A handbook of the current knowledge on and approaches to valuing pollination

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Safeguard
Safeguarding European wild pollinators

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1 Summary

Global biodiversity is under significant pressure from human activities, threatening to destabilise ecosystems and the benefits they provide to human society. In response to this, there has been growing international recognition of the need to incorporate the importance of biodiversity to human societies and wider planetary health into decision-making in order to avoid further declines and support the restoration of ecosystems. Animal pollination is crucial to the reproduction of most flowering plants, including the majority of global crop species, making it a vital component of the stability of many ecosystems and human activities. Several past reviews have outlined the methods to value pollination through a mostly economic and utilitarian lens (e.g. Hanley et al., 2015; IPBES, 2016) but it is widely recognised that other forms of value associated with pollinators and pollination must be considered too in order to achieve effective biodiversity conservation and transformative change.

This handbook is designed to provide an accessible overview of methods which can be used to explore different dimensions of value associated with pollinators. We focus on the methods that have recently been applied to valuing pollinators or pollination rather than all possible methods, and users are encouraged to look for opportunities to expand other suitable methods (e.g. Value chain analyses, Q-methodology, Discourse analysis) to address pollinator related issues. Many, but not all, of these methods concern utilitarian (the value of pollination based on its usefulness) or anthropocentric values (the value of pollinators and pollination for humans). We aim to support users of this handbook in identifying which valuation methods to consider when wanting to assess different dimensions of value and highlight relevant key literature. We categorise these values into four groups (Ecological, Economic, Nutritional, and Socio-cultural) based on the respective disciplines through which values are examined. For each method we also link with the framework presented in the IPBES Values assessment (IPBES, 2022) and, where applicable, identify the areas of the policy cycle where it is most useful.

For each method we explain: 1) what it measures, 2) broadly how it works, 3) what data is required and how this can be acquired, with links to common databases where appropriate, 4) the strengths and weaknesses of the method as a means to assess values and 5) key sources using or further unfolding the method. Each section is written as a stand-alone piece of text, although it may reference other methods.

2 Key terms

Although every effort has been made to keep the language in this handbook accessible, there are some terms that readers may encounter that have specific meanings. We summarise them here.

Actors: In economics, actors are any individual entity that engages in economic activity. This can range from an individual to collective organizations such as businesses, co-operatives, communities or a government. If looking beyond a human-only world view, other species, landscapes or technologies can be regarded as actors too, particularly in the context of ecological and socio-cultural values.

Capital: Capital represents an asset that can underpin economic activities. There are generally considered to be five forms of capital:

- Human capital: representing the skills and labour of people who work to produce economic activity
- Social capital: representing institutions and communities that support and drive economic activity

- Manufactured capital: representing human-made products, such as tools and processed materials, which are used to underpin economic activities
- Financial capital: representing available money to underpin economic activity (e.g. money to pay wages, buy machinery, support research)
- Natural capital: representing the natural assets and resources that are drawn upon to drive economic activities.

From an economic perspective, wild animal pollinators are a form of Natural capital as they are a naturally occurring resource that can potentially support economic activity by increasing crop output or supporting the availability of other economically valuable plants and habitats. Pollinator natural capital is more specifically defined by Breeze et al., (2016) as "the biophysical stocks of potential pollinators available within the surrounding landscape". This definition captures all pollinators of all plants that can be economically valuable.

Managed pollinators are a form of Manufactured capital as they are specifically bred or managed by humans for use in pollination activities. Other capitals may be relevant to the economic benefits of pollinators but do not contribute to pollination services – for example managed pollinators require the Human capital of beekeepers in order to provide pollination services outside of a given location.

Economic benefits and values: Economics often draws a distinction between benefits and values. Benefits are positive impacts of biodiversity, Values are how important those benefits are to the economic welfare of actors; something may be more or less valuable to an actor than the price it is sold for. For example, increasing the volume of a crop, which can result in greater profits and lower consumer prices respectively.

Marginal values: The term "marginal value" is often used to denote a proportionate change in a factor (e.g. a 10% decline in pollination services), as opposed to the absolute presence or absence of the factor (e.g. pollination vs no pollination).

Price: Price is the quantitative monetary value at which a product is exchanged on a market. Price is different from economic value or benefits.

Specific values: The valuation methods in this handbook relate to one or more of three types of specific value which are widely cited within the literature and advocated by the IPBES Values assessment (IPBES, 2022):

- Instrumental values: Those values that relate to the usefulness of biodiversity to human activity and wellbeing (often called an ecosystem service) e.g. the increase in crop production from pollination.
- Relational Values Those values that capture how humans relate to nature e.g. the symbolic value of certain pollinators to people.
- Intrinsic values: Those values which are independent of humans as valuers e.g. the value of pollinator existence for their own sake and the pollination functions provided to wild plant communities.

3 Ecological values

Ecological values reflect the importance of pollinators in their own right, as part of nature (i.e. their influence on the ecosystems they are part of), as transporters of pollen, and more broadly as part of food webs and ecosystems. Capturing ecological value in quantitative, biophysical terms, is crucial to identify the importance of pollinators to the structure and function of ecosystems and ecological networks within a given area. To date, however, few studies have contextualised the roles of pollinators as "ecological values" (but see Fanfarillo and Kasperski, 2021). Here, we outline the methods involved in measuring these different types of ecological values, identifying the key metrics and the methods to generate them.

We group the ecological values of pollinators into three main categories: values of pollinators themselves, values of pollinators as transporters of pollen and wider values of pollinators as part of food webs and ecosystems.

3.1 Pollinators in their own right

Animal pollinators are an essential component of global biodiversity, spanning a wide range of species including bees, flies, birds and bats. Regardless of their utilitarian values, pollinators are a potentially significant component of living in, living with and living as nature (IPBES, 2022) and hold significant intrinsic value to many peoples (IPBES, 2016). Methods to assess the abundance and diversity of pollinators are very well established and have been used in a wide range of ecological research projects, although almost none have framed them as “ecological values”. Here we outline the two main approaches used to assess the ecological value of populations of pollinators.

Key metrics: species occurrence (presence or absence), abundance (number of individuals) and/or diversity (number of species, genetic diversity)

3.1.1 Field methods

What it measures: The observed occurrence, abundance and/or diversity of pollinating animal species in a location. The exact metric will depend on the field methods used and the level of replication in the sampling. These methods are quantitative measures of intrinsic value expressed in biophysical terms.

Methodology: Field methods for sampling pollinators (reviewed in detail in Potts et al., 2021) typically fall into two categories: observational methods, such as timed focal observations (Fijen and Kleijn, 2017), transect walks (Westphal et al., 2008) and camera traps (Krauss et al. 2018), which require an active observation of the animals; and trap methods, such as pan traps (Gonzalez et al., 2020), malaise traps (Ngo et al., 2013) and light traps (MacGregor et al. 2019), which are deployed across a sample site to passively sample pollinators. Each will return different data and has different biases in which species it catches and as such a mixture of methods is highly recommended to ensure the most representative sample of species (O’Connor et al., 2019). The recent EU Pollinator Monitoring Scheme proposal recommends a combination of transects and pan traps in order to capture the broadest range of local pollinator biodiversity, with light traps used to capture nocturnal pollinators (Potts et al., 2021).

Once data has been collected, it can then be used to develop indexes of species abundance, diversity (e.g. Shannon-diversity) or rarity, which give information on the diversity and uniqueness of the community. Communities that are more unique may be considered more valuable, while communities that are more diverse may be more resilient to pressures. Similar logics are applied to indexes of genetic diversity.

Data needs: Field studies to collect primary data on pollinator abundance and diversity should be planned in a bespoke manner. Typically, sampling should be done at the same sites several times per year in order to capture a representative range of pollinators. If the aim is to sample pollinators over time, a statistical power analysis, based on expected catches per year and the samples per site, can be used to estimate the number of sites required (Breeze et al., 2021).

Particular care should be taken when sampling rare and threatened pollinators as lethal trapping may affect their populations. In these cases, dedicated observations around known sites where the species occurs should be undertaken, using e.g. mark-recapture methods whereby individuals are caught, marked with a paint or dye and then released, allowing for accurate estimation of their population sizes (Potts et al., 2021).

Strengths: If sufficiently thorough, field studies can most accurately represent the local pollinator community and, if repeated over time, can be used to monitor the status and trends in pollinator diversity. If repeated over time or over a sufficiently large number of sites, the data generated by field data can be used to estimate the links between management and pressures on populations or inform modelling approaches (Page 8), providing information on how the ecological value of a given pollinator community is likely to change. If part of a structured recording or monitoring effort, field studies can provide an opportunity for public engagement and participation through e.g. citizen science methodology to generate value data, potentially contributing to the socio-cultural values associated with pollinators and leading to attitudinal change (Gustaffson et al., 2017; Sharma et al., 2019). Increasingly, new technologies – including acoustic monitoring, radar and molecular methods – are being developed and introduced to increase both efficiency and scale of pollinator (and wider insect) sampling (Van Klink et al., 2022); and computing science approaches – including those based on AI- come upstream to aid species recognition (Siddharthan et al., 2016, Hansen et al., 2019).

Weaknesses: Most fundamentally, field studies require significant replication in order to reliably capture pollinator species abundance and richness and will often have to be combined with observational studies in order to identify which species are or are not pollinators (Boyer et al., 2020). Field studies are time and labour intensive, often resulting in significant costs (Breeze et al., 2021) that may be prohibitively expensive for large-scale and repeated measurements of the community. Many of the methods involved also have their own intrinsic biases that need to be carefully accounted for - for example pan trap catches can be affected by the availability of flowering resources in the habitat (Saunders and Luck, 2012) or the size of the trap (Gonzalez et al., 2020). Limiting the number of sampling methods may reduce these costs but risks missing key members of the pollinator community – for example transect walks are less effective at detecting smaller bodied bees (Hutchinson et al., 2021). Similarly, the effectiveness of some field sampling methods is affected by the experience of the recorder (Garratt et al., 2019) and in many countries there may not be the available expertise or resources to identify all species reliably (Potts et al., 2021).

When is it suitable: As they rely on primary data, field studies are most appropriately used at smaller scales where sufficient replication to reliably estimate richness and abundance is possible. At larger scales, more simplistic, observation only methods can be used to generate occupancy data over a much wider area, particularly via citizen science initiatives.

Examples:

Aguilera et al. (2020) – this study used observational data from 52 sites in Sweden to assess how pollinator abundance and diversity respond to the amount of semi-natural habitat and diversity of crops at the landscape scale. They found that the abundance of pollinators was positively related to semi-natural habitats whereas pollinator diversity, measured using the Shannon index, depended on an interaction between semi-natural habitat and crop diversity, with a positive relationship to crop diversity only in landscapes with high amounts of semi-natural habitat.

Gillespie et al (2022) – this study used observational and trapping data from 96 sites in the UK to examine how pollinator populations respond to a range of environmental (e.g. topography) and anthropogenic (e.g. chemical use) drivers. They find that the positive effects of floral resources on pollinator abundance and diversity depend upon the diversity of habitats, the level of insecticide use, and several habitat configuration metrics.

Ganuza et al (2022) – This study uses Malaise traps to examine the impacts of climate change and land use shifts on various pollinator biodiversity metrics (including community composition, dissimilarity and species richness) across 60 regions, each comprising of three 1km sites, in Bavaria, Germany. The findings indicate that all aspects of pollinator biodiversity decline with increasing land use intensity while higher temperatures resulted in more homogeneous communities.

3.1.2 Pollinator modelling

What it measures: Estimates of the occurrence, abundance and/or diversity of pollinating animal species across a defined geospatial area. The exact metric will depend on the model used. These methods are quantitative measures of intrinsic value expressed in biophysical terms.

