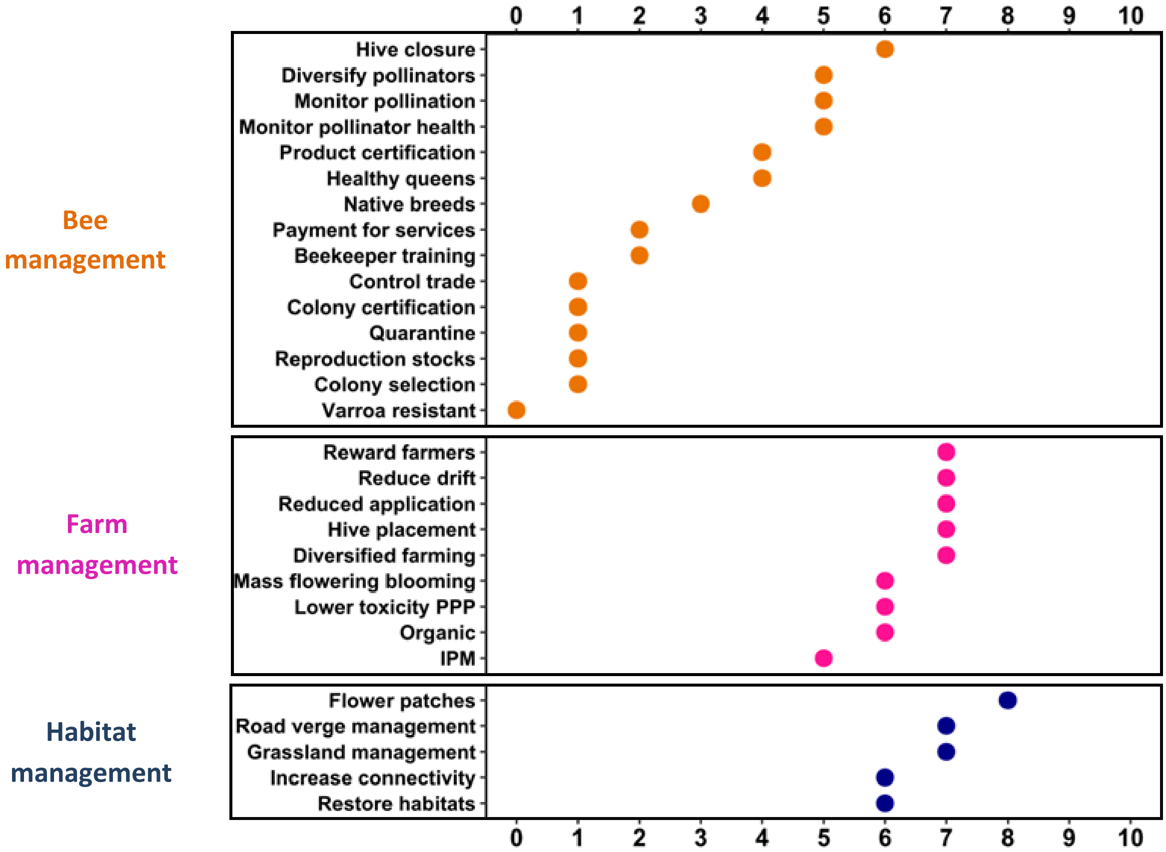

Figure 4: Final median scores for each response option in the Wintermantel case study scenario (pesticide x nutrition).

2.2.4. Siviter Case Study

The Siviter case study differed to the previous three, in that it looked at the impact of an interaction between a pesticide (Sulfoxaflor) and a pathogen on bumble bees, *Bombus terrestris* (Appendix D). The most effective responses in this scenario were bee and farm management options, with eight options equally most effective (Figure 5). This included five farm options - rewarding farmers, reducing spray drift, reducing the application of pesticides, using lower toxicity plant protection products and IPM practices, along with three bee options - prioritising the use of healthy queens, colony selection based on reduced parasite loads and following best practice for the selection of reproduction stocks (scores of 7). Similar to previous case studies, the use of varroa resistant queens/drones was the least effective response (score of 0). A point of difference for this case study was the high number of responses, from across all management types, that had scores of 5 or 6 (medium effectiveness), with 16 options occupying this range and only 5 being less effective than this.

