Economic Benefits of Pollination to Global Food Systems – Evidence and Knowledge Gaps: Final Report

Breeze T.D., Garratt M.P.D., Senapathi D., Willcox B.K. and Potts S.G.

Summary

Pollinators and the food system

1) **Animal pollination is important to global crop productivity.** Over 75% of globally important crops benefit from animal pollination, including high value fruits (e.g. apples), stimulants (e.g. coffee), animal feed (e.g. soy) and oilseeds (e.g. palm).
2) **Pollination directly benefits production but indirectly benefits all actors throughout the food system.** Ample pollination is important to underpinning crop yield, quality and stability for producers but can also benefit other actors in the food system by reducing waste, ensuring reliable supplies, and maintaining prices. Current research focuses on the direct benefits of pollination to production while neglecting other actors, particularly waste.
3) **All actors in the food system can impact upon pollinators.** Production has direct impacts on pollinators though changes in land use and management, applying agrochemicals and through the use of managed pollinators that increase resource competition and disease occurrence. However, processing, retailing and consuming actors can all drive these direct pressures through their demands for specific crops and crop products and all actors, particularly transport and production, can contribute substantially to greenhouse gas emissions.
4) **The benefits of pollination services are important to achieving food system objectives.** By supporting the availability of quality, nutritious foods and reducing waste, pollinators are important to achieving food system objectives such as food security, equitable access to food and resilient production.

Pollinators and Global Trade

5) **Trade in animal pollinated crops is important to international food systems**. Approximately 18% of average national crop consumption (local production + imports - exports) stems from animal pollinated crops, with 3-8% of this consumption arising directly from pollination. Losses of pollinators therefore represents a significant risk to food systems on an international scale.
6) **The importance of pollinated crop imports for consumption and/or export will affect how vulnerable different actors within national food systems are to pollinator losses.** Current literature focuses on the vulnerability of local production to pollinator losses. In reality, a country's trade in pollinated crops can fall into four categories: local dependence (supplies depend on local pollinators), exporting (the export of pollinated crops is a significant economic activity), globally dependent (much pollinated crop consumption is imported) and throughout (countries export almost as much as they import). In each category, different actors will have different degrees of vulnerability to pollinator losses locally and globally.

Measuring and valuing pollinator natural capital

7) **Measuring and valuing pollinator natural capital stocks is important for informed decision making.** National accounts of pollinator natural capital are important for measuring and monitoring the supply of ecosystem services to the food system relative to its demand and estimating the value of these stocks.

8) **Pollinator natural capital stocks cannot be directly measured but must be estimated from primary field data.** Although pollinator populations can be indirectly measured from pollinator monitoring schemes, such schemes are challenging to implement at large scale. Furthermore, as pollinators require multiple habitats to persist and sustain themselves, they cannot simply be attributed to specific habitat types like other natural capital assets. Instead, a combination of species-distribution models of key crop pollinators and process-based models of pollinator abundance within the landscape should be employed to estimate the stocks of key pollinators.
9) **Valuing pollinator natural capital flows is difficult because of the challenges in double counting.** As pollination contributes to crop productivity, its value is theoretically captured by asset valuation of crops. An alternative approach is to value pollination as the costs of replacing pollinator natural capital with honeybees (manufactured capital) but this is unrealistic in many countries where paid pollination isn't commonplace and managed pollinator number are insufficient. A better approach is to value flows of pollination services as a separate asset, subtracted from the asset value of crop production.
10) **Measuring pollinator natural capital is constrained by the availability of ecological data.** Although modelling methods for modelling pollination service stocks and flows exist, they are constrained by a lack of information on i) the identity of key pollinators to specific crops, ii) the links between land use pressures and pollinator populations, and iii) the links between crop pollination and yield, relative to other inputs.

Valuing pollination services in the food system

11) **Economic studies into the benefits of pollination overwhelmingly focus on production**. There are very few studies within the literature that consider the value of benefits to other food system actors or account for the impacts of global trade on the economic vulnerability of countries to pollinator losses.
12) **Economic studies into the impacts of food system actors on pollination focus on production.** The majority of studies have only examined the direct economic impacts of land use and management on pollination. Some studies have explored consumer willingness to pay for pollinator-friendly produce, but no assessment of the impacts of changing consumer demands on environmental standards on pollinators directly has been done.
13) **The value of pollinator natural capital may not always be sufficient to justify preservation at a farm scale**. Several studies into the trade-offs between land use conversion and pollination service provision have concluded that the benefits of pollination from any given habitat patch may be less than the value of additional crops in the same area. In order to more accurately assess this trade-off, the value of pollination should be measured over time and alongside other potential ecosystem service benefits from the same habitat.