Methodology: Modelling methods are spatially explicit statistical models that estimate the value of a pollinator community in a given location based on known ecological information about the taxa to be modelled and input data. Modelling pollinators in this way is relatively new, and there are five main types of model used in this way which we briefly outline below:

- Occupancy models: These models use known records of species occupancy (presence or absence) over time to predict the likely occupancy of that species in different places across time. They can be adjusted to account for factors such as recorder biases (i.e. the likelihood that less experienced recorders will observe less species), seasonality (when a species is active), site type or other prior information (e.g. Outhwaite et al., 2018).
- Abundance index models: These models use information from systematic (i.e. widely repeated following a defined method) assessments of species abundance to extend occupancy models and estimate the relative abundance of species in regions where they are predicted to be present (e.g. Van Swaay et al., 2019).
- Species distribution models: These models use information on a species' occupancy along with other information from the places that species were observed to be present (e.g. climate or habitat data) in order to predict the species distribution under future conditions (e.g. Rasmont et al., 2015).
- Agent-based models: These models use data from all aspects of a species' biology and ecology to estimate how their abundance is likely to respond to external factors within a particular location (e.g. Becher et al., 2018).
- Process-based models: These models use habitat data to estimate the relative abundance of certain pollinators based on i) the nesting and forage resources of the habitats in the landscape and ii) known traits about species foraging and population growth rates (e.g. Gardner et al., 2020).

Data needs: Most of these models are available via open access repositories or web portals. The exact data required will depend upon the model used. Occupancy, abundance index and species distribution models will require species occupancy data collected from a sufficiently large number of sites over several years. Abundance index models also require systematically collected data on pollinator abundance over a similar time period, ideally with information on the structure of the systematic data collection (length of transect, etc.). Process-based models require detailed spatially explicit habitat data, which should be as fine-scaled as possible to capture local habitat features that may provide key resources (Gardner et al., 2021), and information on the nesting and forage quality of the habitat which can be generated by assessments of expert opinion (e.g. Gardner et al., 2020). Process-based and agent-based models also require primary ecological information on the pollinators modelled; for example, flight distances and reproductive rates. A wide variety of other data, such as climate (e.g. temperatures) and land management information (e.g. pesticide applications), can be incorporated into these models, particularly agent-based and species distribution, in order to predict responses to external changes.

Strengths: Providing that sufficient data is available, pollinator modelling is useful for estimating the ecological value of pollinator communities at much larger spatial scales than primary data collection would allow for. This includes the variation in pollinator communities across a region, allowing hotspots to be identified. Species distribution, process-based and agent-based models can also be used to make predictions of future occupancy, diversity and/or abundance based on specific scenarios of climate or land use. They can also be used to identify areas where plants and their pollinators may not overlap at present or in the future, resulting in pollination deficits. Agent- and process-based models do not require long-term primary data on pollinators in order to run. Modelling, especially using open-sourced or publicly available models, is much less expensive than running a field study as the amount of labour required is substantially lower.

Weaknesses: Modelling can only return approximated and relative data and can be very data demanding, especially for more sophisticated species-distribution models, which require significant, long-term data to run. At present no single model can assess occupancy, abundance and species richness together, meaning that multiple models must be used to estimate the full range of pollinator community value metrics. Certain modelling methods have thus far only been applied to certain taxa and often at coarse resolutions. For example, process-based models of pollinators have only been applied to certain guilds of bees (Lonsdorf et al., 2009; Gardner et al., 2020), while agent-based models only exist for honeybees and bumblebees (Twiston-Davies et al., 2021; Becher et al., 2014). Furthermore, while publicly available agent- and process-based models do not require additional data from users beyond in/out parameters and new land maps respectively, they have not been validated outside of a few countries and thus may be less accurate when applied elsewhere (Becher et al., 2014, 2018; Haussler et al., 2017; Gardner et al., 2020). Validating these models is itself a data-intensive process that may not be viable in areas where little primary field data has been collected.

When is it suitable: Modelling pollinator populations is most suitable for large scales, where the spatial variation in the community and identifying hotspots of pollinator populations are key interests. Agent-based models are most suitable for smaller populations in localized areas where only a limited number of environmental factors will vary. Species distribution, process- and agent-based models can also be used to explore the impacts that environmental changes will have upon pollinators.

Examples:

Powney et al., (2019) - This paper, drawing from long-term citizen science data, uses an occupancy model to estimate trends in the occupancy of 139 bee species and 214 hoverfly species between 1980-2012. The findings demonstrate that 33% of species have declined in occupancy over the time period, particularly rarer species, resulting in more homogenous communities across the UK.

Koh et al., (2016) - This paper applies a process based model to examine the abundance of bee populations in agricultural land, and how this had changed between 2008-2013 across the continental United States. The study highlights significant declines in several eastern and central states.

3.2 Pollinators as transporters of pollen

Ecologically, the key impact of pollinators is in the act of pollen transportation itself (Knight et al., 2018). Pollination by animals plays a role in the reproductive systems of a majority of global flowering plants (Ollerton et al., 2011) but the degree of influence that animal pollination has can vary from slight to essential. The identified and quantified role of specific animal pollinators or whole pollinator communities to plants and plant communities represents a key ecological value of pollinators. Many assessments of the reproductive systems of plants simply use behavioural observations of pollinator visitation and assume a link with pollination success (Ollerton et al., 2011) rather than empirically testing the impacts that this has on plant reproductive success.

3.2.1 Pollinator exclusion testing

What it captures: The impact of excluding pollinator visitation on some or all elements of the reproductive success of a plant species. This method gives quantitative measures of intrinsic value expressed in biophysical terms.

Methodology: Pollinator exclusion tests involve excluding pollinators from a plant in order to compare the effect of plant reproductive success with and without animal pollination. This exclusion usually involves placing a mesh around a representative floral unit of the plant (e.g. an umbel or branch) or, ideally, the whole plant to avoid issues of plants re-allocating resources to successfully pollinated flowers (e.g. Knight et al., 2006). This typically involves using a frame to prevent the mesh physically interfering with the plant. The mesh allows wind and gravity pollination but excludes all but the smallest animals. Plants can be wild specimens or can be specially grown, individual plants referred to as phytometers (Woodcock et al. 2014). Phytometers are advantageous in that they allow other factors that could influence reproductive success, such as soil nutrition and specific genotypes or phenotypes, to be controlled but may be less realistic than using wild plants. Once flowering ceases, the resultant seeds or fruits can be harvested and various relevant reproductive characteristics measured such as seed set and seed weight. Lower values of plant reproductive output measures in plants excluded from pollinators are interpreted as pollinator-dependency, and the higher this drop is, the higher dependency. When applied to crops, this method can be used to estimate economic (called a Yield Analysis - see page 18) or nutritional values (see page 31).

Data needs: The protocol involves identifying a replicated set of excluded and open pollinated plants or parts of plants. Care should be taken to randomise treatments and, if possible, exclude or minimise confounding factors such as plant vigour.

Strengths: This methodology is the most powerful in determining the presence and level of pollinator-dependency of plants and is relatively straightforward to apply, requiring minimal materials. By taking a sufficiently large and diverse spatial sample, the method can also be used to assess levels of pollination limitation between different sites.

Weaknesses: Although the method is simple, a large, well replicated survey of pollination services can be time consuming to plan and require intensive field activity, particularly for plants that have a short flowering time. Care should be taken to apply the exclusion structure as this can affect the plant through e.g., microclimate or pests effects, which can lead to an under- or over-estimation of the pollination benefit. This effect can be minimised by adjusting the bag during the season so that it only covers flowering parts and removing it directly after bloom. When cages are used for exclusion, control cages with netted roofs but open sides can be used to minimise the negative effects on microclimate of caging (e.g., Marini et al. 2015).

When is it suitable: Pollinator exclusion testing should be used when the goal is determine the relative contribution of animal pollination to plant reproductive output.

Examples:

Bartomeus et al., (2014) - This study used pollinator exclusion with bags in four crop plant species in four European countries. They found that open pollination increased crop yield by 18 - 71% depending on crop plant species and improved metrics of yield quality in most crops, such as higher oil and lower chlorophyll content in oilseed rape and higher commercial grade in strawberry.

3.2.2 Strength of relationship assessments

What it captures: A quantitative relationship between a pollinator metric such as abundance, visitation rate or diversity and some or all elements of the reproductive success of a plant species. This method gives quantitative measures of intrinsic value expressed in biophysical terms.

Methodology: This methodology has been most widely applied to crops rather than wild plants but is applicable to any pollinated plant. Studies are typically designed to collect data from multiple sites where pollinator abundance and diversity are expected to vary, often due to variation in surrounding landscape complexity (Vassieré et al., 2011). At each site, both measures of pollinators (see field methods – page 6) and plant reproductive output (page 10) are taken. These are then statistically related to each other using correlative or regression analysis. Correlative studies simply explore the strength of relationship between pollinator abundance and plant reproductive output. Regression modelling allows for other factors, such as proportions of semi-natural habitats to be incorporated into the analysis and separate their influence from the relationship between pollinator abundance and plant reproductive output.

Data needs: Pollinators are recorded using the methods described above (Fields methods, page 6). Plant reproductive output can be measured in a variety of ways - at the level of the individual plants - such as fruit set, seeds per fruit, individual seed weight and or seed weight per plant. These are measures taken at the individual plant level, but when combined with surface area and plant density measures those can be scaled up for surface area and planted area or in the case of crop plants, over a larger area. Vassieré et al., (2011) recommend a minimum of 10 sites, and at each site pollinators should ideally be monitored several times over the flowering period of the focal plant species to capture fluctuations in the abundance of pollinator populations.

Strengths: This method is based on realistic field conditions and can capture the variance in the importance of pollinators at different sites, allowing for areas of pollen limitation to be identified. Sufficiently complex field experiments can allow for multiple factors to be explored simultaneously, allowing for a more accurate assessment of how pollinator visitation interacts with other factors to contribute to pollination services.

Weaknesses: The main weakness of the methodology is that it is limited by the availability of information. As such, it cannot be excluded that unobserved factors other than the focal variation in pollinators, such as pests or soil conditions, confound any observed relationships between pollinators and plant reproductive output (Petersen and Nault 2014). Equally important, the method will not be able to establish a link between pollinators and the plant of interest - even if it is animal-pollinated - if the plant is not pollen limited (i.e. it has sufficient receipt of pollen) in any of the sites. Similarly, unless extensive observations of the pollinator community are used to disambiguate the visitor community, it is difficult to determine the relative importance of different species.

When is it suitable: This method is suitable when the goal of the study is to explore if higher values for pollinator metrics are related to improved measures of plant reproductive output. It can be used to explore which aspects of the pollinator communities (such as abundance of particular species, total abundance, or species richness) that are most strongly related to plant reproductive output.

Examples:

Garibaldi et al. (2016) - This study measured flower-visitor density, flower-visitor richness, crop yield and various covariates in 344 fields of various insect-pollinated crops primarily in Africa, Asia and Latin America. using a standardised protocol. Using a regression model, the study found that flower-visitor density was the most important predictor among all variables tested, having a positive effect on crop yield. In smallholdings with a field size of 2 hectares or less, it was estimated that around a quarter of the yield gap (difference between high and low yielding fields) could be removed by increasing flower-visitor density in low yielding fields.

Robinson and Henry (2018) - This study uses hand pollination, pollinator exclusion, observational surveys and artificial warming to model the effects of pollinator visitation on seed set in three arctic plants. The results show that pollination and warming both have an effect upon seed production and germination but that these effects are largely independent of one another.

3.3.3. Hand pollination

What it captures: Whether plant reproductive output increases when receiving more or higher quality pollen. This method gives quantitative measures of intrinsic value expressed in biophysical terms.

Methodology: The protocol involves transferring pollen from donor flowers to experimental flowers by hand using e.g., a brush (Holland et al. 2020). Plant reproductive output such as fruits or seeds per flower from flowers receiving supplemental pollen are then compared against openly pollinated control flowers.

Data needs: Replicate hand-pollinated and control flowers are assigned at each site of interest. Hand pollination of all flowers on a plant as opposed to single flowers are preferred because of the potential of with-plant reallocation of resources mentioned in section 3.2.1, but could be practically infeasible for plants with many flowers or an extended flowering period.