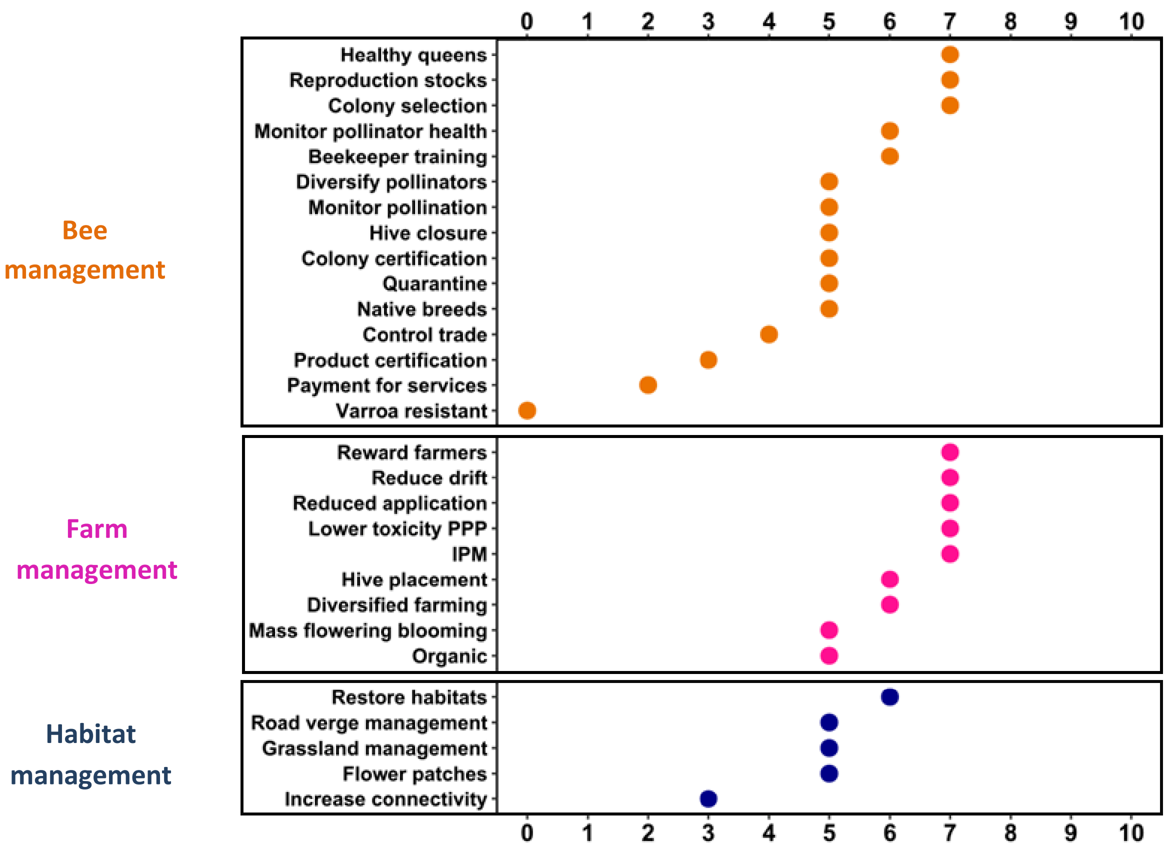

Figure 5: Final median scores for each response option in the Siviter case study scenario (pesticide x pathogen).

3. Discussion

Through this response process task, we found that despite the case studies used here having different focal managed species, active ingredients involved and stressor combinations, there is a general convergence on how to best mitigate for these multiple stressors at a farm scale. However, the effectiveness of specific interventions varied with context. This response-matching task offers a way to update current mitigation responses, which until now have mainly been aimed at individual, well established stressors on bees (e.g., agrochemicals, IPBES 2016) and to work towards mitigating the multiple, interacting stressors faced by managed bees in the environment, which has long been highlighted as a major issue (Vanbergen and the Insect Pollinator Initiative, 2013; Goulson et al., 2015; IPBES, 2016).

Summarising the most effective responses (scores of 7 and above) for each case study identified that three farm management responses are considered highly effective across all of them, including rewarding farmers for using pollinator friendly approaches, reducing spray drift, and reducing pesticide application rates (Figure 6). Clear differences were also evident when it came to the most effective mitigation responses for the two broad categories of stressor combination - pesticide x nutrition and pesticide x pathogens. While farm management response options were common across both categories, habitat management responses were highly effective for pesticide x nutrition stressors, while bee management responses were highly effective when addressing pesticide x pathogen stressors.