High priority research for valuing pollinators in the food system

14) **Further ecological data is needed for accurate natural capital modelling.** Focused field research to establish basic <u>information on the identity of key pollinators</u> to major and emerging crops is essential in many countries. <u>Systematic pollinator monitoring</u> can provide the necessary information to accurately model and map pollinator natural capital stocks across space and time. Experimental research to establish <u>the marginal benefits of pollination, relative to other crop inputs</u> is essential to accurately measure and value the scale of benefits to production.
15) **Analysis of the structure of food systems is crucial to fully measure values.** Analysis of national crop trade and utilization is a necessary step to identify key locally grown and imported animal-pollinated crops. Focused research through interviews and market analysis will be required to identify the structure of specific crop-supply chains within a food system. Developing a simple,

easily replicated international pollinator risk index, based on known pressures to pollinators, is important to identify countries that are vulnerable to pollination service losses.

Conclusion

16) By focusing on the localised interaction between pollination and production (both benefits to and impacts of), current research significantly under-values the benefits of pollination to global food systems. As the value of pollinator natural capital is potentially less than the opportunity costs of expanding agricultural activities, it is important to better capture the value of pollination to these other actors to incentivise greater participation in and funding of pollinator management. More accurate and useable pollinator natural capital accounts can be generated by creating well defined workflows from pollinator monitoring to modelling.

Overview

Pollination by animals is important to the outputs of 75% of global crops plants, ranging from widely grown arable rotation crops such as sunflower and oilseed, to high-value fruits and vegetables such as apples and tomatoes (Klein et al., 2007). The global area of these crops has grown substantially since 2001 and many countries are becoming more dependent on pollination services (Aizen et al., 2019). Although some pollination services are provided by managed insects, such as the European honeybee (*Apis mellifera*), the majority are provided by wild animals, such as bees, flies and bats (Garibaldi et al., 2013; Kleijn et al., 2015). Despite their importance to global agriculture, there is mounting evidence of pollinator decline across the world, driven by pressures from human activities, particularly land use change, the poor use of agrochemicals, and climate change (Dicks et al., 2021). Faced with these declines, there has been global concern over the impacts that pollinator declines could have on the economy, human health and wellbeing and the stability of natural ecosystems that provide other ecosystem services (IPBES, 2016).

Measuring the benefits and values of pollinators in economic terms has been proposed as a means to support pollinator conservation efforts in four ways (Breeze et al., 2016): 1) to illustrate the scale of economic benefits of pollination services to different actors that may not fully understand their importance, 2) to evaluate and incentivise action by supporting cost-benefit or other such economic decision analyses, 3) to highlight the economic vulnerability and resilience of different areas to pollinator declines and 4) to measure, monitor and value pollinator natural capital stocks over time. To date, no study has reviewed pollination as part of a whole food system.

Here, we review the economic links between pollinators and the wider food system, quantify the importance of pollination to national food systems and crop trade, outline the data required to measure and value pollinator natural capital, critically assess the existing methods for economically valuing pollination to the food system and identify key research priorities to better value the importance of pollination in the food system.

Pollinators in the food system

Food systems are complex systems of actors that collectively encompass all aspects of the production, processing, distribution, retail, and consumption of food, and which deliver particular outcomes such as healthy diets, economic activities, or environmental sustainability (Zurek et al., 2018). Food systems are also influenced by outside drivers, such as policy, expert knowledge and social demographics, each of which can influence the actions of activities in the food system (UNEP, 2016).

Below, we illustrate a generalised food system (fig. 1, adapted from Hasnain et al., 2021) using a model of five key actor types within the food system: 1) Production – actors who produce raw food products (e.g. farmers or beekeepers) and those that support them (e.g. agro-chemical companies). 2) Processing and wholesale – actors who refine or disseminate raw food products. This includes livestock farmers who feed crops to animals raised for meat and dairy. Much of the total economic value in the food system is added at this stage (Hasnain et al., 2021). 3) Storage, transport & waste – actors that store, transport, dispose of, or recycle food. 4) Retailing – actors who sell food for final consumption (e.g. supermarkets, restaurants). 5) Consuming – actors who purchase and consume food. Each group of actors benefits from pollinators in particular ways and their activities will have certain impacts upon pollinators. To fully understand the economic impacts of pollinators and their shifts on food systems, it is important to value all of these links.

