Opportunities and knowledge gaps for EU Research and Innovation on pollinators

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1. Background

On 10th of October 2022, REA Unit B.3 “Biodiversity, Circular Economy and Environment” together with the Horizon 2020 project “PoshBee”, organised a workshop of some key EU-funded projects on pollinators (defined as all wild and managed species that contribute to pollination services in the EU).

The objective was to promote dialogue, identify R&I needs and gaps, and define common messages and recommendations in order to contribute to bee and pollinator health, sustainable pollination services, and pollinator monitoring.

Representatives from a number of EU-funded projects (PoshBee, B-GOOD, Safeguard, Ecostack, SPRING, Orbit, Sting, Pulse, Showcase), as well as several EU Commission services (DG AGRI, DG ENV, DG SANTE and REA) took active part at the event. The full participant list can be found at the end of the document.

Participants were invited to identify current knowledge, best practices, and tool availability across 4 main questions that were addressed in parallel groups. The outcomes of the discussions are the object of this publication.

2. First question: “How can we integrate and optimise wild and managed pollinators into a sustainable service for agricultural systems? What can we do and what do we need to know?”

2.1. Preamble

Globally, more than three quarters of our most important crop species depend on insect pollination (IPBES). While there is a general increase in the demand for human food production, the demand for insect pollinated crops has increased disproportionately (Aizen et al. 2019). Hence, there is an urgent need to integrate and optimise the pollination service provided by both wild and managed pollinators.

2.2. Current state-of-the-art

2.2.1. Both wild and managed pollinator species are important for crop pollination

Wild pollinator diversity has been clearly shown to enhance crop pollination services by increasing yield quantity, quality and stability (Garibaldi et al., 2011, Garibaldi et al., 2013, Dainese et al., 2019, Senapathi et al., 2021) and can buffer the impact of stressors, including extreme weather events (Papanikolaou et al. 2017). This pollination service from wild insects is independent of that provided by managed pollinators, although their relative contributions vary with crop type and location (Garibaldi et al., 2013). Managed pollinators include a range of insect species, although the Western honey bee (*Apis mellifera*) (hereafter ‘honey bees’) is by far the most commonly used species (Osterman et al. 2021). Honey bees remain important for pollination of many crops globally in addition to pollination by wild pollinators (a group to which honey bees also belong in their native range). Indeed, pollination of many crops in most parts of the world benefits from pollination by A. *mellifera* (Klein et al. 2007, Rader et al. 2009). Both wild and managed pollinators are under pressure, due to loss of habitat (in particular loss of floral resources), extensive use of pesticides, and diseases, especially in farmland (IPBES 2016). Furthermore, a concern has been raised that honey bees may negatively impact wild pollinators through resource competition and pathogen spill-over (Mallinger et al. 2017). Sustainable solutions for healthy beekeeping, particularly concerning disease management, such as of *Varroa destructor,* are also needed to support healthy honey bee populations, in addition to limit virus spill over to non-managed bees (Fürst et al. 2014; Piot et al 2022).

2.2.2. Different species of pollinators need different resources

It is well established that pollinators need different resources during their entire life-cycle, including nesting sites, floral resources and over-wintering sites. In addition, pollinators with different life history traits, e.g. sociality, nesting habitats, seasonal activity peaks and habitat/food preferences, differ considerably in their requirements for habitats and resources. Consequently, increasing the area of (semi-)natural habitats and overall habitat diversity at the landscape scale has the potential to increase the abundance, richness and resilience of pollinators (Papanikolaou et al. 2017, Boetzl et al. 2022, Ganuza et al. 2022).

2.2.3. Agri-environmental schemes may support pollinators, but effects are context dependent and may vary among species

Beneficial effects of some management options on pollinators and their services, e.g. flower strips, have been established (Rundlöf et al. 2018, Albrecht et al. 2020), but depend on the environmental context (Scheper et al. 2013, Boetzl et al. 2021). Other beneficial management actions, e.g. low-input, organic or diversified cropping systems, have been identified (Lichtenberg et al. 2017), but their effects can vary across scales (Couthouis et al. 2023). However, systematic cross-taxa, cross-scale and long-term studies on measures to optimise pollination services and pollinator diversity are currently missing. Under some circumstances, wild pollinators may suffer from competition with managed pollinators, particularly honey bees (Mallinger et al. 2017, Valido et al. 2019, Rasmussen et al. 2021). Agri-environmental schemes for increasing floral resources often benefit both wild and managed pollinators and practises to avoid or minimise competition between managed and wild pollinators are needed.