	Response Option	Feasibility: WS	Feasibility: WOS	Pesticide x nutrition: Wintermantel	Pesticide x nutrition: Knauer	Pesticide x nutrition: Barascou	Pesticide x pathogen: Siviter
Habitat	Flower patches	9	3	8	8	8	
	Road Verge Management	7	3	7	7	7	
	Restore Habitats	8	3		7	7	
	Grassland Management	7	4	7		7	
Farm	Reward Farmers	9	3	7	7	7	7
	Reduce Drift	8	6	7	7	7	7
	Reduced Application	7	3	7	7	7	7
	Hive Placement	7	5	7			
	Diversified Farming	7	3	7	7	7	
	IPM	8	3			7	7
	Lower Toxicity PPP	7	3		7	7	7
Bee	Colony Selection	7	4				7
	Reproduction Stocks	7	5				7
	Healthy Queens	7	6				7

Very High High Medium Low Very Low

WS = With additional support **WOS** = Without additional support

Figure 6: Summary - response options identified as most effective across each case study (median scores of 7 to 10) and their feasibility both with and without additional support.

Another key aspect of this process has been to layout in clear terms the ease of implementation of these response options across two contrasting scenarios, with and without additional support. Our results showed that if additional support was available to farmers, beekeepers, and land managers, (e.g., payments, training, advice) then most response options were thought to be highly feasible; without this support the feasibility of response options was lower and more varied. An important outcome here is highlighting, in a more targeted way, where investments into improving the feasibility of specific response options are required to have the biggest impact. For example, when we combine effectiveness and feasibility here, we see rewarding farmers for pollinator friendly practices and reducing spray applications are highly effective mitigation responses for multiple stressor combinations but are only feasible when additional support is provided, essentially providing a target for addressing the 'feasibility gap'. In contrast, reducing spray drift was not only equally effective but also feasible with or without this additional support, requiring less intervention for its uptake.

There are different schemes available to support the variety of interventions considered here. Many farm management options are supported by agri-environment type schemes such as those through the CAP (e.g., habitat management, rewarding farmers). In addition, training and advice from governments and industry may be available to support some farming practises (e.g., reduced pesticide use) and beekeeping practises (e.g., improved husbandry). However, the specific support mechanisms available vary between Member States.

The impact of stressors and their interactions on managed bees will differ across local contexts (Boff et al., 2020), similarly we expect both the quality and extent of the application of any mitigation response to vary at the same scale and therefore may not be consistently successful every time it is employed. However, by using strong expert knowledge to distil what is a large and varied pool of evidence into a short menu of potential effective mitigation options, an element of guesswork has been removed from the situation for farmers and policymakers as they move forward. For example, this provides policymakers with the necessary information on the effectiveness of potential response options (for multiple stressors) needed to reinforce and update policies that can then be incorporated into CAP Strategic plans, the Nature Restoration Law, EU Pollinators Initiative, and the Biodiversity Strategy 2030. A step change such as this will provide a way forward where policymakers can act as facilitators, assisting farmers with moving from scenarios without support to scenarios with support, increasing the overall feasibility of effective mitigation options. Furthermore, we see this providing a framework to achieving more consistency in mitigation responses across farming landscapes.

4. Conclusion

This is the first-time that response options, which aim to mitigate the impact of multiple stressors and their interactions on managed bees at a farm scale, have been distilled in a systematic way. The process revealed a selection of overlapping and separate effective responses when mitigating the impact of interactions between pesticide and nutrition, and pesticide and pathogens on managed bees. Another outcome from this process was to highlight 'feasibility gaps' for response options, where despite being considered highly effective the response is only really feasible if additional support in some form is available. As such, this provides a target for policymakers to improve the ease of implementation of effective responses. The approach used here provides a solid initial step towards a more targeted selection of mitigation options to reduce the impacts of multiple stressors. Future work could build on this to explore in more depth particular characteristics of different mitigation options, consider a wider variety of stressor combinations, explore geographic and farming system variation, and also consider wild pollinators in addition to managed pollinators.