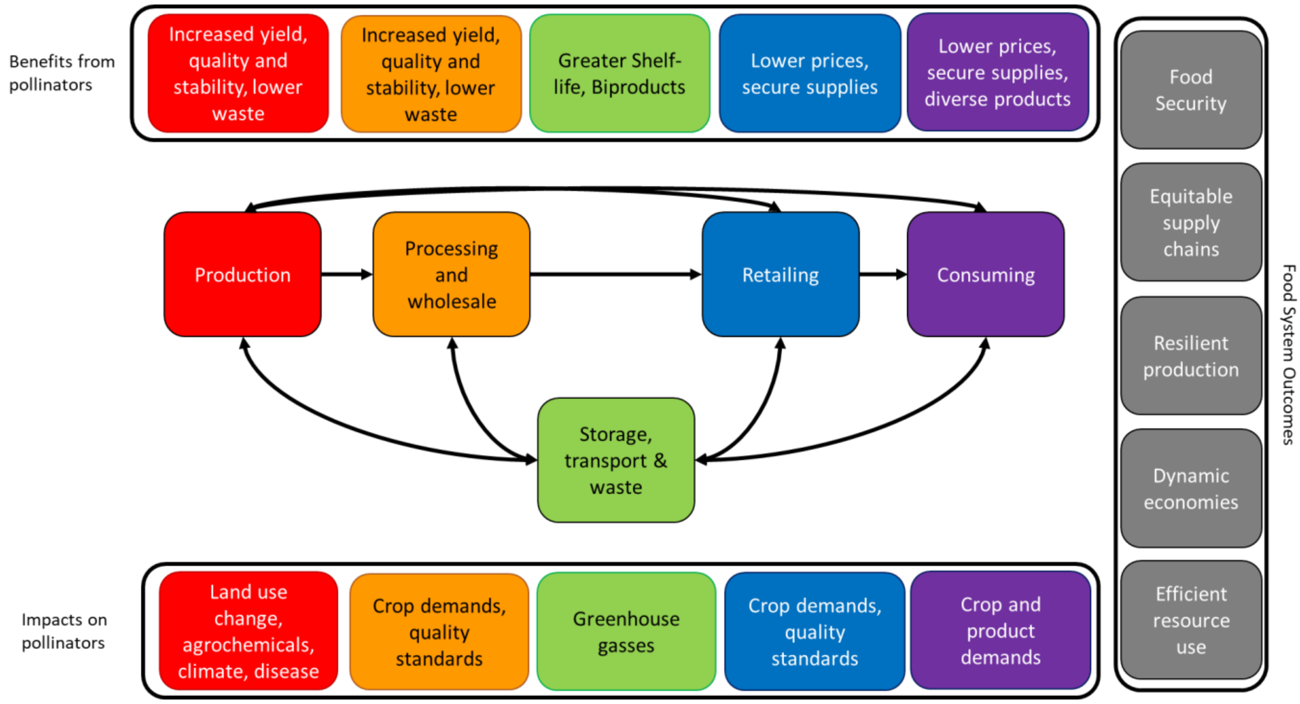

Figure 1: Representation of a food system, including the benefits of and impacts on pollinators for each actor

Benefits: Ample pollination of crops improves the **total yield** (the amount produced) and **yield stability** (how much yield varies from year to year) of many crops, resulting in greater overall stock for sale on the market (Bishop et al., 2022) by both producers and wholesalers (e.g. Bravo-Monroy et al., 2015). This in turn facilitates **secure, competitive supplies** for processors, retailers and consumers (Tremlett et al., 2021). Strong, competitive supplies relative to demand, in turn helps **maintain lower prices** for buyers throughout the system (Lippert et al., 2021) and the **availability of nutritious foods** for consumers (Porto et al., 2022). In some crops, such as apples and strawberries, pollination can i**mprove crop quality**, resulting in price premiums paid to growers and retailers (Garratt et al., 2021; Klatt et al., 2014), although markets may exist for processing lower-quality fruit (e.g. Lye et al., 2011). Parts of some animal-pollinated crops may be useful as **by-products** that can be recycled into the food system (e.g. fruit kernels used in bread-making - Lau et al., 2021). Crop pollination may also affect chemical profiles, resulting in **improved crop shelf-life** (e.g. Klatt et al., 2014), which benefits storage, transport & waste and retail actors, and **improved crop flavour** for consumers (e.g. Zhang et al., 2022; Wietzke et al., 2018).

These benefits will in turn contribute to typical food system outcomes, those characteristics desirable for a functioning and sustainable food system. For instance, by maintaining crop supplies, pollination helps underpin the availability of food and key micronutrients, in turn contributing to **greater food security**, (Smith et al., 2015), and **equitable access** to food (Chaplin-Kramer et al., 2014) as well as facilitating a **dynamic food sector** capable of producing multiple products (ICO, 2021). Pollinator diversity can also contribute to the functional resilience of farming systems (e.g. Gardner et al., 2021; Hutchinson et al., 2022). Finally, reduced waste, and a greater availability of valuable crop by-products (e.g. Gowan et al., 2019) will support **efficient resource use**.

Impacts: Producers exert the largest impact on pollinators, driving population shifts through **changing land use and management (including crop patterns)** (Millard et al., 2021) and **agrochemical use** (Stiver et al., 2021). Managed pollinators, which are often used in large-scale (e.g. Ferrier et al., 2018) or enclosed (e.g. Zhang et al., 2022) crop systems can place **competition** (Lindstrom et al., 2016) or **disease** (Prik et al., 2017) pressures on wild pollinators. Furthermore, the production and storage (via packaging) transport and waste of food is collectively a major emitter of **greenhouse gases** (Tubiello et al., 2021), in turn exacerbating climate change pressures on pollinators (e.g. Kerr et al., 2015). Other actors in the food system can directly or indirectly drive the persistence or change in these practices. Most critical are consumers, who's **demands for different crops and products** will drive domestic and international crop planting (e.g. Green et al., 2019) and who can exert significant influence on retailers, processors and wholesalers to enforce **minimum environmental standards** (Gereffi et al., 2005). However, demands for low prices or certain product qualities may in turn drive environmentally destructive practices, particularly in new or low-income trading partners (Jha et al., 2014).