2.2.4. Multi-species systems are naturally resilient to environmental change, but may be prone to cascading effects

The structure of natural plant-pollinator networks can buffer the impacts of environmental change to some extent (Rohr et al. 2014). However, major environmental changes can cause cascading effects of coupled co-extinctions (Hegland et al. 2009, Schleuning et al. 2016). In particular, our predictive abilities for changing interactions and network structures under novel conditions and communities are limited (but see e.g. Valido et al. 2019, Pichler et al. 2020, Sydenham et al. 2022 a,b).

2.3. What can currently be achieved?

Current actionable knowledge can be translated into effective management practices

Basic knowledge about most requirements of some pollinator species' is available, and in these cases limitations in pollinator conservation are related to the lack of implementation of this knowledge. Adopting a multi-actor approach, involving multiple local stakeholders, farmers, NGOs, municipalities, and inhabitants, in addition to policy makers, would help ensure actionable knowledge is translated into effective management practices, enabled by stimulating political incentives and considering the socio-economic context within a full value-chain.

Closing current knowledge gaps can be achieved

Basic Ongoing EU projects on pollinators and pollination are targeted at improving knowledge to promote both managed and wild pollinators, and remaining knowledge gaps should be prioritised.

Scale-specific conservation and restoration interventions are possible

Evidence suggests the focus should be on the landscape-level, as most pollinators forage over large spatial scales (100s of m to several kms). Specific requirements of pollinators should therefore be provided at the landscape scale (not field scale only).

Green infrastructure provides option space

All aspects of green infrastructure, i.e. not only surroundings of the fields, but also, e.g. verges of transport or electrical infrastructure, natural habitats, and diversified cropping systems can be managed to improve pollinator status.

Networks of connected habitats can facilitate pollinators

Maintenance and creation of well-connected networks of semi-natural habitats and other (semi-)permanent habitat structures in agricultural landscapes can improve the stability of pollinator populations.

Agri-environment and eco-schemes, implemented in the right context, can improve pollinator populations and communities

For beneficial and sustainable effects on pollinators and pollination, agri-environment and eco-schemes should be properly designed, e.g. by combining measures that provide complementary resources, i.e. by improving the amount, diversity and temporal continuity of nectar, pollen and reproductive resources, and by reducing the impacts of other stressors, such as pesticides, intensive mowing, soil disturbance, or mismanagement of hedgerows.

2.4. Key R&I gaps to address

2.4.1. Research and Innovation

A systems-approach for optimising conditions for pollinators is needed, including regional-, landscape-, and farm-level, and long-term (decades) planning

A holistic approach considering multiple habitats in parallel (field, semi-natural and protected areas), over a longer time perspective, including temporal turnover, and understanding inter-dependencies of mitigation options and environmental contexts is needed. The sustainability of both agricultural and 'semi-natural' areas, and high quality of protected areas, as well as the functional redundancy and resilience of systems, in the long-term (across multiple years) and at landscape level (within regional contexts) needs to be assessed. The efficacy of long-term interventions, including interactive effects of climate and land use, needs to be assessed.

Conservation status and ecological knowledge gaps need to be filled, particularly for non-bee pollinators

The threat status of some taxonomic groups of pollinators is well known (in particular for butterflies), while, e.g., for wild bees, a high proportion (~56%) of species are data deficient in the European Red List, incl. wild Apis mellifera. In general, we have limited knowledge on the ecology of rare and endangered species. Similarly, our knowledge about the ecology, distributions and population trends of both bee and many non-bee pollinators, and in particular about their relevance as pollinators of crops and wild plants, is extremely limited. Large-scale standardised and enhanced monitoring of both bee and non-bee pollinators is urgently required.

Prediction abilities need to be improved

Predictive abilities in terms of assessing both the impacts of changing environmental conditions and the effects of mitigation actions need to be improved. There is also an urgent need to improve our ability to predict changes in plant-pollinator interactions, and respective network structures, under changing and novel environmental conditions and communities to assess and mitigate their impacts on the robustness and long-term sustainability of pollination services for crop and wild plants. Furthermore, knowledge should be improved around the population dynamics, genetic diversity and gene flow of wild pollinator species and the genetic origin of locally produced managed pollinators, such as Bombus terrestris, if they are to be properly included in predictive models.

Finally, there is a clear need to improve knowledge about the impacts of interventions, including diversified cropping systems and future farming systems and their interactions with other management practices, on pollinators.