Strengths: Hand pollination studies provide direct experimental evidence of pollen limitation in plant that can be linked with observations of pollinator visitation rates or abundance.

Weaknesses: Hand pollination is often time and labour intensive, especially if widely replicated and may require different tools for pollinating different plants. Unless all flowers on a plant are hand pollinated, the effect of supplemental pollen on plant reproductive output might be overestimated due to reallocation of resources to hand pollinated flowers within the plant (Knight et al. 2006).

When is it suitable: This method is suitable when the goal is to establish if plant reproductive output is limited by insufficient receipt of pollen. If pollen limitation is found in animal pollinated plants, plant reproductive output would likely increase if the quantity or quality or pollinator visits increased.

Examples:

Castro et al., (2015) - This paper studied the pollination ecology of the critically endangered perennial herb *Dracocephalum austriacumb.* Pollen limitation was studied in four populations by supplementary pollen addition by hand. Evidence of pollen limitation was found in all four populations.

Holland et al., (2020) - This study quantified pollen limitation in four insect-pollinated crops across 105 crop fields in six countries Europe. Overall they found a modest level of pollen limitation with a 2.8% lower harvestable crop biomass in flowers that did not receive supplemental pollen by hand. This was more significant for mass flowering crops (oilseed rape and sunflowers) than it was for more highly dependent but smaller scale crops (pear and pumpkin).

3.2.3 Individual pollinator efficiency

What it captures: The contribution of individual pollinators to pollen transportation, pollen deposition and/or plant fertilisation. These methods give quantitative measures of intrinsic value expressed in biophysical terms.

Methodology: This method relates plant reproductive success to individual pollinators. This method has two forms 1) the more simple single visit pollination efficiency, 2) precise measures of individual pollen grains deposition (Ne'eman et al. 2010).

Single visit efficiency: This involves obtaining individual floral visits by a single pollinator to previously unvisited (bagged or caged) flowers, which are then bagged or caged again immediately following this single visit. The resultant flowers are followed through to maturity and the seeds and fruits harvested and assessed. Statistical analysis can then be undertaken to compare between different pollinators. Multiple visits can also be allowed before bagging to assess cumulative deposition rates of a species (e.g. Garratt et al., 2014a).

Individual pollen grain deposition. This method involves extracting the flower following a single visit and evaluating the number of grains deposited. This can be done by using gels to remove the pollen and manually or electronically counting the pollen grains (e.g. Diller et al., 2019; Staedler et al., 2018; Vansynghel et al., 2022) or by waiting for the pollen to begin to descend down the stigma and then chemically staining the stigma to count pollen tube growth (a representation of the number of viable grains deposited) (Stavert et al. 2020).

Data needs: This method requires bespoke data collection and can be undertaken in both field and laboratory conditions. In field conditions, it will be important to gather a representative sample of plants within a site and, ideally should span multiple sites. Laboratory conditions, where plants are enclosed with specific pollinators, allow for more control over the observations as flower can be guaranteed to have not been exposed to pollinators. A large number of flower visits is required to obtain sufficient data for analysis using either approach.

Strengths: These methods give a mechanistic understanding of the contribution of specific pollinator species to the plant reproductive output. They can be readily combined with observations of pollinator behaviour to distinguish between the efficiencies of different types of visits (legitimate visits to the whole flower, nectar raising, only partial visits etc.) by a single species and with observations of the pollen grain uptake on body parts of each pollinator that come into contact with the stigma, and the quality of pollen deposited.

Weaknesses: The methods are typically laborious to obtain robust sample sizes, especially for rarer pollinator species. Pollen-based methods require laboratory space, equipment, and consumables, such as staining fluid which can be costly when applied over a large sample.

Pollinators cannot be collected as they visit the flowers, making field identification of many species difficult. Thus, high levels of taxonomic expertise might be required to identify pollinators on the wing. Although experimental settings are easier to control, it is often difficult to maintain normal pollinator foraging behaviour in caged or laboratory conditions. Furthermore, cage studies are limited by the number of commercially available pollinator species, necessitating bespoke laboratory breeding methods at further expense.

When is it suitable: These methods should be used when seeking to understand the value of individual pollinators within a community to the pollination of key plants, crops or otherwise. By combining it with behavioural observations it can also be used to identify the mechanisms that determine pollination efficiency per visit (e.g. Diller et al., 2019).

Examples

Tang et al (2019) – This study used a combination of field observations and pollen deposition analysis to determine the relative efficiency of male and female *Andrena emeishanica* to the flowering plant *Epimedium pubescens* in China. The analysis involved collecting pollen from bee bodies as well as measuring the amount deposited and found that male bees collected less pollen but deposited more per individual.

Diller et al (2019) – this study examined the relative pollen deposition of honeybees and local bird species to the African Aloe plant (Aloe ferox). The findings indicate that specialist nectar-feeding birds that visited the flower did not deposit any significant amount of pollen while honeybees and especially opportunistic bird visitors deposited substantial quantities each.

Garratt et al (2014b) – This study used controlled cage study experiments to examine the single-visit pollination efficiency of four pollinators (honeybees, bumblebees, mason bees and hoverflies) on two common UK pollinated crops – oilseed rape and field beans. Flowers were bagged after 1, 2 or 4 visits by individuals of each taxa and followed through to fruit/pod production. The results demonstrate that only bumblebees are efficient pollinators of field beans, a deep corolla flower with difficult to access nectar, while other bee taxa were effective pollinators of the more open flowered oilseed rape.

3.3 Wider ecological values of pollinators in ecosystems

Insect-pollinated plants affect ecosystem functioning in every possible way through which plants influence ecosystems. Given they are our world’s primary producers, the indirect ecological value of pollinators is infinite and unfolds at any scale, and can include: shaping chemico-physical and biological process in the soil (e.g. soil porosity, rates of nitrogen and phosporous cycling); mediating competition in and diversity of plant communities (Johnson et al. 2022); and stocks and flows of energy and matter through ecosystems, food webs and the atmosphere. Apart from the trophic interaction with plants in form of this pollination mutualism, pollinators are also prey and hosts for predators and parasites (Goulson et al. 2018), and for example in the case of hoverflies, themselves important predators in food webs (Saunders et al. 2016, Rodríguez-Gasol et al. 2020).

While these indirect ecological values have a significant influence on the structure and function of ecosystems, none of those have so far been given due attention, and thus what is likely to be the greatest impact of pollinators on the world they are part of remains mostly undisclosed and the methods that could be used to evaluate them have not been tested. A key question for future research is thus how different the impact of plants on ecological processes are between species that are dependent upon pollinators versus those that are not. Addressing this difference for key ecological aspects would likely open different ways of thinking about the intrinsic value of pollinators and their place on Earth.

4 Economic values of pollinators

Pollination influences the production of the majority of global crop species and consequently has a significant influence on human economic activity. Expressing values in these terms is widely undertaken by policy and research in order to justify conservation and management actions. To date, over 100 studies have assigned some measure of economic value to pollinators or pollination services. Quantifying the economic value of pollination is most often used to illustrate the impacts of pollination service losses at a field or larger scales (e.g. Lippert et al., 2021) or to assess the economic consequences of decisions that affect pollinator populations (such as converting habitats to cropland – e.g. Ricketts and Lonsdorf, 2013). Within the IPBES values framework (IPBES, 2022), Economic values are instrumental values, although some methods can be applied to capture intrinsic values too.

The methods review concerns methods for valuing pollinators and pollination. Honey and other managed pollinator products do not require specific valuation methods as they are already traded on markets for set prices. The value of plants in the environment to these pollinator products is not covered by these methods but the production function (page 22) and spatial modelling methods (page 28) could be adapted to do so.

The principal methods for measuring and valuing the economic benefits of pollination services are broadly divided into five key groups:

Replacement Costs – these methods equate the economic benefits of pollination services provided by pollinator natural capital to the costs of replacing them with manufactured capital, such as managed pollinators or artificial pollination technologies.

Factor Income – these methods quantify the contribution of pollinators as an input into an economically valuable system. There are three methods in this family:

- Yield analyses – the impact of pollination on economically valuable characteristics measured directly in field conditions.
- Dependence ratios – information from past literature used to estimate the impact of pollination on economic output, usually at a large scale.
- Production function – field data on pollination, alongside other inputs, used to directly estimate the marginal changes in economic output.

Stated preferences – these methods elicit the economic value of pollinators or pollination services through surveys. This family includes a range of different survey types but here we present them as one due to their similarities.

Surplus modelling – these methods are economic models that build upon the outputs of other methods (usually Factor Income) to evaluate the impact of pollination services on the economic welfare of parts of society. There are two types of surplus models:

- Partial equilibrium models – the effects of pollinator losses are evaluated for some sections of the economy but not the economy as a whole.
- General equilibrium models – more complex models that measure the net impact across the whole economy.

Spatial modelling – there has been growing integration of spatial modelling methods alongside Factor Income methods and other forms of field data to estimate the value of pollination services in a spatially explicit manner. These methods are sufficiently distinct from Factor Income models to be presented separately.

4.1 Replacement costs

Replacement Cost methods are widely used in economic valuation of ecosystem services. Here, the economic benefits of an ecosystem service provided by natural capital are linked with the costs of replacing that service with a manufactured capital substitute, providing a measure of the costs saved by the presence of wild animal pollination. This aligns well with economic theory as it equates the otherwise unmeasured economic action of the ecosystem service with something that is already captured in existing markets.

What it captures: The commercial market costs of using manufactured capital to replace pollination services provided by natural capital (wild pollinators)[1]. This is a quantitative economic method that measures instrumental value in monetary terms.

Methodology: Estimating the replacement cost involves calculating the total cost involved in the replacement technology. Typical replacement technologies include hand pollination with paintbrushes (Allsopp et al., 2008) or pollen sprays (Dahab et al., 2020). A number of studies simply use the price of hiring or purchasing sufficient managed pollinators to replace wild pollinators (e.g. Hoshide et al., 2018; Davinsky et al., 2017).

It is important that the replacement is 1) at the lowest cost possible, 2) provides equal or greater impacts to the service it is replacing and 3) would realistically be used by affected actors rather than simply switching to alternative crops, varieties or land uses (Söderqvist and Soutukorva, 2009). Costs should be assessed through field studies, considering the total costs of all aspects of the method (fixed costs such as equipment and variable costs such as labour). Effectiveness should be derived from detailed field study, using methods similar to those outlined in yield analysis (page 18). Users willingness to adopt the technology can be assessed using a number of methods including stated preference surveys (page 24) or through more evaluative (qualitative) approaches (e.g. interviews - Morris et al, 2017 or Q methodology - Vecchio et al, 2022).

Using the Replacement Costs method, the value of pollination service is estimated as the total costs of all materials, consumables and paid labour involved in providing pollination services to the crop per hectare. For managed pollinators available in local markets, this becomes a simple multiplication of a) the price per unit (e.g. honeybee hive or bumblebee colony) of managed pollinators and b) the number of units required to pollinate one hectare of crop or to replace the proportion of pollination services provided by wild pollinators.

Data needs: The costs of technological replacements will typically be estimated on a bespoke basis, using local cost data for materials and consumables involved in the specific replacement technology (e.g. pollen sprayers and pollen - Dahab et al., 2020). Labour costs are then estimated from tests or assumptions of the time required to pollinate a hectare of crop effectively, multiplied by at least the local minimum wage, which can be obtained from national government sources (e.g. US Bureau of Labor and Statistics, 2022) or international organisations (e.g. World Bank, 2022). For some fairly simple technologies it may be possible to extrapolate part of the necessary data from past case studies (e.g. Majewski, (2018) uses the labour time for hand pollination from Allsopp et al (2008)).

Honeybee hive prices are openly available where there is an established local market for commercial pollination, such as in the USA. However, for other countries, prices may have to be estimated from surveys of beekeepers, particularly professional ones who are more likely to enter into agreements to supply hives (e.g. Breeze et al., 2017 – UK). Prices for other managed pollinators are usually available directly from the manufacturer.