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6. Appendix A

BARASCOU Case Study

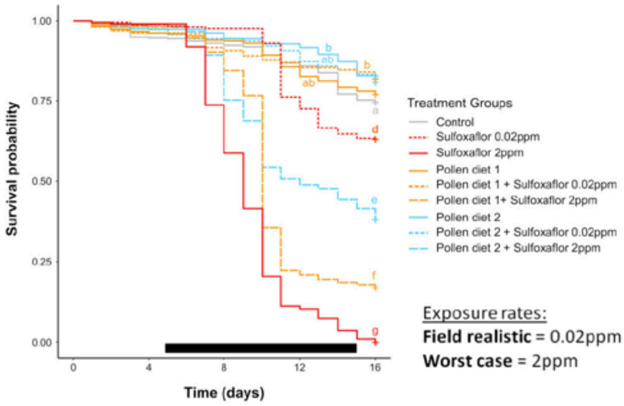
Pollen nutrition fosters honeybee tolerance to pesticides

Background: pollen is a major source of nutrients for honeybees. However, due to differences in their nutrient content, pollens from different floral species are not of the same quality for honeybees.

Question: can variation in pollen diet quality affect the sensitivity of honeybees to pesticides?

Real world context: Willow (*Salix*), Oak (*Quercus*) trees and oilseed rape (Brassicaceae) are widely distributed throughout semi-natural habitat and agricultural settings across the EU. Sulfoxaflor is systemic and in this study was applied via a sucrose solution at concentrations corresponding to field realistic and higher insecticide exposure rates.

Effects of pollen feeding and sulfoxaflor (insecticide) on bee survival



Exposure rates:
Field realistic = 0.02ppm
Worst case = 2ppm

Under field realistic conditions

Sulfoxaflor at rate of 0.02ppm

Pollen 1 = **Brassicaceae / *Quercus*** species

Pollen 2 = ***Salix*** species

Sulfoxaflor reduced **honey bee survival**, but this reduction was **less** when bees were able to **consume pollen**. In addition, at higher exposure rates, some **pollens** were **better than others** in reducing the sensitivity of honey bees to the insecticide sulfoxaflor.

Bee survival probabilities

Control: **75%**

Pollen 1: **77%**

Pollen 2: **80%**

Sulfoxaflor (0.02ppm): **62%**

Sulfoxaflor (0.02ppm) & Pollen 1 **or** 2: **>80%**

Key Findings: This specific study indicated that pollen from *Salix* species was better at reducing sensitivity to Sulfoxaflor than Brassicaceae or *Quercus*. Therefore, the type of pollen available may be an important consideration when assessing response to stressors.

Source: Barascou L., Sené D., Barraud A., Michez D., Lefevre V., Medrzycki P., Di Prisco G., Strobl V., Yanez O., Neumann P., Le Conte Y., Alaux C., 2021. Pollen nutrition fosters honeybee tolerance topesticides. *R. Soc. Open Sci.* 8: 210818. https://doi.org/10.1098/rsos.210818

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7. Appendix B

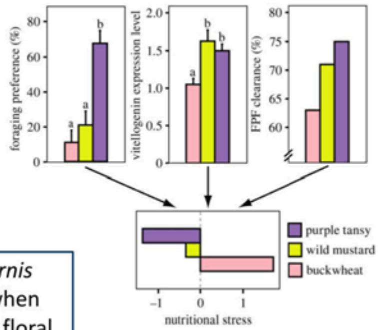
KNAUER Case Study

Nutritional stress exacerbates impact of a novel insecticide (flupyradifurone) on solitary bees' behaviour, reproduction and survival

Background: food stress and pesticide exposure are two major threats to bees. However, their potential synergistic effects are poorly understood under field realistic conditions and are not considered in current pesticide risk assessments.

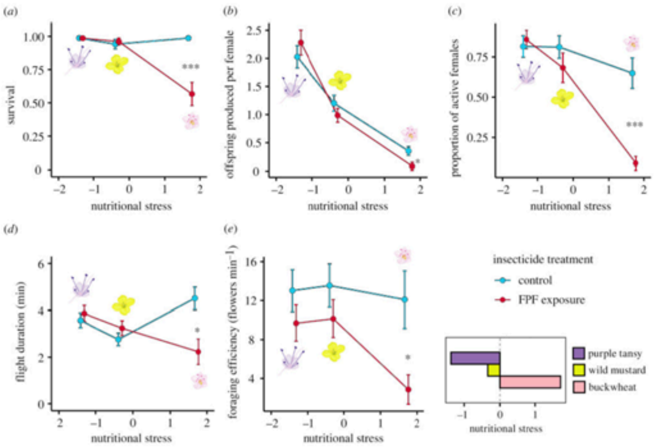
Question: can nutritional stress increase the impact of an insecticide on the solitary bee, *Osmia bicornis*?

Study design: A semi-field experiment with three flowering species commonly found in an EU agricultural context.
Flupyradifurone is a systemic insecticide and was applied at highest recommended rate (205g active ingredient per hectare) in this study, with a spray application in the early morning.