2.4.2. Implementation

A coherent policy framework for agri-ecological transition is needed

Currently, there is room for improvements in policy frameworks, in particular through greater cross-sectoral coherence in legislation and policy, e.g., across environment and agriculture. In addition, “full-cost” accounting including societal costs and benefits of land use practices of both public and private goods/services are required. In terms of coherence, one transition, including climate, agriculture, conservation, etc. should be promoted. Better knowledge exchange, co-development and promotion of pollinators in collaboration with farmers and other actors, as well as improved information flows and advice about refunding sources and pathways to farmers is needed. As the main steering instruments, Common Agricultural Policy and pesticide legislative frameworks need to include obligations towards the protection of wild pollinators.

Large-scale demonstration regions are required

Large-scale demonstration regions and farmer communities to promote the implementation of conservation interventions and to foster peer-peer knowledge transfer should be created. To this aim, full co-design and co-creation from the individual farm level to the larger-scale communities should be considered and full use of synergies should be made by combining different agri-environment schemes and conservation and restoration interventions across scales covering both crop fields and (semi-)natural areas.

2.5. Summary

Human food security is highly dependent on insect-pollinated crops and global demands are constantly increasing. Both managed and wild pollinators contribute independently to crop pollination but they are threatened by multiple anthropogenic drivers and environmental pressures. Adequate and effective conservation and restoration actions to mitigate the impacts of those drivers and even reverse the currently observed pollinator declines need to consider species-specific requirements for habitats and resources, and context- and scale-dependencies of interventions, e.g. within agri-environmental schemes. Although the current actionable knowledge can in principle be translated into effective management practices, considerable knowledge gaps remain to be addressed, such as:

i) Limited knowledge on the effects of interventions from a systems perspective, covering multiple habitats and landscapes, multiple spatial scales, synergistic effects across larger scales, long-term efficiency, and impact on pollinator community resilience;

ii) Insufficient knowledge of the ecology and conservation status of rare and non-bee pollinators;

iii) Limited predictive abilities, in particular for the impacts of environmental change or restoration actions on the functional structure of plant-pollinator networks;

iv) Lack of a coherent cross-sectoral policy framework;

v) Lack of large-scale demonstration regions and farmer communities to promote the implementation of conservation interventions.

3. Second question: "What proportion of wild pollinators, particularly bees, can utilise/survive in European agricultural landscapes?"

3.1. Preamble

Wild pollinators play an important role in crop and wildflower pollination, yet the European agricultural environment is largely hostile to wild pollinators, and wild bee species in particular. Though hard evidence is scant, we draw some broad generalities about the unsuitability of modern European agriculture for wild pollinators, derived from recent literature and expert opinion. We then highlight critical gaps in knowledge which, when addressed, will provide the database to support the restoration of wild pollinators in European agricultural landscapes.

3.2. Current state-of-the-art

An estimated 0-50% of European bee species can utilise agricultural landscapes; for hoverflies and butterflies this percentage is probably lower

These broad estimates are based on expert judgement by those writing this section of the report because a quantitative underpinning is lacking. For instance, national distribution data show that, in the Netherlands, 13% of the bee species and 3% of the hoverfly species are being observed more frequently than expected by chance in intensively cultivated agricultural landscapes (Ozinga et al., 2018). Yet, few data are available in other parts of Europe. The actual proportion of bee species that can use agricultural landscapes strongly depends on context, particularly semi-natural habitat cover, the intensity of farming and the bio-geographic location within Europe.

Landscape context largely determines the number of pollinator species that use and/or survive in agricultural landscapes

Most wild pollinators cannot complete their life cycle on cropland and depend to a large extent on semi-natural habitats for food, nesting sites, larval habitats and shelter. Pollinator richness and abundance in these semi-natural habitats seem to be largely determined by the flower availability independently of the intensity of nearby farming (Li et al., 2020) and is furthermore unrelated to the diversity of insect pollinated crops (Martinez-Nunez et al., 2022). This means that the number of bee and hoverfly species that can use agricultural landscapes results, at least in part, from the cover and quality of semi-natural habitat in these landscapes (Fijen et al., 2019).

Many agricultural landscapes may be unsuitable for reproduction but are annually colonised by pollinators from distant source habitats

It is well known that some hover flies and butterflies can disperse over large distances (Baguette, 2003; Ovaskainen et al., 2008; Wotton et al., 2019). A recent paper suggests that the same probably holds for nest site dispersal in bumblebees (Fijen, 2021). This implies that the occurrence of pollinators in agricultural landscapes is no proof that the landscape is suitable for a species to complete its life cycle.