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[1] This method can also be used to estimate the value of pollination services provided by non-commercial beehives (manufactured capital) within an area.

The number of managed pollinators required per hectare can be found in relevant scientific literature (see Breeze et al., 2014, for a review of European crops) or through directly asking farmers what their typical usage rate is (e.g. Hoshide et al., 2018). If this information is not available, or a more exact local estimate of the number of colonies is desirable, then this can be estimated using standardised field studies (outlined in Delaplane et al., 2013).

Strengths: Unlike other methods, Replacement Costs capture pollination as a commercial input and thus reflect the price of pollination services within existing market structures, independent of the price of the crops pollinated. This makes their estimates more consistent across both crops and time and comparable with the costs of other inputs such as pesticides (pest control) and fertilisers (crop fertility). Localised price differences in the replacement method can also capture important variations in the perceived value of pollination between crops (Rucker et al., 2012), pollinators (Calzoni and Speranza, 1998) and even the strength of honeybee colonies (Goodrich and Goodhue, 2020). This makes them more realistic to local market conditions.

Weaknesses: As they only measure the market price for the commercial provision of that pollination service, replacement cost analyses do not consider the relative importance of pollination services to productivity and thus may overestimate value in crops where pollinator dependence is relatively low. Where the cost per crop is variable, such as with managed pollinators, several studies have demonstrated that the price of hiring beehives for pollination more closely reflects beekeeper expenses and the potential value of honey harvested (Breeze et al., 2017; Rucker et al., 2012; Sumner and Boriss, 2006) than the pollination benefits provided. Further research, using yield analysis (see page 18) in particular, is necessary to determine how replacement costs compare to the relative benefits of pollination (e.g. Breeze et al., 2017).

Using managed pollinators as a replacement is less suitable in countries where paid pollination services are rare. Although the use of commercial honeybee pollination is widespread in the USA (Rucker et al., 2012; Goodrich and Goodhue, 2020), in many other countries such markets are rare (Breeze et al., 2019). Similarly, the use of certain managed pollinators may be legally restricted due to e.g. biosecurity laws (Hogendoorn et al., 2007) or commercial limitation (e.g. breeders being unwilling to sell small numbers of colonies), restricting the ability of small holders to access them (Zhang et al., 2022).

Furthermore, due to the limited data on recommended stocking rates per hectare of crop and the proportion of pollination services provided by wild pollinators, studies often use proxies or expert opinion (e.g. Divinsky et al., 2017; Hosidae et al., 2018) that may not accurately reflect the real number of colonies required to replace wild pollination, especially of honeybees are not very efficient pollinators of a given crop (e.g. field beans – Garratt et al., 2014b).

When it is suitable: This method should only be used where there is both a viable commercial market for managed pollination and where managed pollinators are likely to form a significant proportion of pollination services (e.g. in commercial greenhouses or large monocultures). Although more technologically advanced approaches are also in development, e.g. using drones to gather and distribute pollen directly (e.g. Abutalipov et al, 2016) or via soap bubbles (Yang and Miyako, 2020), there are other serious concerns about these methods (e.g. life cycle and other environmental impacts of the parts involved – Potts et al, 2018; Nimmo 2022) that should be considered before they are used.
In general, the method is most useful to assess the current market value of pollination from commercial insects in comparison to other factors (e.g. other inputs, wild pollinators), or where a strictly market based view of value is required.

Examples:

Allsopp et al., (2008) – This study examines the costs of replacing pollination services with hand pollination (via paintbrush) in the Cape Fynbos region of South Africa. It contains the most detailed assessment of the Replacement Cost method.

Hosidae et al. (2018) – this study uses a combination of literature data and farmer perceptions of pollination service provision by wild bees to estimate the number of beehives needed to replace wild pollinators. This value is then compared with the benefits of wild pollination services and consumer willingness to pay for conservation via price premiums for sustainable fruit products (see Stated Preferences – page 24).

4.2 Factor income methods

Production Function methods, sometimes called Factor Income methods, estimate the value of pollination services based on their relative impact on the production of economically valuable outputs (e.g. crops). There are three main forms of these analyses within the literature: 1) Yield analyses – which instead directly measure the total impact of pollination on economically important aspects of yield 2); Dependence ratios – which use information from published literature to estimate the proportion of yield that would be lost in the absence of pollination to estimate its total economic value and 3) Production function models – which estimate the marginal impacts of pollination services on yields relative to other inputs. Collectively, these three methods are the most common valuation tools among the published literature; the three main forms are separated here due to the different nuances in their use and interpretation.

4.2.1 Yield analysis

What it Captures: The commercial price of additional crop production arising from pollination services in the affected crop at a local scale. This is a quantitative economic method that measures instrumental values in monetary terms.

Methodology: Yield analyses use information from agronomic experiments into the effects of pollinator exclusion on crop yields. The method can be broken down into three steps: 1) exclusion experiments, 2) measuring crop yield and 3) estimating the economic impact. The economic benefits of pollination are the differences in economic benefits between the open and excluded treatments.

1) Exclusion experiments: The experimental treatment, similar to those for wild plants (page 10), involves excluding pollinators from a sub-sample of crop plants while leaving another designated sub-sample exposed to animal pollination or pollination by hand. Exclusion involves placing a fine mesh gauze, sometimes with a wooden frame as appropriate, over a) an individual plant (in the case of herbaceous crop plants such as strawberries – e.g. Lye et al., 2011), b) an area of crop plants (in the case of high-density crops such as oilseed rape) or c) a specific branch (in the case of tree crops – e.g, Garratt et al., 2014b). The mesh should be fine enough to allow for wind-pollination and not so restrictive as to interfere with self-pollination.

2) Measuring crop yield: At harvest, all economically relevant aspects of the crop should be measured in order to estimate total economic impact per plant/area of pollinator presence or absence. This can include final crop set (initial fruit set is likely to be affected by factors such as fruit abortion or manual thinning; Bos et al., 2007), total weight and quality parameters that may affect sale price (for example in crops that are sold at different commercial grades). It is important to capture all economically significant aspects as individual crop

characteristics may give different estimates of pollination benefit (see Bishop et al., 2020 for a review).

3) Estimating the economic impacts: Once the economically important yield per treatment is established it can be multiplied by the price per unit weight (usually tonnes or kg) for different crop quality grades (e.g. Lye et al., 2011). This gives an estimate of the total economic output per treatment. In some crops, pollination-induced changes in the fruit set may also affect farmer variable costs such as labour costs involved in harvesting. The total economic benefits of pollination on gross output per hectare can then be extrapolated either by taking the average or median relative differences between all plants in the two treatments as representative. In some crops, pollination-induced changes in the fruit set may also affect farmer variable costs (e.g. labour costs involved in harvesting if less or more fruit is produced). Estimates of such changes in variable costs can be factored in to produce an estimate of benefits to net output per hectare, representing the change in raw profitability due to pollination (e.g. Garratt et al., 2014b).

Additional steps: As Yield analyses are relatively simple field experiments, they have been expanded in a number of ways to provide additional insights into the economic benefits of pollination. Some of the most common expansions are briefly described below:

- Information on the relative efficiency and visitation rates of different pollinator taxa can be used to estimate the economic benefits of these different taxa (e.g. Bushmann and Drummond, 2020; Garratt et al., 2016) and the synergies between them (Greenleaf and Kremen, 2006).
- Comparing the difference in crop production and economic gross/net output from hand pollination to open pollination treatments, in addition to pollinator excluded treatments, can form an assessment of local pollination deficits (the shortfall between maximum achievable yield and actual, obtained yields - e.g. Garratt et al., 2014b; Stein et al., 2017; Toledo-Hernandez et al., 2020).
- Variance in the effects of pollination on different yield components can be used to explore the sensitivity of the estimates to unmeasured factors (Magrach et al., 2019).

Data needs: The field experiments that underpin Yield analysis must usually be conducted on a bespoke basis, ideally following established agroecological protocols to make them comparable to other studies (e.g. Vaissiere et al., 2011; Delaplane et al., 2013). This should include an appropriate level of replication for both the exclusion and open pollinated treatments (as well as any further treatments conducted) in order to generate sufficient samples in both the open- and pollinator-excluded treatments. Ideally these should be conducted in realistic field conditions rather than in artificial laboratory conditions where more optimal management conditions may affect the results. In some cases, existing studies have examined the impacts of pollination on yield but not converted this to economic value (e.g. Bartomeus et al., 2014), and as such may be a suitable basis for such analyses.

Crop price data per kg (or per tonne) can be gathered from local sources, such as national agricultural agencies (e.g. DEFRA, 2022) or directly from farmers or co-operatives (e.g. Bravo-Monroy et al., 2015). If no local sources are available, global databases such as FAO can be used (FAOSTAT, 2022). However, national and global databases often do not include the price differences for crops of different qualities, which may skew the price per hectare if crops tend towards higher or lower classes (see Garratt et al., 2014b for an analysis of this difference).

For crops with multiple sale prices based on crop quality parameters, the relevant thresholds should be obtained from collaborating farmers, or local co-operatives or wholesalers. In some regions, this may be codified legally (e.g. apples in the European Union - EC, 2004).

Certain crop harvesting and sale costs (e.g. packaging) may vary due to final crop yield and should ideally be incorporated into Yield analysis to derive a measure of the impacts of pollination on net crop output. Such costs should ideally be gathered from the farmers or landowners that are hosting the field work. However, labour costs can also be gathered using applicable minimum wages (available from National Statistical Agencies or international organisations, e.g. Eurostat, 2022) as a minimum baseline.

Strengths: If all economically important factors and price variations are considered, Yield analysis provides a relatively precise estimate of the total benefits of pollination services under local, field realistic conditions when all other factors are equal. The field experimentation required is relatively simple and does not require significant expertise or resources to undertake. The method can also be easily adapted or expanded to provide more detailed information (e.g. levels of pollination deficit, relative value of different pollinators).

Weaknesses: Although relatively simple to execute, yield analysis can require significant time and resources to set up a well replicated study over multiple sites. They also require waiting for the crop to fully mature, making them less suitable for more rapid assessments of economic benefit (Ratto et al., 2022). Unless sample sites are widely distributed, yield analyses only assess the economic benefits to individual varieties of crops in specific locations. Upscaling the benefits from a single area to large, national scales may not be appropriate, particularly in large countries, if a number of different varieties are grown in a range of different locations and growing conditions (Bishop et al., 2020).

Finally, yield analyses only assess the impacts of total pollinator exclusion and does not account for the relative impacts of other inputs (e.g. water and nutrients - Klein et al., 2015) or ecosystem services (e.g. pest regulation - Lundin et al., 2013). These factors will each have an influence on the final economic output, resulting in the benefits of pollination being overstated- or understated. This is especially significant in crops with extremely high pollinator dependence (e.g. watermelon – Winfree et al., 2011), where this method effectively estimates that all economic benefits are due to pollination when in reality other factors can significantly influence output.

When is it suitable?: Yield analyses are most appropriate to explore the economic benefits of crop pollination to farm businesses at a local scale. They can be upscaled but a large, representative number of sites would be required to do this meaningfully. As such, the method is well suited to niche crops that are only grown in small areas. The method is also particularly suitable to smallholder crop production where many crops are sold locally and are thus not captured by national statistics (e.g. Stein et al., 2017; Liu et al., 2019).

Examples:

Tremlett et al. (2021) – This study uses yield analysis to examine the economic benefits of bat pollination to Pittaya cacti in Mexico. Most innovatively, the study then uses information from other actors within the relatively small and localised Pittaya value chain to determine the benefits of pollination to other actors in the chain. The findings indicate that these benefits increase substantially in scale further up the value chain, demonstrating that the economic benefits of pollination extend into the whole food system.