Nutritional stress: Foraging *O. bicornis* showed highest nutritional stress when they only had access to buckwheat floral resources. Axis scale (nutritional stress) is inverse of nutritional value scale (e.g., low value nutrition = high nutritional stress).

Synergistic interaction is seen between flupyradifurone (FPF) exposure & nutritional stress on *Osmia bicornis* (day 1)



The **interaction** of nutritional stress (buckwheat) and insecticide exposure **increased bee mortality**.

No impact of **insecticide exposure** on bees was detected in **intermediate** (wild mustard) or **low** (purple tansy) **nutritional stress** plant species.

% change compared to control in nutritional stress cages (buckwheat)

	FPF exposure
Survival of adult females	**↓43%**
Offspring production	**↓76%**
Flight activity	**↓86%**
Flight duration	**↓51%**
Visitation frequency	**↓83%**

Key Findings:
This study shows that risk of FPF to *O. bicornis* varies depending on the food plant chosen. Such synergistic effects may therefore need to be carefully considered in intensively managed agroecosystems.

Source: Knauer, A.C., Alaux, C., Allan, M.J., Dean, R.R., Dievart, V., Glauser, G., Kiljanek, T., Michez, D., Schwarz, J.M., Tamburini, G. and Wintermantel, D. (2022) Nutritional stress exacerbates impact of a novel insecticide on solitary bees' behaviour, reproduction and survival. *Proceedings of the Royal Society B.* https://doi.org/10.1098/rspb.2022.1013

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8. Appendix C

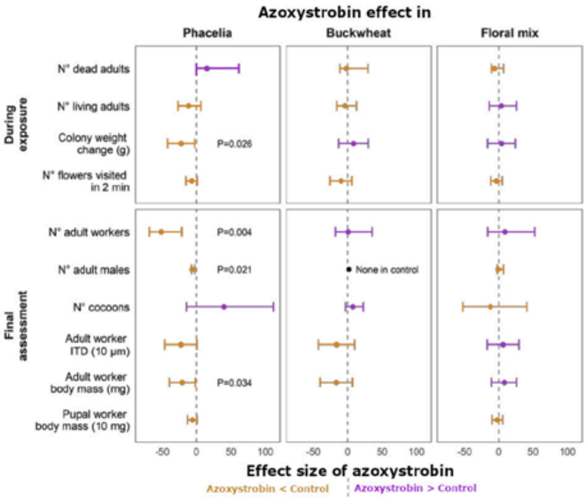
WINTERMANTEL Case Study

Flowering resources modulate the sensitivity of bumblebees (*Bombus terrestris*) to a common fungicide (azoxystrobin)

Background: the impact of pesticides on bees is assumed to be consistent across bee-attractive crops. However, flowering resources provide varying amounts of protein, which can benefit bumblebees, and may interact with fungicides.

Question: do flowering resources, that provide differing amounts of protein, affect the impact of a fungicide, azoxystrobin, on *Bombus terrestris*?

Real world context: Semi-field experiment with three different flowering resources common to EU agricultural settings. Azoxystrobin is a systemic fungicide. In this study, azoxystrobin was applied via a sprayer at product label application rates.



Impact of floral resources on colonies

Foraging on **buckwheat**, which has a low-protein pollen, **reduced colony fitness** compared to *Phacelia* (high-protein pollen) and the floral mix.

At the end of the experiment, **buckwheat** colonies had:

- **86% fewer cocoons** than *Phacelia* or floral mix colonies, and
- **57% fewer adult workers** than *Phacelia* colonies.

No significant differences were found between colonies foraging on ***Phacelia*** or **floral mix.**

Key Findings:

In this specific case, the impact of azoxystrobin exposure on bumblebees depends on the forage plant they have access to.

Buckwheat, a low-protein pollen resource, reduced colony fitness but did not make them more susceptible to azoxystrobin exposure.

This may suggest that a high protein pollen content is generally beneficial for *B. terrestris* but does not increase fungicide detoxification or tolerance.

Impact of fungicide and floral resources on colonies

At the end of the experiment, colonies exposed to **Azoxystrobin** through **treated *Phacelia*** compared to untreated *Phacelia* had:

- **55% fewer** adult workers,
- **88% fewer** adult males, and
- a **14% reduced** body mass of adult workers.