Spring-flying pollinator species are better adapted to agricultural landscapes than summer-flying species

The availability of floral resources in agricultural landscapes is often much higher in spring than in the rest of the growing season (Scheper et al., 2014; Timberlake et al., 2019). This is partly due to the fact that most insect-pollinated crops (fruit trees, oilseed rape) and woody species occurring in woodlots and hedgerows generally flower in spring and that most agricultural grasslands have not yet been cut or grazed. This may result in it being easier for spring-flying wild bee species to reproduce than for summer-flying species.

3.3. Key R&I gaps to address

We have poor knowledge of the fine-scale distribution and abundance of wild pollinator species in many locations, particularly in agricultural landscapes

In large parts of Europe, especially in the South and East, we lack basic data on pollinators: where and at what densities do pollinator species occur? For most Mediterranean countries, even basic tools such as species identification guides are missing, making it unlikely that such data will be collected in the near future without considerable investment. In all countries, agricultural landscapes are under-sampled because they are generally species-poor and therefore less attractive to citizen scientists that do most of the survey work; however, some schemes are addressing this under-representation (e.g. eBMS).

Where do species reproduce and how successful is this in agricultural landscapes?

Identification of nesting or other reproduction sites of pollinators is difficult (Potts et al., 2005). For the dominant bee species, we do not really know how nesting site availability is affected by agricultural management and for many non-dominant species we do not even know where they nest or reproduce. Key questions therefore are: how many pollinator species actually nest and/or reproduce in agricultural landscapes? Where do they do this? How successful is this, and how does this all depend on landscape context? A complementary question is: how many species colonise agricultural landscapes each year from outside habitats but fail to maintain viable populations?

Population genomics/genetics of wild pollinators is too poorly known: key questions include - what is their effective population size? are there cryptic species? What is the efficacy of conservation measures?

Genetic diversity is a key component of pollinator biodiversity and fitness (Maebe et al., 2013; Tarpy, 2003). Yet studies examining population genetics in pollinators are strongly biased towards managed species (Cejas et al., 2021; Soper et al., 2021). We still know very little about genetic diversity in wild pollinator species, how this is affected by agricultural practices, land use change, fragmentation and climate change and what reduced genetic diversity means for local adaptation and minimum viable population sizes (Hart et al., 2022). Moreover we know very little about the genetic consequences of the potentially high dispersal capacities of bees. For example, a species' ability to recolonise a restored habitat should be a key element of conservation strategies. Finally, monitoring without genetic information has only limited explanatory power, especially for r-strategist and eusocial species, e.g. bumblebees, in which the number of foragers is almost completely meaningless with respect to population size. This calls for greater attention to the population genetics and genomics of wild bee species (Webster et al., 2023).

How can we accurately characterise the quality of landscapes or individual habitats for pollinators?

In agricultural landscapes, semi-natural habitats determine the carrying capacity of the landscape for pollinators (Fijen et al., 2019; Li et al., 2020). Semi-natural habitat cover is often used to predict abundance and species-richness of pollinators, but habitats can vary widely in quality and therefore their use by pollinators (Cole et al., 2017). Including an estimate of habitat quality would greatly improve the accuracy of predictions of what proportion of pollinators could exist in agricultural landscapes. For bees, models are available that predict bee abundance in agricultural landscapes but these still need improvement with respect to effectively scoring nesting site availability and floral attractiveness of habitats (Gardner et al. 2020). Currently, we have no efficient, standardised method to assess habitat quality for pollinators.

What proportion of wild pollinators is exposed to unacceptable levels of pesticides in agricultural landscapes?

Many crop species are well-visited by pollinators (Kleijn et al., 2015) and these are therefore potentially exposed to pesticides (insecticides, fungicides and herbicides). What are acceptable effects on wild pollinators in general of pesticides used in agricultural landscapes? Wild bees vary in pesticide sensitivity from honey bees (Sgolastra et al. 2018; Linquadoca et al. 2022), but most toxicity tests use honey bees or, more recently, Bombus terrestris or Osmia bicornis and only focus on short term effects, omitting fitness as the key parameter for any wild population, as well as the longer-term, cumulative and interactive effects (Straub et al. 2020). It is unclear whether the results of such tests are representative for wild pollinators in general. There is great need for new procedures to select representative model species for experimental studies in the laboratory and in the field, and to assess long-term effects at the population level.