Bishop et al. (2020) – This study is the most detailed examination of the yield analysis method. It compares estimates of the economic benefits of pollination to UK field beans using a number of different varieties, hand-pollination methods and economically important yield measurements. The results demonstrate that the benefits of pollination vary greatly depending on what combination of these factors is used, highlighting the importance of capturing all yield variables and differences in varietal responses to pollination before upscaling.

Sritongchuay et al. (2021) – This study estimated the effect that chemically-induced early flowering had on Longan yield in Thailand, with and without the addition of honeybees, demonstrating that when flowering was induced early, the benefits of pollination were substantially lower without managed honeybees due to the lack of suitable wild pollinators.

4.2.2 Dependence ratio

What it captures: The commercial price of additional crop production arising from pollination services in one or more crops in a given area. This is a quantitative economic method that measures instrumental values in monetary terms.

Methodology: Dependence Ratio studies use metrics of the proportion of economic output lost in the absence of pollination services to estimate the current contribution of pollination services in a region. The benefits of pollination are estimated by multiplying total commercial value (total production in kg or tonnes multiplied by prices per tonne/kg) of each crop by its dependence ratio, taking this proportion of the total as the benefits.

Data needs: Dependence Ratio metrics can be drawn from published agronomic literature (including yield analysis studies – Breeze et al., 2021) or from expert opinion (e.g. Morse and Calderone, 2000; Majewski et al., 2014) depending on the availability of data. Ideally, a range of dependence for each crop should be used to estimate the possible range of benefits. Many studies use the median values of crop pollinator dependence from the global review by Klein et al. (2007), as this covers the majority of globally significant crops, although some crops are missing from this database (Bourges et al., 2020).
Crop yield (t/ha to total produced tonnes) and commercial value ($/ha or total $ value) statistics can be obtained from local data (e.g. farmer co-operatives) or from national or international databases (e.g FAOSTAT, 2022). However, local data sources are preferable as they may contain information on niche crops (e.g. Bourges et al., 2020) or price variations (e.g. Garratt et al., 2014b) that are not captured in these largely aggregated international databases.

Strengths: The dependence ratio method requires relatively little data to undertake and is computationally simple, making it especially suited for quick assessments or where there are no resources for fieldwork (Melathopolous et al., 2015). The method is also suitable for assessing the benefits to multiple crops, or whole national crop sectors, simultaneously. At a smaller scale, yield analyses may be more appropriate as this can give more precise estimates of benefits (Ratto et al., 2022).

Weaknesses: Dependence ratios do not account for the influence of other inputs or ecosystem services on yield, which can modulate the benefits of pollination services (e.g. Klein et al., 2015). By relying on second hand data, which may not be specific to the area considered, there is a risk that the dependence ratios used can over- or under-estimate the benefits of pollination services to local crop yield. This is especially significant in crops where pollinator dependence has not been assessed for several years, as changes in varieties and management may have a substantial effect on pollination services (Garratt et al., 2021). Furthermore, many studies used as the basis for dependence ratios do not account for all economically important aspects of crop yield, further risking under- or over-estimation. Some studies instead use a range of values from Klein et al., (2007), who report pollinator dependence rates of each crop in % terms, within categories. However, these categories are not evenly distributed, for example the “great dependence” category ranges from 40-<90% dependence while the “modest” dependence category ranges from 10-<40%. Finally, the method fundamentally assumes that pollination services are already at maximum levels, whereas in reality there may be localised or widespread deficits in pollination services, meaning that the method may overestimate the total loss. Unless additional assumptions are made to redress this, Dependence Ratio is not a suitable route for estimating any potential economic gains from increased pollination services.

When is it suitable? Dependence ratio methods are best used to illustrate the general economic benefits of pollination services at larger scales and where comprehensive crop data is available (Bourges et al., 2020; Chaudhary and Chand, 2017).

Examples:

Lautenbach et al. (2012) – This study is the most widely cited global estimate of economic benefits from pollination services. The authors use the 2000 global crop map to estimate the economic benefits of pollination services at a 10km global scale, producing a detailed map of pollination benefit hotspots at a global scale.

Bourges et al. (2020) – This study uses local primary data sources to capture the full range of economically valuable crops in Para state, Brazil. They note that the economic benefits of pollination are heavily dominated by Acai (*Euterpe oleracea*), which accounts for ~64% of the total benefits of pollination but has only recently been added to local data collection and thus would be absent from assessments otherwise.

Breeze et al. (2021) – This study uses a modified Dependence Ratio method, in which benefits are linearly related to pollinator abundance, to illustrate the potential economic benefits of a number of fully costed and statistically robust potential UK pollinator monitoring schemes. This study is an example of an applied cost-benefit analysis against a real policy to influence decision making (in this case to finance pollinator monitoring). This study also uses a bespoke set of dependence ratio values drawn from UK-centric literature for greater accuracy.

4.2.3 Production function models

What it Captures: The commercial price of yield increases from pollination services on crop output alongside other inputs and ecosystem services into a crop production system. Unlike other Factor income methods that only consider the presence or absence of pollination, Production Function Models can consider pollination as a marginal input and thus estimate the economic benefits of different amounts of pollination service. This is a quantitative economic method that measures instrumental values in monetary terms.

Methodology: Production functions are a family of regression models that measure the relative impacts of different inputs on an output (e.g. crop yield). Inputs can be measured in various ways: from the quantity applied in the case of manufactured capital inputs to relevant measures of ecosystem services such as soil carbon measurements. The costs of these inputs, including the opportunity costs of maintaining ecosystem service providing habitats, can be incorporated into these models to give a full measure of the economic benefits of pollination. Production function models can take a number of structures such as additive functions, which assume that all inputs can perfectly substitute for one another, and Cobb-Douglas functions, which assumes no input can be substituted at all. All of them produce saturation curves with diminishing marginal returns (i.e. there will be a cap on the maximum benefits from each input/ecosystem service and each unit of input/ecosystem service is assumed to add less benefit than the previous unit).

Data needs: Production function models ideally require a range of data that are able to link crop production to inputs or ecosystem services. This typically requires primary field data where these multiple factors can be assessed simultaneously. In the case of pollination, as an economically marginal input, this will follow the methods described for yield analysis with open and excluded pollinator treatments. The levels of pollination services can be quantified as the number of pollinator visits (possibly weighted by the efficiency of the taxa visiting) and/or individual pollinator efficiency (page 13). The absolute presence and absence of pollination (following e.g. Delaplane et al., 2013) can be used but will be less accurate than predicting the benefits of partial pollination.

This data should be complimented with other information on the quantities of inputs and/or other ecosystem services into the crop, for example the quantity of pesticides applied or the base soil quality. Input data can be gathered from collaborating farmers and should ideally include specific details such as the chemical pesticides used and the timing of their applications. Fieldwork will often be necessary to assess the levels of ecosystem services, with specific methods required to quantify each aspect of the farm system (see e.g. pest control – Lundin et al., 2013). Finally, data on local climate across the whole crop season, notably rainfall, temperature and light, may also be necessary and can be gathered from local meteorological agencies (e.g. Met Office, 2022).

Crop output will require both price data and, where applicable, quality parameters. Crop price data can be gathered from growers directly or from national statistical agencies (e.g. DEFRA, 2022). Quality thresholds should be gathered from local growers, co-operatives or from any national standards (e.g. EC, 2004). Ideally, the production function model should also include the costs of inputs in order to estimate the impact of pollination and other inputs on net crop economic output. This can be gathered from retailers or farmers directly, or from relevant agricultural handbooks.

Strengths: Production function models are able to estimate the benefits of pollination services in relation to other inputs, meaning that with sufficient data, they can provide a more accurate estimate of the benefits of pollination than other methods. Notably, they are especially suitable for estimating the benefits in crops that are very highly dependent upon pollination, where other methods may, inaccurately, attribute almost all the crops' value to pollinators. As they estimate benefits based on units of input, they are also able to estimate the economic impacts of partial gains or losses in pollination services rather than their absolute losses.

Weaknesses: Production function models require considerable amounts of data, ideally gathered from multiple sites and under multiple conditions, to estimate the relative impacts of pollination among other inputs. Although methods exist for assessing pollinator visitation rates and pollen deposition, these can be time and resource intensive. Finally, a key challenge in developing production function models for systems as complex as crops, which benefit from multiple inputs and environmental/ecological factors, is developing concise models that are both informative and useful. The number of variables in the model can be reduced using e.g. Akaike Information Criterion or other model selection procedures, principle component analyses or other methods of creating aggregate variables, or through transforming variables into more meaningful alternatives – for example changing pesticide applications into a single toxicity index. However, each of these is a potentially time intensive step and requires specialist knowledge to apply soundly.

When is it suitable?: Production function models are an ideal standard for assessing pollination service benefits at a local scale where multiple factors can be assessed. Extrapolating the results to a larger scale is possible, but a sufficiently large number of sites must be sampled in order to capture site variation and there may be difficulties in accurately determining the relative levels of inputs.

Examples: None. To date there have not been any dedicated pollination production function models (although see Hoshide et al., 2018 for an example of a model using managed honeybees only). The method however is widely described and advocated (e.g. Hanley et al., 2015; Breeze et al., 2016).

4.3 Stated preferences

Stated Preferences are a family of economic methods for assessing the monetary value ascribed by people to a particular subject. Within ecological economics, stated preferences have often been used as a way of eliciting values for ecosystem services, rare/endangered species or other natural capital assets that are not directly measured by markets. Here, we present a concise overview of the main methods discussed within the literature.

What it measures: The economic value of the existence of specific ecosystem services, taxa or habitat and/or the non-market value of benefits of these ecosystem services, taxa or habitats (e.g. aesthetic value of insect pollinated wild flowers). This method is principally a quantitative method, but qualitative elements can be added. The method can be used to measure intrinsic, instrumental or relational values in monetary or socio-cultural terms.

Methodology: Stated preference studies typically use a questionnaire survey to generate data, although other socio-economic research tools can also be adapted. The survey acts as a hypothetical market for an ecosystem service, taxa or habitat that is not currently captured in existing market structures. Respondents are then presented with bundles of goods within this hypothetical market, each of which will include a price attribute, in order to estimate the monetary value they attach to their choices. The prices can either be framed as a willingness to pay (WTP) to either gain or avoid a loss of the bundle or a willingness to accept (WTA) payment to allow a degradation or forgo a gain in the bundle.

There are several forms of stated preference questionnaire types but the two most commonly used are contingent valuation and choice experiments. Contingent valuation surveys present respondents with a choice between a single alternative bundle of goods or a zero-cost alternative bundle, in which the ecosystem service, taxa or habitat are allowed to degrade. This can be double-bounded, in which case respondents are asked if they would be willing to pay for a higher or lower priced bundle depending on whether or not (respectively) they are willing to pay for the initial bundle. Choice experiments are similar but more complex. These surveys present respondents with a series of bundles (referred to as a choice set) with different attributes (including cost), again one of which is usually a zero-cost alternative which allows the asset to degrade. The respondents are then asked to make repeated choices between different choice sets, recording which bundles they chose in each set. The analysis then reveals their marginal choice probability and willingness to pay for the various attributes of the bundles, as well as the bundles as a whole.

Through sampling numerous respondents, the probability of respondents selecting a given bundle, and their aggregate WTP/WTA can be estimated using a number of discreet choice models. Discreet choice models are a form or regression model that are used to estimate the likelihood of making a choice given certain parameters about that choice and the respondent making it. They can take several forms, but logit and probit models are most commonly used as these models are suitable for binary outcomes (e.g. choice accepted or rejected).

Stated preference surveys are necessarily bespoke and require rigorous planning. The survey instrument should be designed following standard survey design principles (e.g. Henscher and Johnson, 1981, Newig, 2011) and, where possible, existing surveys to aid comparison. Analyses should ideally be identified prior to survey design in order to ensure the right questions are asked. Once designed, the survey should ideally be piloted in two stages: first with a focus group discussion to refine the wording of the questions and second with small pilot survey that can give an indication of variation in the responses. For example, if most of the pilot survey are willing to pay the highest amount for a bundle, it may be necessary to increase the payment amounts or make another amendment to make the most expensive option less attractive and avoid lack of variation needed to statistically estimate willingness to pay.