No significant differences were observed in colonies exposed to **treated buckwheat** (vs untreated buckwheat) or the **treated floral mix** (vs untreated floral mix**).**

Source: Wintermantel, D., Pereira-Peixoto, M. H., Warth, N., Melcher, K., Faller, M., Feurer, J., ... & Klein, A. M. (2022). Flowering resources modulate the sensitivity of bumblebees to a common fungicide. *Science of The Total Environment*, *829*, 154450. https://doi.org/10.1016/j.scitotenv.2022.154450

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9. Appendix D

SIVITER Case Study

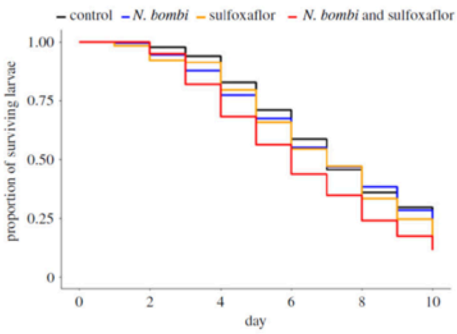
Individual and combined impacts of sulfoxaflor and *Nosema bombi* on bumblebee (*Bombus terrestris*) larval growth and mortality

Background: pesticides are an important stressor for bees. However they do not work in isolation and there is a need to understand the impact of their interactions with other stressors, such as parasites, on bees. Additionally, it also remains unclear as to which life-history stage is critically affected by exposure to stressors.

Question: is the impact of pesticide exposure increased by parasite load in bumblebee larvae?

Real world context: Field realistic exposure rates of both sulfoxaflor (5 ppb) and *N. bombi* spores (50,000) used in a lab experiment. Sulfoxaflor is a systemic insecticide and in this study was fed to bumblebees via a pollen and sucrose solution at the relevant concentration.

Larval mortality



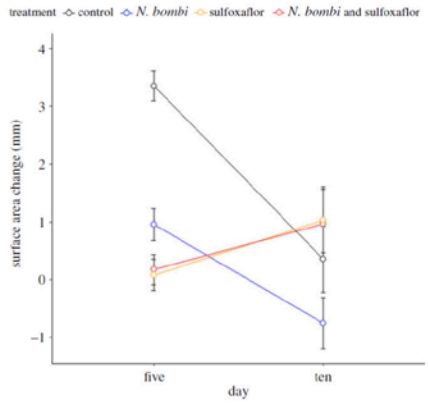
In **isolation**, sulfoxaflor (5 ppb) and *Nosema bombi* (50,000 spores) had **no significant impact** on **larval mortality**.

However, in **combination** there was an **additive, negative** effect on **larval mortality**. That is the smaller individual impacts of each stressor summed to produce a detectable negative impact.

% Surviving larvae (day 10)

Control: **30%**	*N. bombi*: **~28%**
Sulfoxaflor: **25%**	*N.bombi* & Sulfoxaflor: **~15%**

Larval growth



Day 5 surface area change = individual larval surface area day 5 minus surface area at the start of the experiment.

Day 10 surface area change = larval surface area day 10 minus surface area at day 5

In **isolation**, **both** sulfoxaflor (5 ppb) and *Nosema bombi* (50,000 spores) exposure **reduced** bumblebee **larval growth**.

In **combination,** there was also a significant **negative** impact on **larval growth**. However, their **interaction** was **antagonistic** i.e., their combined impact was not as great as the predicted sum of each stressor alone.

Larval growth change (from start of experiment to day 5)

Control: **3.4mm²**	*N. bombi*: **1mm²**
Sulfoxaflor: **0.1mm²**	*N.bombi* & Sulfoxaflor: **0.25mm²**

Larval growth change (from day 5 to day 10)

Control: **0.4mm²**	*N. bombi*: **- 0.7mm²**
Sulfoxaflor: **1.2mm²**	*N.bombi* & Sulfoxaflor: **1.1mm²**

Key Findings

In this specific study, impacts of the interactions between pesticides and pathogens vary depending on the survival or fitness consequence being tested (i.e. lethal effects versus sub-lethal effects). While additive impacts affecting survival are recorded, the individual effects of the stressors are greater than interactive impacts when it comes to physiological impact

Source: Siviter H, Folly AJ, Brown MJF, Leadbeater E. 2020 Individual and combined impacts of sulfoxaflor and *Nosema bombi* on bumblebee (*Bombus terrestris*) larval growth. Proc. R. Soc. B 287: 20200935. https://doi.org/10.1098/rspb.2020.0935

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