3.4. Summary

European agriculture is hostile to most wild pollinators, especially wild bee species, and the presence of wild pollinators in fields is largely dependent on surrounding semi-natural flower-rich habitats, namely the dispersal of wild pollinators from non-agricultural to agricultural habitats. Temporal and spatial heterogeneity exists across Europe in the suitability of its agricultural landscapes to wild pollinators, with spring-flying wild bee species and those in Mediterranean regions likely impacted less by agriculture than other EU biogeographic regions. But huge knowledge gaps exist that hinder the design of appropriate management to support wild pollinators, including:

i) lack of identification keys, lack of taxonomic expertise for identification, and lack of sampling in agricultural sites across the EU; all of which will allow better characterisation of the extent of the problem that current agriculture poses to wild pollinators;

ii) lack of studies on the source of wild bee species found in agricultural sites and quantifying their reproductive success when breeding under current agricultural practices - under-utilised genetic/genomic tools could provide important leverage in this area;

iii) lack of tested criteria to enable quantification of the suitability of non-agricultural habitats to support wild pollinator species - this would enable design of region-aware management practices to promote wild pollinator species.

4. Third question: “New and developing tools for monitoring pollinator health and drivers of bee health? What do we have and what is missing?”

4.1. Preamble

Pollinator health has been a key research area for many years. In recent times, bee populations were assessed and followed by new technologies such as automated tools. These tools generate huge data sets, creating a need for bioinformatics and development of pipelines enabling the analysis of these data. Given this, and the amount, complexity and scope of the data needed to assess the health of the huge diversity of pollinators in Europe, more should be invested in the harmonisation of the existing data format, the connection between different data sets (holistic data, GPS, climate,...), statistics of big data sets and artificial intelligence. This general remark applies to data collected by the tools we present in the first part of this section. Key research areas are subsequently identified and listed in order to fill current gaps of knowledge.

4.2. Current state-of-the-art - pollinator health

Very few tools are available for wild pollinators

There is a distinction between the tools for monitoring the health of managed honeybees and those of other wild pollinators. While the list would be almost encyclopaedic for managed honeybees, it is rather modest for wild pollinators. Estimating the health of wild pollinators on a holistic scale is a real challenge. There are some tools available - often developed in the context of honeybees like disease diagnosis and pesticide identification - but these are rather limited. Estimating the resilience and robustness of the ecosystem could provide a good indirect estimate of health here.

Many tools are available to assess honeybee health

The EFSA HEALTHY-B report (EFSA 2016) brings together most of the honeybee health monitoring tools available at the time of publication (several tens are listed in the document). In short, these tools mainly rely on monitoring of colony mortality, visual inspection of colonies, disease diagnosis and pesticide identification.

4.3. Tools in development – pollinator health

Research projects funded by the European Commission have resulted in challenging and innovative tools for managed honeybees and some wild pollinators.

Outputs from the PoshBee project

In PoshBee, a method has been developed to identify and monitor health markers in bee haemolymph. This method utilises two distinct mass spectrometry approaches. MALDI mass spectrometry (MALDI BeeTyping®) to follow bee health through molecular mass fingerprints and off-gel bottom-up proteomics to identify markers of health dysregulation. On-site tools are in development for two markers (colorimetric and enzymatic tests).

A tool for measuring pesticide exposure in honeybee hives has also been developed, named APISH for Atmospheric Passive Integrated Sampler in Hive, which enables the identification and quantification of some pesticides present in the hive air.

Tools developed in the B-GOOD project

In B-GOOD, remote sensing to monitor temperature, weight and sound in the hive further exploits the concept of precision beekeeping with the final objective being the assessment of the health status index. Accelerometers for measuring pulsed vibrations or gas sensors for CO2 detection are new innovative tools being developed. Estimating pollen and nectar availability is predicted based on dynamic landscapes. A mathematical model of a bee colony (ApisRAM) is placed in this virtual environment, which will soon form the basis for risk assessment for pesticides (Duan et al., 2022).

Finally, Lateral Flow Devices for rapid detection of pesticides have also been developed in different matrices (Capela et al., 2022).

Pesticide detection with APIStrip

The APIStrip (Absorbing Pesticides In-hive Strips), a plastic strip with a pollutant adsorbent for non-invasive sampling of environmental contamination based on in-hive sampling, emerged from the Insignia-EU project (Murcia-Morales 2020).