Once designed and tested, it is important to define the population to be sampled, referred to as the sample frame. The sample frame could be the general population (Diffendorfer et al., 2013; Breeze et al., 2015) or specific groups of people such as farmers (Narjes and Lippert, 2016) or beekeepers (Penn et al., 2019), but ideally the final sample should be representative of the frame as whole to avoid bias. The survey can then be distributed via post, telephone, in-person or online. Postal, telephone and in person surveys are more expensive but allow for longer, deeper questionnaires to be utilized. Online surveys can be disseminated via e-mail but ideally using social media through appropriate organisations to share a link.

For pollinators, these studies are often used to explore public willingness to pay for species conservation (Diffendorfer et al., 2013; Mwebaze et al., 2018; Penn et al., 2019) or for various benefits of pollination services such as animal pollinated aesthetic wildflowers, that are not captured in existing markets (Breeze et al., 2015; Hoshide et al., 2018).

Data needs: By their nature, stated preferences require bespoke survey instruments to gather data. However, prior information may be required to ensure the bundles in the choice/choice sets and the payment scenario are realistic. For example, if the bundles include links between certain management actions and percentage changes in bee populations, these links should be as accurate as possible. Similarly, prior information on the structure of the sample frame is required for determining the representativeness of the final sample. In the case of the general population, this can be attained from national population statistics on demographics such as age, gender and income (e.g. World Bank, 2022). More specialist sources may be required for data from more niche groups, for example statistics collected by government departments on e.g. farm business sizes, number of employees, turnover etc.

Strengths: Stated preferences allow researchers to estimate the economic value of potentially any environmental asset, even those that do not, or only loosely, interact with markets such as rare species of pollinators. The outcomes can provide evidence of the willingness of certain groups to pay for conservation and management policies, regardless of their other economic benefits. This is especially useful where the costs of management are likely to exceed the benefits of pollination services to crops (e.g. Kirchweger et al., 2020). This information can also be useful for developing alternative funding mechanisms beyond taxation, such as ecolables (assessing people’s willingness to pay for “bee friendly” products – e.g. Hoshide et al., 2018). The surveys can also be combined with qualitative methods such as focus groups (e.g. Lienhoop, 2018) in order to provide deeper insights into the motivations and interpretations of the values estimated.

Weaknesses: Like all survey-based methods, stated preferences require considerable time and resources to plan, implement and analyse. For large sample frames, such as the ‘general public’, a very large number of responses can be required to get a representative sample while more niche sample frames may not generate enough responses for strong statistical analysis. Stated preference surveys are often subject to a range of biases that can skew responses. For example, if the survey scenario is not convincing enough to the respondents, they may ignore the costs of options in the knowledge that they do not actually have to pay, resulting in very high support for the highest cost options (hypothetical bias -

Henscher, 2010). Although they can be used to value rare species and other non-market goods, respondents may also have difficulties forming preferences for such unfamiliar goods, especially if they do not interact with them (Christie and Gibbons, 2011). Some of these can be dealt with using careful survey design and statistical analysis, for example asking respondents if they ignored any attributes when making their decisions and incorporating this behaviour into the model (e.g. Breeze et al., 2015). The method cannot be used to capture the value of crop pollination services as this amounts to double-counting the benefits of pollination that are already captured in the crop price (whereas Production function methods, page 22, extrapolate this proportion of benefit from the market price).

When is it suitable? This method is most suitable when assessing the economic value for conserving pollinators or the non-market benefits they provide. Due to the numerous biases, careful study design is required to gain meaningful estimates of value in this way. The method is potentially more suitable for estimating willingness to pay for tangible pollinator friendly products (e.g. Khachatryan et al. 2017) or pollinator management (e.g. Penne et al., 2019) where the more realistic situation is likely to produce more reliable results.

Examples:

Breeze et al. (2015) – This study uses a choice experiment to estimate UK public willingness to pay for the conservation of pollinators and for the pollination services they provide towards maintaining local food supplies and the provision of aesthetic wildflowers. It uses different models to estimate WTP, one accounting for attribute non-attendance (respondents self-reported ignoring of certain attributes) and one without. The findings indicate a high general WTP for bee conservation and a relatively greater WTP for aesthetic wildflower pollination than for maintaining the availability of locally sourced animal pollinated foods.

Penn et al. (2019) – This study uses a contingent valuation survey to estimate WTP for purchasing a bee hotel as a means of supporting local solitary bee populations in Louisiana, USA. The study compared the general population with beekeepers and estimates the results using both differentiated and certainty adjusted models. The findings indicate that beekeepers are substantially more willing to pay than the wider public.

Narjes and Lippert (2016) – This study uses a choice experiment to examine Thai farmers willingness to pay for avoiding a 50% loss of local bee abundance and to make a 50% gain in local bee abundance. The results indicate a much greater WTP to avoid a loss of pollinators than to gain pollinators. This WTP is nonetheless significantly smaller than the estimated benefits of pollination to longan crop yield (using dependence Ratios, see page 21), but are still higher than the investment required to support local pollinator conservation.

4.4 Surplus modelling

Surplus modelling is a further step that builds upon factor income or replacement cost methods in order to convert estimates of economic benefit into estimates of the economic welfare value of pollinators. Surplus modelling involves the use of often complex econometric models that predict the impacts of shifts in supply and/or demand on welfare. Here we present a broad overview of these methods as they have been applied to pollination services. We do not detail specific models, the suitability of which will depend on the data available, the length of the time period assessed and the area under consideration.

What it measures: The economic value of pollination services to the welfare of consumers and/or producers, either within a single market (partial equilibrium model) or to several, interlinked markets (general equilibrium model). This is a quantitative method that measures instrumental value in monetary terms.

Methodology: Surplus models require an estimate of the supply and/or demand curves of a given crop in relation to its price on a specific market. These markets can be a whole country, an international commodities market or a small scale local market within a country. These curves are representations of the quantity available (supply) and the quantity consumed (demand) by the market at a given price. For most goods, as price rises, demand will fall as the product becomes unaffordable or undesirable for some consumers at the new price. Similarly, as supplies fall, prices will rise as the product becomes more or less available relative to demand, making it sensible to sell to higher paying consumers. Market equilibrium is said to occur at the point when the supply and demand curves intersect. Econometric regression models are then used to estimate the impacts that a shift in supply, caused by e.g. a loss of pollinators, would have on the price of the affected crop and the subsequent impacts this will have on the economic surplus of producers (Kasina et al., 2009), consumers (Breeze et al., 2021), or both (Gordon and Davies, 2003). This price change is estimated based on crops' price elasticity, a measure of what percentage change in price will result from a 1% change in supply or demand, assuming all other factors remain equal. Economic surplus is a measure of economic welfare: Producer surplus represents the cumulative difference between the costs of producing each unit of a crop and its sale price. Consumer surplus represents the total difference between what consumers actually pay for the crop and the maximum they are willing to pay for it. These surpluses represent the welfare of both groups: in the case of producers, it represents their net profitability, for consumers it represents the additional money they are able to use on other economic activities (spending, saving, investing, etc.) while still gaining the benefit of consuming the crop.

Most studies using surplus models use partial equilibrium models, where only a single market (that of the affected crop/country) is considered and which do not consider substitution effects (i.e. consumers' ability to swap between crops available to them or producers' ability to substitute pollination with other inputs). However, more complex general equilibrium modelling can be employed to explore the effects of pollinator loss on whole food systems, as different actors that benefit from the affected crop substitute different inputs or crops to compensate for the loss of pollinators (Bauer and Wing, 2016; Lippert et al., 2021). These require additional cross-price elasticities that measure the percentage change in the price of alternative products or inputs in relation to a 1% change in the price of the affected product.

Data needs: In order to estimate the impacts of pollinator loss on overall supply, most studies use dependence ratio metrics (see page 21), drawn from existing publications (e.g. the review by Klein et al., 2007) or expert opinion (e.g. Southwick & Southwick, 1992). A range of possible dependence values can be used to provide a measure of uncertainty. Data on crop production, usually by total volume, and sale prices per unit (kg or tonne) can be drawn from international databases (e.g. FAOSTAT, 2022), although local data sources may contain information on a greater number of crops (Lippert et al., 2021). Information on crop price elasticities can be estimated using economic modelling or gathered from existing data sources (e.g. Andreyeva et al., 2010). Cross-price elasticities are more complex to estimate and thus far studies have only used hypothetical, dummy ranges (e.g. Bauer and Wing, 2016). For many crops that are part of global food trade networks, it may also be necessary to consider the impacts of global trade on supply and prices (Murphy et al., 2022). These can be obtained from international databases (FAOSTAT, 2022) or from more local sources in the case of specific supply chains.

Strengths: Unlike other methods that relate pollination to losses in productivity, surplus models provide an estimate of economic value, in terms of welfare, rather than economic benefit in market terms. By capturing shifts in prices, this method better captures the real impacts of pollinator shifts on consumer and/or producer wellbeing. General equilibrium models can provide further realism and more conservative estimates of the real value of pollination within and across market sectors.

Weaknesses: Surplus modelling is very data intensive, especially if elasticities are to be estimated as this requires large amounts of long-term data. A reliance on dependence ratios to estimate pollination service losses means the estimates are very sensitive to errors in these metrics. Modelling consumer surplus is only really suitable for use at large scales, unless considering a very niche crop market as otherwise the impacts on supply, even in very highly pollinator dependent crops, are unlikely to be big enough to cause a significant shift in the market. As they do not account for substitutions within markets or inputs, partial equilibrium models are likely to overestimate the value of pollination to markets. General equilibrium models also require large amounts of additional data on cross-price elasticities and can be computationally complex to undertake. At larger spatial and temporal scales, these models inevitably require a number of assumptions that can bias their results in different directions (Southwick & Southwick, 1992; Lippert et al., 2021; Murphy et al., 2022).

When is it suitable?: Surplus modelling is most suitable for exploring the impacts of pollinator losses on producer welfare, especially for crops that are difficult to substitute. They can be illustrative at large scales and shorter time periods (e.g. Murphy et al., 2022; Lippert et al., 2021) where the projected shocks to crop yield changes are likely to cause significant shifts in global markets but before it would be realistic to expect a market response.

Examples:

Murphy et al., (2022) – This study used partial equilibrium consumer surplus models to explore the effects of pollinator losses in subsets of countries (based on their vulnerability to specific pressures) on global crop markets. Their results indicate that the biggest impacts are often not in those countries affected but in their trading partners who now have to pay higher prices, especially for crops with a relatively limited growing range.

Lippert et al., (2021) – This study estimates the impacts of both short- and long-term pollinator collapses on both producer and consumer surplus using a partial equilibrium model, on a global scale and using Germany as a case study. They conclude that partial equilibrium models are not suitable for estimating the long-term effects of both positive and negative pollinator shocks because of the adaptive capacity of producers and the market, concluding that a more comprehensive general equilibrium modelling approach is necessary to examine the impacts of producer responses to catastrophic pollinator losses.

Bauer and Wing, (2016) – This study is, to date, the only one to use the more comprehensive general equilibrium model that accounts for substitution effects between inputs and crops. Their study demonstrates that while partial equilibrium models may overestimate the direct value of pollinator losses, the full impacts of pollinator losses across sectors are substantially greater than on the directly affected agricultural sector alone.

4.5 Spatial modelling

What it measures: The economic benefits of pollination services from individual parcels of land. This is a quantitative method that measures instrumental values in monetary terms.

Methodology: Spatial modelling of economic values is relatively new. There are two variants of the approach to date, both of which attribute economic value of pollination services to particular habitats within a landscape, although they could be used to estimate the value of managed pollinators at particular points within the landscape.