The Importance of pollinators to global trade networks

A key element of many national food systems is the trade in raw crops between countries for processing and consumption (UNEP, 2016). Animal pollinated crops include some of the highest value per tonne crops (e.g. watermelon, tomato) and several globally traded commodity crops that are key to specific parts of the food system (e.g. soy, coffee) (FAOSTAT, 2022). Pollinator declines in any given country may therefore cause supply chain disruptions and price rises to food system actors around the world (Murphy et al., 2022; Vysna et al., 2021).

Previous studies have used similar data to explore the vulnerability of countries to pollinator losses (e.g. Aizen et al., 2019; Gallai et al., 2009) but have only focused on the vulnerability of initial production. In reality, global trade in animal pollinated crops determines what actors are vulnerable and thus the total economic risks and benefits within the system. This is especially true in countries which are significant processors and re-exporters of pollinated crops as these actors add the most value to the end product (e.g. coffee, where the greatest price increase is added at the roasting stage - Utrilla-Catalan et al., 2022).

Analysis of production, import and export data from 163 countries and non-self-governing-territories (NSGTs) in the FAO statistical database (FAOSTAT, 2022) indicates that, the average proportion of total crop consumption from animal pollinated crops is 18%, and an average of 7.7% - 3.4% of total consumption would be lost without pollinators. Globally, animal pollinated crops account for more than 25% of total consumption in 42 countries and NGSTs, and only accounts for less than 5% of total consumption in 10.

Based on our analysis, countries/NSGTs can be broadly grouped into four categories of food system vulnerability to pollinator losses (listed below). This is illustrated using the G20 nations (Table 1)

1) **Locally vulnerable consumers**: locally grown pollinated crops account for a substantial proportion of total pollinated crop consumption, with few imports or exports. Pollinator losses

in these countries would require a pivot towards imports to avoid food security issues. This would damage producers and consumers but may benefit distributors, retailers and transport. Examples: India, Turkey

2) **Locally vulnerable exporters**: significantly more pollinated crop is produced than is consumed, with a large proportion dedicated to exports and little imports. Pollinator losses in these countries would disrupt international trade, causing significant economic losses in the affected countries and their trade partners. Examples: Brazil, Canada, Malaysia
3) **Globally vulnerable consumers**: Pollinator dependent imports are a significant proportion of total crop consumption, after factoring in exports. Local pollinator losses would be less disruptive to actors beyond producers, but their food systems are more vulnerable to pollinator losses in trading partners. Examples: Japan, Germany, Saudi Arabia
4) **Neutral**: pollinator dependent imports are similar in scale to exports with the same product often being re-exported. Local pollinator losses would likely require the local food system to shift towards retaining imports, causing disruption to all food system actors except local producers. Examples: France, Italy, Russia

Table 1: Animal pollinator dependence of G20 countries

Country	Proportion of **total consumption** (t) from animal pollinated crops	Proportion of total animal pollinated consumption from **imports**	Proportion of total animal pollinated production **exported**	Vulnerability class
Argentina	32.9%	3%	22%	Exporter
Australia	6.3%	10%	46%	Exporter
Brazil	8.1%	2%	39%	Exporter
Canada	17.1%	17%	53%	Exporter
China*	25.3%	15%	1%	Globally Vulnerable
France*	12.6%	42%	31%	Neutral
Germany	17.9%	72%	29%	Globally Vulnerable
India	14.6%	8%	1%	Locally Vulnerable
Indonesia	8.7%	7%	37%	Exporter
Italy	27.5%	28%	15%	Neutral
Japan	17.5%	54%	1%	Globally Vulnerable
Mexico	18.4%	24%	22%	Throughput
Republic of Korea	16.3%	38%	2%	Globally Vulnerable
Russian Federation	14.1%	21%	11%	Neutral
Saudi Arabia	22.5%	54%	8%	Globally Vulnerable
South Africa	10.7%	18%	38%	Exporter
Turkiye	31.4%	12%	9%	Locally Vulnerable
United Kingdom*	13.5%	60%	21%	Globally Vulnerable
United States of America*	16.1%	4%	21%	Exporter

* These countries are presented as their mainland only, not including overseas territories or special administrative regions. Note that the G20 comprises the above 19 countries and the European union.