4.4. Key R&I gaps to address for monitoring pollinator health

Further developing powerful tools to monitor pollinators

There is huge potential to assess pollinator diversity through environmental DNA (eDNA), for example to capture pollinator footprints on petals of plants in bloom. In this context, a search could also be made for characteristic hydrocarbons. There are studies indicating species-specific sounds or vibrations generated by wings during the flight. Some species also have a distinctive flight pattern. All this may potentially enable us to harmlessly determine species richness in a biotope, based solely on sound/vibration or image recordings. The discussion group expressed its concern about some current practices, whereby monitoring the richness of pollinators often also harms the populations (using pantraps or Malaise tents which kill insects) and therefore recommends a move towards non-lethal sampling methods as described above, in combination with current non-lethal transect walk approaches. Although this opinion may not be a consensus in the scientific community, it is important to direct research towards non-destructive methods.

How can we accurately evaluate pollinator genetic diversity?

In the face of global warming, pollinator genetic diversity will become a critical aspect of resilience. There is a need for population genetic studies, but suitable genetic markers are often lacking. In order to find these, we should be able to utilise and, where necessary, initiate genome sequencing projects on a large scale so that the reference genomes are available for a wide range of pollinator species.

How can we measure pollinator health?

As stated previously, some tools with high potential are currently being developed to monitor pollinator health. However, more research should be done to increase their operability. Given the importance of haemolymph samples for monitoring the health status of pollinators, finding harmless haemolymph sampling methods is urgent. The possibilities of pulsating vibrations to monitor the health and/or development of honey bee colonies also need to be further explored.

Optimise collaborations with citizens to increase the power of science

We should maximise opportunities to involve more citizen scientists in data collection through user-friendly identification tools (e.g. phone apps). Further, the range of model organisms should also be expanded, thereby allowing for further broadening of pollinator research (e.g. including r-strategists such as hoverflies and moths).

Taxonomists are a rare species

The scientific community is facing a dire shortage of taxonomists. Taxonomic knowledge is already a limiting factor for research on pollinators. Action should be taken to support and encourage future generations of taxonomists as a long-term goal. The establishment of a (semi-)permanent European Pollinator Research Center should be seriously considered. In addition, further tools for training in taxonomy and long term monitoring should also be offered building upon ORBIT, SPRING, Taxo-Fly and EU PoMS. Software for image analysis is needed so that the users can better identify the species of any given pollinator from a photo. For the wild pollinators, the ORBIT project works on taxonomy with keys for identification, fact sheets with information on biology, distribution and monitoring. The SPRING project has started training and data collection on pollinator abundance in 12 countries.

Long-term actions are the key to success

Finally, the discussion group would like to point out that the European Commission's research projects are often challenging and innovative, but that their limited duration (e.g. usually 3-5 years) sometimes hinders the full realisation of the ambitions. Specific programs enabling further, integrated analyses, once large datasets are produced, should be supported. This will add significant value by bringing together currently fragmented databases to produce comprehensive conclusions.

4.5. Summary

Tools to monitor honeybee heath are available for the different stakeholders. At the moment, remote sensors are developed to even better understand honeybee colony biology and health. This is not the case for wild pollinators that are numerous with a wide range of ecological and biological specificities. The most important gaps of knowledge are listed below

i) lack of powerful tools to monitor pollinators. In this sense environmental DNA is a promising tool to capture pollinator footprints. Other non-destructive ways for assessing wild pollinators should be further developed, tested in the field and implemented in national and european schemes.

ii) lack of trained taxonomists. To identify thousands of wild pollinator species, there is a need for specialised scientists. Taxonomy in particular needs a long training. Therefore, efforts should be done at European level to promote this area of work.

iii) lack of long-lasting actions. Once large datasets are produced through large-scale studies on pollinators, there is a need to comprehensively study the results to extract as much scientific information as possible. Pollinator genetic diversity will become a critical aspect of resilience. To reach the appropriate level of knowledge in this area, long lasting studies are needed to finally conduct population genetic studies.

5. Fourth question: “What is not known about pollination services in agricultural and semi-natural/natural ecosystems? How do we find out?”

5.1. Preamble

Knowledge on status and trends of pollinators is variable across taxa and Member States, with relatively good data for some taxa such as butterflies, hoverflies and bees, and less data for other groups such as moths (IUCN Red Lists). However, our understanding of the status and trends of the pollination services they provide is very incomplete (IPBES 2016). There are a number of initiatives and schemes ongoing or planned which will help address outstanding gaps for pollinators but almost nothing focussing on pollination itself. Robust high-quality data on pollination services is essential to meet the requirements of policies and management practices to restore healthy ecosystems, maintain wider biodiversity and ensure food and nutritional security (e.g., Biodiversity Strategy 2030, CAP Strategic Plans, Nature Restoration Law, IUCN Red Lists[1]).