Distance Decay functions: This model involves using dependence ratios, theoretical metric of the proportion of crop yield lost in the absence of pollination, for crops within the landscape to estimate the maximum potential economic benefit of pollinators. Then, a distance decay function is applied to each field to reduce this value, based on the proportion of the field that is further away from pollinator-supporting semi-natural habitats (e.g. Ratto et al., 2022).

Process-Based models: These models are more complex as they simulate processes involved in generating pollinator populations. Habitat data is used to estimate the relative abundance and visitation of certain pollinators based on i) the nesting and forage resources of the habitats in the landscape and ii) known traits about species foraging and population growth rates. The models can be extended to include an economic component by relating the projected visitation to maximum economic benefits, as determined by crop pollinator dependence ratios, by removing select habitat parcels and examining the difference in overall pollination services (e.g. Ricketts and Lonsdorf, 2013).

Data needs: Spatial modelling requires information on i) crop pollinator dependence, ii) crop yield and prices and iii) the structure of the focal landscape. Crop pollinator dependence ratios can be gathered from primary data, expert opinion or reviews of existing literature (e.g. Klein et al., 2007). Crop yield (t/unit area) and price data ($/per kg or similar) can ideally be drawn from local sources, such as farmer co-operatives, or if this is not available, from national or international databases such as the FAO Statistical Database (FAOSTAT, 2022). Where possible, this data should account for differences in prices between crop classes where quality is an important factor, particularly as national and international datasets often do not capture this quality variation (Garratt et al., 2014b).

Landscape data can be gathered in either vector (high resolution polygons of distinct land use types) or raster (landscape pixels containing information on the land uses within each cell) from national or international satellite mapping sources such as CORINE land cover data (Copernicus, 2018) or from local site data. Ideally the most detailed mapping data should be used for process-based models but more coarse data can be used for Distance Decay Functions.

Distance Decay Function models require specific functions to estimate the decay in visitation from the habitat. This can be a generalised value (e.g. from Ricketts et al., 2008) or use specific values for different taxa (e.g. Hipolito et al., 2018) and should ideally be based on primary ecological data, although expert opinion can be used (e.g. Summers et al., 2021). Process based models require additional data on foraging distances and reproductive rates of the pollinator guilds modelled, typically from primary ecological data, and the relative nesting and forage quality of each habitat type within the landscape, typically from expert opinion (e.g. Gardner et al., 2020). In both models, there should ideally be a relationship curve between visitation and crop output. Most studies assume that this is linear (i.e. pollinator-dependent yield is directly proportionate to pollinator visitation) but non-linear forms can be assumed or data from a production-function model (page 22) can be used.

Strengths: Spatial modelling is a potentially valuable planning tool, allowing for the identification of i) areas which are experiencing economic pollination service deficit, where pollinator restoration should be prioritised, ii) identifying key habitat patches for conservation and management, iii) evaluation of the costs and benefits of converting specific habitat to other land uses or vice versa and iv) developing accounts of pollinator natural capital stocks and flows within the landscape. Process-based models are particularly realistic and can be used to explore the economic benefits of particular habitat configurations or future land management scenarios (e.g. Lopez-Cubillos et al., 2021). Distance Decay Functions are less accurate but require only relatively limited data (basic mapping data and ecological information on forage ranges) and computational power to estimate, economic benefits over any area.

Weaknesses: Spatial modelling can be particularly data-intensive, requiring accurate landscape maps over the area under consideration over the full span of time considered. This can be problematic in areas where crops are rotated between years as the actual demand for pollination will not be static between years. Furthermore, many satellite datasets do not distinguish between different crops, making it difficult to determine whether animal-pollinated or wind-pollinated crops are grown in a particular field in a given year. Similarly, fine-scale edge features are often very important to supporting pollinator visitation (Gardner et al., 2021) but are often absent from many mapping datasets.

The results can also vary significantly depending upon the quality (Magrach et al., 2019) and resolution of the data used to construct them: notably the relationships between pollinator visitation and crop output which have thus far only been crudely estimated using pollinator dependence ratios. Distance Decay Function models are much simpler but potentially much less accurate as they do not account for the abundance of pollinators within the landscape or their behaviour throughout the year. Process-based models are computationally intensive, making them highly demanding for larger scales and multiple sites and have only been developed for bees and not other pollinator taxa.

When is it suitable?: Spatial modelling is mainly useful for i) assessing the impacts of changes in land management, ii) identifying areas of pollinator deficits and iii) measuring the value of pollinator natural capital over larger areas. Due to the fine scale at which habitat changes affect pollinator populations and pollination services, the models are most accurate with high resolution data but this can be challenging to acquire for large areas. Studies over larger areas should be mindful of this.

Examples:

Ricketts and Lonsdorf (2013) – This study used a process-based model to examine the value of forest parcels in a shade-coffee landscape, identifying the key forest parcels that contributed the greatest economic value to pollination services.

Capriolo et al (2020) – this study used a process-based model to examine the economic value of pollinator natural capital stocks across the entire country of Italy. The study contrasts the available supply of pollinators with the value of pollination services, highlighting that many areas of strong pollination services have relatively limited economic value and vice versa.

Hipoloto et al (2019) – This study uses a Distance Decay Function to examine the economic benefits of pollination services to crops in the Serra da Bocaina national park, Brazil. The study notably uses different decay functions for different bee taxa based on the taxa observed within the park.

5 Nutritional values of pollinators

In addition to the economic impact that pollination has on crop productivity, by supporting the availability of food, pollination can also play a significant role in human nutrition. Measuring the value of pollinators and pollination in a nutritional context is relatively new with less studies directly assessing these benefits. These studies are also largely illustrative, exploring the benefits of pollination to the nutritional value of individual crops and the potential consequences of pollinator losses on human welfare. To date, no studies have explored the impacts of pollinator loss on non-human animal nutrition or the nutritional profile of soils.

The methods for exploring the nutritional values of pollinators are derived from those used to measure the economic values of pollinators. As such, they are still relatively basic and can be classified in two ways: crop nutritional value and dietary value.

5.1 Crop nutrient analysis

What it captures: The impact of pollination services on the micro and/or macro-nutrients available in the crop. This is a quantitative method that measures instrumental values in biophysical terms.

Methodology: This method involves conducting agroecological experiments to eliminate animal pollination from a crop grown under realistic conditions and comparing the quantities of nutrients produced in crops with (open treatment) and without pollination (excluded treatment). It is very similar to yield analysis (page 18) except that it explores nutritional, rather than economic responses.

Exclusion treatments involve placing a fine mesh gauze, sometimes with a wooden frame as appropriate, over a sub-sample of either a) an individual plant (in the case of herbaceous crop plants such as strawberries), b) an area of crop plants (in the case of high-density crops such as oilseed rape) or c) a specific branch (in the case of tree crops). The mesh should be fine enough to allow for wind-pollination and not so restrictive as to interfere with self-pollination. At harvest, the total weight of each harvested fruit, pod or seed should be measured in order to estimate the concentration of each focal nutrient. Once harvested, crops should be appropriately prepared for chemical analysis for each of the focal nutrients in the crop for both the open and excluded treatments. Which analyses are to be undertaken will vary depending on the nutrient(s) to be analysed and the facilities available but can include near infrared spectroscopy for fatty acids (Armenta et al., 2007) and atomic absorption spectroscopy for minerals (Wood et al., 2022). Analysis is typically expressed as nutritional concentration per unit weight but can also be upscaled to a per fruit or per unit area of crop basis.

Data needs: Field studies should be well replicated in order to produce a sufficient number of samples for nutritional analysis in the open and excluded treatment. Ideally, exclusion experiments should follow standardised protocols (e.g. Delaplane et al., 2013; Vaissiere et al., 2011) and be conducted under realistic, field conditions. Key nutrients in each crop can be identified from nutritional databases such as the USDA FoodData Database (USDA, 2022). When selecting sites, it is important to consider the varieties grown in each field, as their responses can differ (e.g. Garratt et al., 2021).

Strengths: This method gives a precise measure of which nutrients are or are not affected by animal pollination under field realistic conditions. The ecological methods are relatively straightforward and do not require significant expertise or resources to undertake. It is also relatively straightforward to expand the method in order to incorporate other treatment factors, such as variation in crop inputs.

Weaknesses: Crop nutrition analyses can require considerable laboratory resources to undertake the chemical analyses, especially if conducted at a large scale, using multiple treatments. This in turn can limit the number of nutrients it is possible to analyse. The basic method also does not account for the influence of other factors that can affect nutrient levels, such as fertilizers and water (Wang et al., 2018). Similarly, without significant spatial replication, this method only gives results for a specific area and often only for a single variety, making the results difficult to generalise.

When is it suitable?: Crop nutritional analysis is mainly useful for illustrating the potential benefits of pollination to specific crops and, potentially, as data generation for larger scale nutritional analyses on key animal pollinated crops. In crops such as watermelons where pollination is critical to the production of economically viable yields, this method is of relatively little value as such crops, without pollination, crops are unlikely to ever enter the market, meaning comparisons have little value. As such, it is more meaningful when applied to crops which have a more modest degree of pollinator dependence (e.g. sunflower, soybeans – Klein et al., 2007). Caution should also be taken when interpreting results as lower concentration of nutrients per unit area of crop may be compensated by higher total nutrient availability per unit of crop due to increases in total weight or fruit set.

Examples:

Garratt et al., (2014b) – this study examined the impacts of open and hand pollination on nine different nutrients in UK gala apples. In both cases, the analysis indicates that nutrient concentration is generally lower in the pollinated treatments, particularly for magnesium and zinc, but this is greater in the hand pollinated treatment. However, as the same study also demonstrates a significant pollination-driven yield deficit in gala apple orchards, the sum quantity of nutrients available per hectare is likely to be limited by pollinator limitation.

Silva et al (2018) – this study examines the impact of pollination on three Tocopherols and nine fatty acids in Brazilian sunflowers. Open pollination resulted in an increase in all Tocopherol and six fatty acids, most notably polyunsaturated fats such as Omega-6 and Omega-3 that have notable health benefits.

5.2 Dietary dependence analysis

What it measures: the proportion of nutritional intake attributed to animal pollination and the potential health consequences of the loss of this intake. This is a quantitative method that measures instrumental value in biophysical terms.

Methodology: This method involves using data on food consumed and nutritional quantities per unit of food in order to identify the gross proportion of each nutrient that can be attributed to animal pollinated crops. Then, for each food, quantitative measures of the proportion of yield lost in the absence of pollinators (dependence ratios, see page 21) are then multiplied by total nutrient in order to estimate the promotion of current nutritional intake that is dependent upon insect pollination.

Data needs: This method requires three principal forms of data: crop pollinator dependence data, food consumption data and nutritional data. Pollinator dependence data can be drawn from published literature, notably the global review by Klein et al (2007), which is widely used within the existing literature (e.g. Eilers et al., 2011; Smith et al., 2015; Gosh and Jung, 2018). Food consumption data should ideally be drawn from primary data, stratified by demographics such as the EFSA Comprehensive European Food Consumption Database (EFSA, 2021) or local surveys and food diaries (e.g. Novalis et al., 2016). However, local food production data from the FAO statistical database (FAOSTAT, 2022) or other agricultural statistical data is often used as a proxy where local consumption is not available. Nutritional data on specific foods can be drawn from open access databases such as the USDA FoodData Database (USDA, 2022). Ideally, the method should also be augmented with information on crop substitution among consumers to identify likely responses to pollinator losses and combined with economic analyses to determine the consequences of these market shifts.

Strengths: Dietary Dependence analysis allows for an in-depth analysis of the role of pollination in supplying specific nutrients to the population and how diets may need to adjust in response to losses. The method is also relatively straightforward once the required data is collected and is suitable for rapid or large-scale analyses of whole countries or comparison between different groups of consumers.