This assessment, although informative, is relatively shallow as it does not account for how national markets interact with the specific markets for particular crops. Markets for crops can range from very niche and localised (e.g. Tremlett et al., 2021), to highly diverse and dispersed (e.g. Lye et al.,

2011) or concentrated in certain parts of the food system. For example, trade in global commodity crops is often highly concentrated at the wholesale stage, with much of the sale to processors and beyond handled by a few large actors who purchase from across the world (Heron et al., 2019; Utrilla-Catalan et al., 2022). Analysing the structure of these crop supply chains and their link with the wider food system is a valuable next step that will help identify who in the system is vulnerable to pollinator losses and how this affects the vulnerability of the food system as a whole.

Understanding how particular national food systems are vulnerable to pollinator losses could influence how actors value and finance pollinator management. Globally vulnerable countries will see benefits concentrated in non-producer actors and would benefit from supporting pollinator conservation in their trading partners, particularly exporter countries, through e.g. Green Bonds (Thompson, 2022). Locally vulnerable countries on the other hand will see benefits concentrated in production and consumption and would benefit from investment in local pollinator natural capital.

Measuring and valuing pollinator natural capital

Although the importance of pollinators to the food system is widely recognised, information on the status of pollinators and thus the risks to the food system as a whole remain sparse (IPBES, 2016; CBD, 2016). In order to bring pollinators into economic decision making at a landscape scale and assess the economic risks of pollinator losses, there has been growing interest in measuring pollinators as part of spatially-explicit natural capital accounts, allowing for targeted interventions where pollination services to food crops are lacking (Vallecio et al., 2018; Capriolo et al., 2020). Natural capital assets are, under the UN System of Ecological Economic Accounts (UN SEEA, 2021), measured as **stocks** of the asset and **flows** of ecosystem service benefits from that asset. Here, we summarise existing work and identify key considerations in establishing pollinator natural capital accounts.

<u>Measuring pollinator natural capital</u>**: Stocks** of pollinator natural capital are, in theory, measured as the approximate number of pollinating animals available from local habitats while **flows** of pollination service are the levels of pollination services delivered (UN SEEA, 2021). Exact estimates of pollinator populations can be established from dedicated pollinator monitoring programmes but the costs of doing so at a suitable spatial scale (regional, national or international) for natural capital accounting are prohibitively expensive (Potts et al., 2021). As such, pollinator natural capital stocks and flows must be estimated based on their projected populations within a landscape (Capriolo et al., 2020). However, unlike other natural capital assets, the quantities of pollinator natural capital cannot just be linked to the presence or extent of specific habitats (as in Smith et al., 2021) as pollinators utilise multiple habitats in order to provide sufficient forage across their life cycle, and often nest in different habitats to those they forage in. Furthermore, different crops will have different pollinator communities and the effectiveness of particular species may vary between crops (Hutchinson et al., 2021; Kleijn et al., 2015). Thus, estimating pollinator natural capital requires modelling of both species abundance and diversity within a landscape.

Species occurrences can be estimated using <u>species distribution models</u> (e.g. Hutchinson et al., 2022), which project the distribution of specific species based on landscape or other characteristics. Pollinator abundance can be estimated using <u>process -based models</u> (e.g. Lonsdorf et al., 2009; Zulian et al.,2013; Gardner et al., 2020) which project relative abundances and visitation for different pollinator guilds within landscapes, using primary ecological data (e.g. flight distances) and expert-derived weights for habitat nesting and forage quality. The two model types can be combined to produce an estimated abundance of pollinator populations, weighted by the efficiency of the different local species in each guild. Presently, only one study, Vallecio et al., (2018) has linked the two models but did not weight the species effectiveness. The output of this modelling approach captures the **supply** and **use** of pollinator natural capital over time enabling the identification of areas where stocks are below demand (Vysna et al., 2021). To date, such models have only been developed for bees and no other pollinators and only tested in a few countries at a fine scale (e.g. Gardner et al., 2002; Koh et al., 2016; Vallecio et al., 2018).

<u>Valuing pollinator natural capital flows</u>: Once measures of stocks and flows have been established, they can be converted into economic values. As crop pollination is a regulating service, i.e. it contributes marginal benefits to economic activity (e.g. crops) rather than resulting in an economic value by itself, the economic value of pollination service flows to crops is captured in the sale price of the crops themselves. Thus, the UN SEEA recommends valuing pollination service flows as the costs of replacing wild pollinators with managed pollinators (UN SEEA, 2021). However, this is an unrealistic and often impractical means of measuring value as few countries have well established pollination service markets from which such prices could be drawn (Breeze et al., 2019) and does not capture the true scale of benefits from pollination (Hanley et al., 2015).