5.2. What are the key open questions in terms of understanding pollination services in agricultural and semi-natural/natural ecosystems in Europe?

We have identified four priority key open questions (Q1 to Q4).

Q1. What are the key pollinators of wild flowers and crops, and what is the status and trends of these pollinators and associated provision of pollination services?

We have good evidence on what the main pollinators are for a small number of economically important crops (e.g., apple, oilseed rape, strawberries) and some wild flowers in both agricultural and semi-natural/natural habitats (e.g., Ollerton et al. 2011, Kleijn et al. 2015, Allen-Perkins et al. 2022). However, to target policy and practice actions to enable adequate crop pollination and ensure effective wild flower and habitat

[1] See References

conservation, we need to know the relative contribution of different species and communities of pollinators in different contexts. Of critical importance is to understand how the identity of pollinator communities, and their interactions with plants and pollination efficiency, differ with crop and wild flower species/variety, farm type, habitat, biogeography, member states (MS), and through time (season, years); current evidence suggests these vary greatly (IPBES 2016).

We also need to understand the status and trends of pollination services themselves. There are complex negative feedback loops between animals and the plants they pollinate (Hadley & Betts 2012), with pollinator declines being linked with parallel declines in wild plants (Biesmeijer et al. 2006). It is critical to know how widespread, and to what extent, there are pollination deficits (i.e., shortfalls in pollination services) in different crops and wild flowers. This is currently well understood for a very limited number of crops, e.g., apples (Garratt et al. 2021), and wild flowers (Knight et al. 2005), and so needs assessing much more widely to allow an understanding of how services and deficits vary across species/varieties, habitats, farm types, MS and years. We need to know which crops and wild plants are most vulnerable to loss of pollination services, so that management and conservation practices can be effectively targeted to reduce deficits (see Q4). In particular, how do pollination limitations affect the reproductive success and population maintenance of wild flowers, and how does this in turn impact pollinator populations.

Q2. What are the full range of benefits and values from pollination services?

While the contribution of pollination, by a range of pollinators, to crop yield and quality is known for some crops (e.g., apple, Garratt et al. 2021) there remain many gaps, especially relating to how deficits impact crop yield, quality, nutritional value and shelf-life. Further, the flow of economic and nutritional benefits from pollination services to other actors within food systems, such as growers, suppliers, processors, retailers and consumers is almost entirely unknown. This gap limits our ability to understand where pollinator losses or enhancements would have the greatest total benefit, both within the EU and across global supply chains, which are critical for European food security (Murphy et al. 2022).

Beyond food and nutritional values of pollination, there is a need to better understand the medicinal, socio-cultural, symbolic, biocultural, aesthetic and other supporting and regulating ecosystem service values derived from pollinator-dependent plants. Wild flowers provide critical support for wider biodiversity through the provision of forage and shelter for other insects, birds, and mammals (Pocock et al. 2012). However, these linkages remain unquantified, as does a system understanding of how pollination losses affect wider ecosystem health and other ecosystem services.

Q3. What drives pollination service provision?

While general principles of how the abundance and diversity of pollinator communities drives the delivery of pollination services are known, the scale and context dependence of this relationship, and how it relates to crop yield/quality and wild flower reproductive success remains an open question. For a few case studies, pollination (as an agricultural input) interacts with other inputs (e.g., fertilisers) (Tamburini et al. 2019). However, there is a critical need to understand more broadly how pollination interacts with other inputs and management practices as part of sustainable agricultural systems where all inputs are optimised.

There is a substantial body of evidence, about the effects of individual and multiple stressors on pollinators (Potts et al. 2016) but relatively little knowledge on how this translates into the provision of pollination services. In particular, how will pollination delivery be impacted by stressors in the short-term (e.g., by extreme weather, land management, consumer demand) and in the long-term (e.g., through land use and climate change, and policy shifts). It will be important to understand how pollination deficits are projected to respond under environmental and societal change and how this will impact food security and wider biodiversity conservation.

Q4. How do we build resilient landscapes for sustainable pollination services?

It is well established that pollinators are under threat, and likely that pollination services are too (Potts et al. 2016). Building upon the knowledge needs of Q1 to Q3, it will be essential to understand what agricultural and semi-natural habitat combinations, including their management and configuration, are needed. This is crucial to ensure that landscapes can deliver sustainable pollination services that are resilient to future pressures in demand, climate and available agricultural resources, while contributing to plant and pollinator conservation (Martin et al. 2019). Building these landscapes will require a multi-actor approach to identify, support, educate and motivate relevant actors, including not only farmers, but also the wider agri-food sector (many of whom directly benefit from pollination, Q2), local and national policy support, conservation managers and citizens.