Weaknesses: Accurate dietary data is often difficult to acquire, particularly for specific groups such as pregnant women or children. Many studies have used crop production data to approximate consumption however this needs to be supplemented with trade (import and export) data to accurately determine final consumption data as many crops are widely traded (Sliva et al., 2021; Murphy et al., 2022) and this still does not account for crops that are processed, altering their nutritional properties. To date, studies have only used pollinator dependence data derived from studies that consider the effects of pollination on total yield, rather than the specific loss of key nutrients, which may become more concentrated in the absence of pollination, partially mitigating the yield losses. This could be addressed by upscaling crop nutrient analysis studies where possible (page 31).

When is it suitable?: Dietary Dependence Analysis is useful to illustrate the value of pollinators to overall human health. It can be applied at any scale, however there are inherent trade-offs: at a smaller scale, more accurate dietary information may be obtained but, unless food supply chains are well understood, it is more difficult to determine the main sources of pollinator dependent food risk. At larger scales, dietary information may be more generalised but appropriate large scale information on food availability may be more accessible.

Examples:

Smith et al (2015) – This study extended the Dietary Dependence Analysis by using data on the links between recommended intake of micronutrients and preventable diseases to explore the impacts that a reduction in nutrition would have upon mortality and quality of life. The findings indicate that around 1.7M preventable deaths would occur and 27 million people would suffer poorer quality of life as a result of this loss.

Chaplin-Kramer et al (2014) – This combines a dietary dependence analysis with spatial information on global crop production and information from the World Health Organization on incidence of vitamin deficiency to examine the overlaps between pollinator-dependent micronutrient production and existing nutrient deficiency. They find a strong overlap between the consumption of pollinator-dependent vitamin A and Iron and areas of existing nutrient deficiency, indicating that pollination is especially valuable to nutrition in these areas.

6 Socio-cultural values

As the previous sections highlight, distinct methods have been developed to determine the ecological, economic and nutritional values of pollinators. Arguably, economic and nutritional values are socio-cultural by nature, as they are anthropocentric, i.e. relate to the direct impacts on or relationships with humans (financial gain, pollinators and pollination within ecosystems) and focus on the benefits to us (Hall and Martins 2020).

However, there are further socio-cultural values of pollinators which are less or unlikely revealed through these other methods. Those include pollinators’ importance to leisure and recreational activities (non-commercial beekeeping, pollinator-friendly gardening, butterfly recording), cultural identity and heritage (traditional crop varieties, wildflower meadows), aesthetics (pollination-dependent flowers in landscapes), inspiration (visual arts) and emotional and spiritual values (IPBES, 2016). Pollinator conservation itself can be viewed as a socio-cultural value too, as in part carried out for moral, ethical or aesthetic reasons (and sometimes providing spiritual benefits). Some of those dimensions bring value also from a more biocentric view, i.e. ethics-based value of pollinators by themselves.

All these socio-cultural values are explored by the social sciences and humanities, who study those and related dimensions using a diverse array of methodologies. Yet, to date, there are very few social scientific studies focusing on pollinators or pollination. Instead, the signposting to wider socio-cultural values so far is largely done by natural scientists and economists, in part as motivation for their individual studies but more importantly by research teams coming together to produce synthesis work aimed at bridging the interface between science and policy (Hall and Martins, 2020). Here, the socio-cultural dimensions typically embed more quantifiable (ecological or economic) arguments for greater impact and stronger connection to various audiences including decision-makers. It is here, therefore, that we see the greatest role of allocating socio-cultural values of pollinators: to provide linkages between the disparate dimensions for which hard evidence can or has been given. In the following section we provide an overview of the groups of activities, or means, in society that put value on pollinators and how they do so.

Activities in society that put value on pollinators

Through a dedicated search of the literature, we have identified three means through which socio-cultural values of pollinators are expressed, namely:

1) Through ecological and economic science-based assessments, including both individual research and consolidated works

2) Through activism, both individual and collective actions, including policy development

3) Through social scientific studies explicitly identifying attitudes, values and barriers to progress.

6.1 Ecological and economic science-based assessment

There are a large number of ecological studies of specific aspects of pollinators and pollination in which wider socio-cultural values are chosen to be included to stress the importance of the topic to society. Those works serve and contribute to the process of discourse formation and coalition, whilst signalling positions and creating legitimacy.

Yet more influential are synthesis works aimed at providing a scientific consolidated view, typically aimed at providing ‘state of the art’ and ‘knowledge gaps & needs’ (e.g. IPBES 2016, Stout and Dicks 2022). It is here where all the evidence of pollinator declines and their importance to society are brought together, with economic and ecological findings summarized and interwoven with socio-cultural aspects. These works can be generated from within the scientific community, but more likely involve other entities that then ‘request’ a synthesis. Those works typically build on earlier assignments, bringing in the latest quantitative evidence and combining those with socio-cultural values to make the strongest possible case for the need for action.

As part of the IPBES global pollinator assessment (IPBES, 2016), cultural values of pollinators were collated and synthesized, and included knowledge and values of pollinators held by indigenous peoples and local communities (IPLCs). Here, socio-cultural values serve an important role in the rhetorical armoring of specific conservation discourses (e.g. Arts et al 2012 for this principle in conservation, and the IPBES pollinator assessment as an example thereof). Whereas individual studies sometimes aim to address or shape policy (mostly relying on relatively passive means of diffusion), syntheses tend to direct and want to inform policy directly; to do so effectively requires getting the balance and relationship between 'scientific evidence' and wider socio-cultural values right.

6.2 Activism

Communicating the value of pollinators to wider society through activism often concerns demanding changes in policy and practice or demonstrating different approaches. Various forms can be identified that sometimes overlap, yet are sufficiently identifiable as such:

Co-developed research: Teams of researchers pairing up with other professionals to as directly and powerfully as possible influence policy and public opinion, often in association with major synthesis work (e.g. IPBES 2016)

Individual writing: For example, influential books (Goulson 2013, 2022; Lunde 2015), opinion pieces (Van der Sluijs et al 2021), giving public talks (Splivak 2013), magazine articles (https://www.discovermagazine.com/planet-earth/5-ways-to-help-save-pollinators-with-citizen-science), etc., to inform, raise awareness and influence broader society or more specific audiences therein (e.g. spatial planners - Wilk et al 2019)

Creation of action groups: Citizen science programmes (e.g. https://xpollination.org/), programmes by nature organisations (e.g. Friends of the Earth) and other actors (e.g. Royal Horticultural Society), etc., aimed at making pollinators visible as well as their socio-cultural value. These have often academics at the heart of initiatives, instigating (e.g. Bumblebee Conservation Trust founded within Stirling University, U.K.) and bringing in others with skills in marketing. The role of the press and social media key here, as is the development of meaningful activities to connect people with the plight of pollinators.

Individual non-academic actors demonstrating that things can be done differently (organic farming, bottom up rewilding initiatives, etc., sometimes morphing into collective action).

Examples:
IPBES (2016) - Authoritative assessment of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food production. This assessment was crucial towards successfully integrating pollinators into the 2016 Cancun agreement of the Convention on Biological Diversity (CBD, 2016) and has inspired numerous national pollinator strategies.

Goulson (2022) - This book clearly and concisely, explains the importance of insects to our survival, and offers a strongly expressed demand for action to avoid a looming ecological disaster of our own making.

6.3 Social scientific studies

Pollinator-centric social scientific studies that explicitly identify attitudes, values and barriers to progress are scarce. Papers relating to the cultural values of pollinators are highly dispersed and no standard or specific approaches were identified.

We identified the following categories of studies that investigate socio-cultural value of pollinators and pollination:

Literature reviews and searches. Cultural values in social scientific studies are often captured through literature reviews of published peer reviewed literature on the use and cultural values of pollinators, either with a focus on specific groups (e.g. stingless bees –

Quezada-Euán et al., 2018; bats – Low et al., 2021), or wider groups that included pollinators (e.g. insects – Duffus et al., 2021), or wider types of knowledge (e.g. Indigenous and local knowledge – Hill et al., 2019; practitioner knowledge - Anderson et al 2020). Databases used in these searches include organizational web searches, web search engines and bibliographic checking. Searches are carried out in English (e.g. Low et al., 2021), but also other languages, depending on the focus of the paper (for example inclusion of Spanish and Portuguese in papers focussing on tropical America - Quezada-Euán et al., 2018).

In some cases, the literature reviews are highly structured, for example capturing a range of information in each search (e.g. type of web search, date, search details, search terms, hits, and output, after replicate removal - Quezada-Euán et al., 2018). Other searches can be less structured or a first step towards identifying examples that could be explored in-depth (e.g. Duffus et al., 2021). Some reviews also include grey literature, including policy or government documents, conference papers, popular articles, dissertations and websites (e.g. Quezada-Euán et al., 2018; Low et al., 2021). Undue focus on the socio-cultural focus on honeybees, comes at a cost, as Hall and Martins (2020) point out; and more coordination among biological and socio-cultural researchers is called for to overcome problems of that kind.

Mixed methods: A number of papers identified through the REA used a mixed method approach to assess cultural values of pollinators. For example, Sumner et al. (2018) used an online survey with qualitative and quantitative elements, together with a number of searches to understand perceptions towards four insect groups (wasps, bees, butterflies and flies). Respondents were asked for words to describe each group (to obtain a qualitative assessment of emotion for each insect group visualised in a word frequency diagram) and ratings for each insect group to obtain a quantitative assessment of people’s emotion in respect to each insect group; statistical models were used to assess what factors might explain differences in emotion. Von Heland and Folke (2014) used mixed ethnographic research approaches including field walks, interviews and participatory observation as part of a wider study on culture and ecosystem services in Madagascar. Finally, to understand the local ecological knowledge of stingless bees in Mexico, Reyes-Gonzalez et al. (2020) used a combination of ecological sampling, semi-structured interviews and participant observation.

Assessment: As highlighted above global assessments also include social scientific approaches. As part of the IPBES pollination assessment, data was collected through a global call for indigenous and local knowledge (ILK) holders of Indigenous Peoples and Local Communities (IPLCs) resulting in discussions and information gathering; followed by the co-construction of an analytical framework; a literature review and spatial analysis to map data syntheses and examples against the framework (Hill et al., 2019).

In terms of the findings on cultural values attributed to pollinators through social scientific publications, a full summary can be found in Hill et al., 2019. Values include key roles in traditional beliefs (e.g. Duffus et al., 2021) and rituals (e.g. Quezada-Euán et al., 2018; Von Heland and Folke (2014)). Pollinators also play a key role in mythology (e.g. Quezada-Euán et al., 2018), while bats are sacred in many parts of the Asia-Pacific region (Low et al., 2021). Other cultural values of pollinators include their role in biocultural governance systems (Hill et al., 2019) – for example the Tanying tree in Malaysia revered for the hives of the honeybee *Apis dorsata* (Franco et al., 2014). Cultural values of pollinators are also associated with art (e.g. paintings, ceramics), architecture, fashion (e.g. jewelry and textiles) and design, as well as media, recreation and hobbies (e.g. collections, citizen science initiatives) (Duffus et al., 2021, Hill et al., 2019, Low et al., 2021). In terms of systematic ways of thinking about pollinator declines, Ellis et al., 2018 stands out, highlighting the need for connecting bee-related advocacy with struggles to confront capitalist agriculture.

Examples

Duffus et al., (2021) - A perspective article that highlights the key areas in which insects have changed our cultures, from culinary traditions to architecture to fashion and beyond. It proposes a framework to help portray insects —and their benefits to our societies—under a positive light.

Ellis et al., (2020) - Focussing on honeybees and North America, this social scientific work offers systematic ways of thinking about the bee crisis by examining the changing dynamics of pollination within industrial agriculture.

Hall, D.M. and Martins, D.J. (2020). - This review provides a good overview of the various connections between biological and socio-cultural dimensions of pollinator conservation. It also makes clear how important it is to bring those fields of research closer together.

Hill, et al., (2019) - Using the conceptual framework of IPBES, and centring on indigenous peoples and local communities, biocultural approaches to pollinators across 60 countries are identified. Three categories are identified, namely: the practice of valuing diversity and fostering biocultural diversity; landscape management practices; and diversified farming systems.

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