Pollination service flows can more accurately be valued by separating them from total value of the crop itself (La Notte, 2022). Again, this may be possible by monitoring pollination service levels with controlled experiments but is also likely to be prohibitively expensive on a large scale (Breeze et al., 2021). Instead, the projected visitation rates from process-based models can be converted into yield using distance decay or visitation-yield curves and the resultant projections valued based on the crops known pollinator dependence ratio (e.g. Ricketts and Lonsdorf, 2013; Capriolo et a., 2020). However, there is a lack of information on the relative importance of marginal changes in pollination compared with other inputs. Consequently, the value of pollination relative to other inputs may be under- or over-stated depending on the estimated dependence of the crop and, as threshold levels of pollination services are not established, visitation-yield curves are often based on assumed relationships (Capriolo et al., 2020; Kay et al., 2019). Furthermore, pollinators use different habitats in different time periods, particularly when crops are not in flower so the value of habitats in sustaining pollinators cannot be allocated to nesting resources alone, except in very simplified landscapes (e.g. Ricketts and Lonsdorf., 2013). As a result, current natural capital accounting over-attributes value to cropland at the expense of other ecosystems (Vallecio et al., 2018). Finally, as pollinator natural capital may exist outside the proximity of economically valuable crop production, it is also important to capture these potential flows as separate assets for future landscape planning, for example if markets shift to incentivise the production of mass flowering crops (e.g. the renewable fuels directive - Breeze et al., 2014) or to factor in future crop rotations (Gardner et al., 2021)

<u>Links with monitoring</u>: Although pollinator monitoring alone is not suitable for measuring or valuing pollination services, many of the challenges in valuing pollinator natural capital can be overcome by using widespread monitoring data (e.g. EU Pollinator Monitoring Scheme – Potts et al., 2021) to further refine and validate these models against real data (see Gardner et al., 2020). It is therefore important to create a dedicated workflow between monitoring and modelling, whereby projections are continually re-validated against monitoring data to improve their accuracy and monitoring efforts are partially re-targeted to explore projected deficits and trends in pollinator natural capital.

Based on our assessment, we recommend estimating stocks and valuing flows of pollinator natural capital, in a multi-step process:

1) **Identifying pollinated crops**– this can be done from existing databases of pollinated crops (e.g. Klein et al., 2007) and should ideally include crops that have the potential to be grown in the area, even if they are not presently.
2) **Identifying the pollinator community** – this can be done through field studies over multiple years or through a synthesis of existing field data from the area or climatically similar neighbouring areas (Hutchinson et al., 2021).
3) **Gathering primary data** – Pollinator populations can be directly measured through targeted monitoring efforts using standardised protocols such as the EU's Pollinator Monitoring Scheme (Potts et al., 2021).
4) **Modelling pollinator populations** – In many areas, it will not be practical to accurately monitor pollinator populations across the whole area. Instead, primary data can be used to develop models of i) the species occurrence of key crop pollinators using species distribution models (e.g. Hutchinson et al., 2022) and ii) the abundance of pollinator guilds, using process based models (e.g. Zulian et al.,2013; Gardner et al., 2020) to estimate populations based on the area and configuration of habitats within landscapes. These models can then be linked to provide a species weighted measure of pollination service supply.
5) **Valuing existing pollination service flows** – Pollination should be valued based on the marginal contribution of pollinator abundance to overall crop output (e.g. Capriolo et al., 2020), applying discounting as appropriate (UN SEEA, 2021). This accounts for pollination as a final rather than intermediate service and should be subtracted from the total value of crops (La Notte, 2022).
6) **Valuing underutilised service flows** – The value of service flows to fields not currently producing crops can be valued by replacing crop fields growing wind-pollinated crops with animal pollinated crops and capturing the difference in total flow and value. This should aim to be as realistic as possible, using crops within local rotations where appropriate.

Valuing pollination services in the food system

In the previous sections we outlined the economic importance of pollinator natural capital to the food system. Here we review the evidence of the scale of those values across the system via a rapid evidence assessment of the existing literature base via Web of Knowledge, adding further publications from literature cited within the results. Within the literature there are five main methods for valuing pollinators: 1) **Replacement costs** – where the value of pollination is equated to the costs of replacing some or all animal pollination with a technological replacement – most often the costs of hiring managed pollinators to replace wild pollinators. 2) **Production function methods** - a family of three related methods a) *Yield Analysis* – where the value of pollination is based on the difference in output (yield and quality) between pollinator and no/supplemental pollination treatments from field experiments. b) *Dependence Ratio* – where the value of pollination is based on metrics of yield loss in the absence of pollination (dependence ratios) derived from past studies or expert opinion. c) *Production Function Models* – where the value of pollination is based on marginal changes in crop output based on marginal changes in pollinators, controlling for other factors. 3) **Stated preferences** – where the value of pollinators or pollination service benefits is estimated through economic surveys of members of the public which ask them their willingness to pay for an ecosystem service benefit. 4) **Surplus models** – where the value of pollinators is estimated using economic models of the impact that yield losses would have on pollinator dependent crop prices and the subsequent effect that this price change would have on the welfare of producers (profits) and/or consumers (disposable income). 5) **Spatial modelling** – where the value of pollination services is modelled from spatial data on visitation rates with some form of marginal visitation to yield curve. This is often used to value pollinator natural capital.