5.3. How do we find out?

Based on the four key open questions (Q1 to Q4) above, we have identified four broad recommendations (R1-R4) to address these.

R1. Develop new modules to monitor pollination services as part of EU PoMS

EU PoMS will deliver high quality species abundance and distribution data for a variety of pollinators, however this needs linking to knowledge of the roles of different species in wild flower and crop pollination. Therefore, EU PoMS should develop modules, standardised methods and indicators to: (i) monitor wild flower and crop visitation; and, (ii) directly measure pollination services/deficits to key crops and wild flowers. This could be done in conjunction with approaches to identify pollen from pollinators through conventional and DNA barcoding approaches (e.g., building on INSIGNIA).

R2. Establish a centralised knowledge hub and database on pollination

EU PoMS, in conjunction with multiple projects and initiatives, are/will be generating valuable information on wild flower and crop pollinators, and pollination services and deficits. This needs bringing together and making openly available to governments, researchers, conservation NGOs and agri-food actors. Ongoing funding to allow the analysis of these combined databases will allow for broad trends to be assessed and highlight critical data/knowledge gaps to target new data collection/analysis (R3) and inform policy (R4).

R3. Fund targeted R&I projects to fill outstanding gaps in our knowledge of pollination

- Understanding pollination services across Europe. A targeted and large-scale field campaign to identify key pollinators of crops, wild flowers, priority habitats, and in MS where significant gaps exist. It should rapidly assess the pollinator dependency of most vulnerable wild plants (e.g., Red Listed) and economically/nutritionally important crops across MS and habitats. This should be integrated with EU PoMS through shared sites as far as possible.
- Wider values of pollination. Bring together, analyse and build upon the currently fragmented data on plant-pollinator and wider ecological networks to understand the relationships between plants, pollinators and wider biodiversity and ecosystem stability; gaps in data would be addressed through targeted fieldwork. Complementing this with trans-disciplinary approaches to value the wider socio-cultural services associated with pollinators and pollinator-dependent plants/habitats/landscapes.
- Multiple pressures on pollination. Requires a large-scale, long-term, network of landscapes to assess the impacts of multiple interacting stressors on pollinators,

pollination and benefits. This would be tightly coordinated with EU PoMS, EMBAL, LUCAS, and also act as a testbed for a range of mitigation options (e.g., habitat restoration, managing honeybees). Data from this network would be used in conjunction with existing models (e.g., JRC MAES, INVEST, and Poll4Pop) to improve them and create multi-scale maps of current and projected pollination services/deficits for wild flowering plants in semi-natural habitats as well as crops.

- Mitigation impacts of pollination service risks. This would establish/strengthen/empower multi-actor networks to design, implement and evaluate landscapes for sustainable pollination services. Training, education and knowledge exchange activities would inform, train and motivate farmers and land users to manage landscapes for both pollinators and pollination. Modelling and fieldwork would be used to 'design pollination systems' for managed and wild species in different agroecosystems to ensure long-term stable pollination delivery.

R4. Strengthen policies to support the restoration of pollination services in addition to protecting pollinators

To facilitate the building of sustainable pollination services across MS it will be critical to support R1 to R3 through enabling policies. Soft policies, such as EU PI, and hard policies, such as CAP strategic plans, Nature Restoration Law, and Biodiversity Strategy 2030, should all have elements to support public goods and services linked to pollination.

5.4. Summary of knowledge gaps and recommendations

We have identified four broad priority areas where key knowledge is lacking: Q1 What are the key pollinators of wild flowers and crops, and what is the status and trends of these pollinators and associated provision of pollination services? Q2 What are the full range of benefits and values provided by pollination services? Q3 What drives pollination service provision? and Q4 How do we build resilient landscapes for sustainable pollination services? These are consistent with the DPSIR framework covering State (Q1), Impact (Q2), Drivers/Pressures (Q3) and Responses (Q4). Based on the four knowledge gaps we have identified a package of four recommendations to address them: R1 Develop new modules to monitor pollination services as part of EU PoMS; R2 Establish a centralised knowledge hub and database on pollination; R3 Fund targeted R&I projects to fill outstanding gaps in our primary knowledge of pollination of both wild plants and crops; and, R4 Strengthen policies to support the restoration of pollination services in addition to protecting pollinators.

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