Most economic valuation studies only consider the benefits of pollination to crop output (**total yield** and **improved crop quality**) at a producer level and do not account for any effects on other actors within the food system. Some studies use consumer surplus modelling to explore the impacts that higher **prices** resulting from pollinator declines would have on consumers (e.g. Lippert et al., 2021). These are only applied to the immediate consumers at the farm gate who are seldom identified (but will usually be wholesalers or processors). Two studies have considered consumer willingness to pay for **secure local supplies** of pollinated crops (Hoshide et al., 2018; Breeze et al., 2015). No studies have yet examined the economic values of pollination to **yield stability over time**, **reduced food waste**, **improved crop flavour**, **improved crop nutrition** or economically valuable **by-products**.

Very few studies value the benefits of pollination from a wider food system perspective. To date, only a single study (Tremlett et al., 2021) has evaluated the benefits of pollination to multiple actors across a whole supply chain (bat pollinated pittya cacti in Mexico). They find that, due to bulk purchasing and value-addition from processing, these benefits are greatest for processors and market retailers. Murphy et al (2022) demonstrate that pollinator losses in lower income countries could have large impacts on consumers in higher income countries, due to crop trade networks. Finally, Bauer and Wing (2016) demonstrate that the negative impacts of pollinator losses are likely to be greater outside of the crop sector itself, due to producers' ability to switch crops. These studies highlight the importance of considering pollinators to whole food systems but are limited by available data on crop markets (Bauer and Wing, 2016; Murphy et al., 2022) or focus on niche markets (Tremlett et al., 2021).

Of the food system outcomes, only a single study has estimated the economic value of pollination service **resilience**, and only in a single crop without considering other farm business factors (Matsushita et al., 2018). As noted previously, some studies have explored the economic (e.g. Gallai et al., 2009), production (Aizen et al., 2019) and nutritional vulnerability (e.g. Smith et al., 2015) of countries to pollination service losses but as these studies do not account for crop trade or the economic consequences of pollinator losses on public health, they do not yet fully measure the value of pollination to **food security**. No studies have yet assessed the impact of pollination on other food system outcomes such as **supply chain equitability**, **economic dynamics** and **efficient resource uses**.

In terms of valuing impacts on pollinators, the existing literature is also production focused. Studies have evaluated the economic impacts of **land management,** such as maintaining non-agricultural land as pollinator habitat (e.g. Ricketts and Lonsdorf, 2013; Hipolotio et al., 2019) or adopting pollinator-friendly practices (e.g. Agroforestry - Kay et al., 2019, field margins – Blaauw and Isaacs, 2014), **agrochemical use** (Kleczkowski et al., 2017) and **pest/disease pressure** (Cook et al., 2007; Vysna et al., 2021). More recently, studies have begun to explore consumers' willingness to pay for produce with pollinator friendly **environmental standards** (e.g. Hoshide et al., 2018). We did not identify any studies that estimate the impacts of **climate change** or **consumer demand** on the economic benefits of pollination.

Several studies on the impacts of management on pollinators explore the trade-offs between this management and production, forming a link between food system activities and pollinator natural capital management. Analyses of controlling pest and disease pressure to pollinators at a national scale overwhelmingly shows that management is cost-effective (Cook et al., 2007; Vysna et al., 2021). However, studies of land management and agrochemical use are more mixed, with some concluding that pollination services are not sufficiently valuable to offset the opportunity costs of maintaining habitat in most or all circumstances (e.g. Kleczkowski et al., 2017; Kirchweger et al., 2020) while others demonstrate that the cost-effectiveness is contextual (Cong et al., 2014), time dependent (Blaauw and Isaacs, 2014) or sensitive to data (Magrach et al., 2019) or objective variation (Lopez-Cubillos et al., 2021).

In light of these mixed results, future assessments of these trade-offs should capture other ecosystem service benefits, such as carbon capture or pest control stemming from pollinator supporting habitats (Wratten et al., 2012), and evaluate the long-term impacts of management on pollination services, which may affect yield stability (Gardner et al., 2021) and long-term economic resilience (Matsushida et al., 2018). However, these results also highlight the shortcomings in basing natural capital decision making on production benefits alone. While farmers may lack an incentive to act, other actors in the food system who benefit from pollination indirectly may have incentive to subsidise management through e.g. ecolabels or privately funded agri-environment management.

Key knowledge gaps

Pollination services provide significant economic benefits to actors across the food system, both at a country and international scale. Yet, to date the majority of research into the economic benefits of pollination services have been concentrated on production and not other actors. Furthermore, there are significant gaps in understanding of the economic vulnerability of food systems to pollinator losses because of: 1) shortcomings in our capacity to accurately map pollinator natural capital stocks and 2) limited understanding of how crop trade affects food system exposure to pollinator losses. Despite the importance of pollination and growing evidence of pollinator decline, studies into the cost-benefit of pollinator conservation are very mixed, with several studies indicating the costs of mitigating impacts can outweigh the benefits to producers alone. If the full scale of pollination benefits from multiple actors could be quantified, this may help identify new streams of support and investment in pollinator conservation.

Here we summarise the key knowledge gaps around a) the benefits of pollinators to the food system, b) the impacts of food system activity on pollinators, c) the relative economic risks of pollinator losses to food system actors and economies and d) the methods which are used to estimate the value of pollination to these different actors.

<u>High Priority</u>: These knowledge gaps are primary data collection and core analyses that need to be undertaken as a precursor to more advanced analyses. They are all fundamentally valuable and can be used to incentivise action on their own.

Knowledge Gap	Requirements	Outputs
What are the major crops used within different food systems?	• Analysis of national balance of trade • High-level study of crop use by the processing and retailing sectors	List of key animal pollinated crops grown locally and imported
Who are the key pollinators of each major (or future) crop?	• Observational field studies • Synthesis of data from neighbouring countries	List of key crop pollinators for targeting conservation action and natural capital modelling
Which countries are most at risk from local or international losses in pollination?	• Identifying key national statistics that can be used as large-scale proxies of risks to pollinators • Trade network analysis to identify volume of trade between countries	1) National scale pollinator risk metric, capturing local pressures. 2) Global risk index capturing the sum local risks from trading partners.
What is the structure of pollinator dependent crop supply chains within the food system?	• Interviews with key stakeholders • Trade network analysis	Overview of the number of actors that benefit from pollination and the economic data necessary to evaluate the value of pollination to these actors
How are marginal changes in pollination affected by marginal changes in other inputs and ecosystem services?	• Well replicated field experiments in different contexts where inputs are systematically manipulated. • Crop production function modelling of this data.	Ecological-economic production functions that can be used as the basis for natural capital valuation and cost-benefit analyses.
How do we link pollinator occurrence and abundance data to models of natural capital?	• Systematic pollinator monitoring • Species distribution and process-based models of key pollinators	1) A data workflow that links primary pollinator monitoring to continually refined models of pollinator natural capital stocks and flows 2) Spatially explicit maps of pollination service supply

<u>Medium Priority</u>: These knowledge gaps build on the high priority gaps to develop robust valuations of benefits and appraisals of risks to the food system.

Knowledge Gap	Requirements	Outputs
How do shifts in pollination services affect the economic welfare of actors through the supply chain?	• Price transmission analyses using market data • Consumer surplus modelling of impacts on different actors	Estimated value of pollination services to each actor within the food system
How do pressures on pollinators affect the delivery of pollination services?	• Pollinator monitoring data (in relation to pressures) • Data on pressures (e.g. hazard level of pesticides used, climate change etc.) • Spatial mapping of pollinator natural capital	Quantitative links between pressures and pollinator natural capital, allowing for more detailed assessment of trade-offs from land use and management.
What is the value of pollinator natural capital resilience?	• Long-term models of pollinator natural capital • Data on projected land use change (e.g. scenarios) • Models of links between pollination and yield, in relation to other inputs and pressures • Discount rates	Long-term values of pollinator natural capital and pollination services to production that can be used for long-term planning (e.g. improving stability where capital is already strong)
How do we model other pollinator natural capital besides bees?	• Pollinator monitoring data of non-bee pollinators • Modified versions of existing models that account for multiple life stages and dispersal	More comprehensive models of pollinator populations for use in natural capital and cost:benefit analyses.
How resilient are producers to pollination service losses?	• Farm business data on farm inputs and outputs • National data on the distribution of farm types • Models of quantitative links between pollination and yield, in relation to other inputs and pressures • Information on possible farm responses to pollinator gains and losses	Tools for assessing farm- and national-scale vulnerability to pollination service losses, their capacity to adapt and potential benefits from gains.
How resilient are other food system actors to pollination service losses?	• Information on the economic benefits of pollination for each actor • Information on pollinated crop consumption in consumer diets	Standardised risk assessment tools for other food system actors to assess their resilience to pollination service losses.
How do habitats that support pollinator natural capital support other natural capital?	• Review of existing natural capital account measures from pollinator habitat • Combined ecosystem service modelling	Multi-service models for use in cost-benefit analyses

Lower Priority: These knowledge gaps are important to consider but are more niche and thus less impactful overall

Knowledge Gap	Requirements	Outputs
How do consumers value pollinator friendly produce?	• Surveys into willingness to pay for pollinator-friendly produce • Panel studies into pollinator management and governance	An evaluation of the market potential of pollinator friendly products and how they can be implemented (e.g. ecolabels)
How does pollination affect economically costly waste and economically valuable by-products?	• Synthesise existing knowledge on by-products • Controlled experiments on the effect of pollination on crop shelf-life	For specific products, a more holistic assessment of the full economic benefits of pollination services and potential impacts on waste, transport, and retail
How do consumer preferences and/or changes in supply chains affect animal pollinated crop patterns?	• Long-term market data on crop demands and prices • Long-term data on farm input costs and other exogenous factors. • Spatial data on crop growing patterns	Assessment of the impacts of changing consumer preferences on cropping patterns – this can be combined with pollinator natural capital mapping to estimate changes in the supply and demand of pollination.

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