European Commission

Science for Environment Policy

FUTURE BRIEF: Pollinators: importance for nature and human well-being, drivers of decline and the need for monitoring

May 2020
Issue 23

Environment

Science for Environment Policy

Pollinators: importance for nature and human well-being, drivers of decline and the need for monitoring

Contents

To cite this publication:

Science for Environment Policy (2020) *Pollinators: importance for nature and human well-being, drivers of decline and the need for monitoring.* Future Brief 23. Brief produced for the European Commission DG Environment. Bristol: Science Communication Unit, UWE Bristol.

Acknowledgements

We wish to thank the scientific advisor, Adam J. Vanbergen (UMR Agroécologie (AgroSup/INRA/uB/UBFC), France), for his input to this report. We also wish to thank the following for their contributions: Claire Carvell (CEH, UK); Andrew Polaszek (Natural History Museum, UK); David Roy (CEH, UK); Helen Roy (CEH, UK); Constantí Stefanescu (Museu de Ciències Naturals de Granollers, Spain).Final responsibility for the content and accuracy of the report, however, lies solely with the authors.

Print	978-92-76-00597-1	doi:10.2779/699559	KH-BB-01-001-EN-C
PDF	978-92-76-00596-4	doi:10.2779/070	KH-BB-10-001-EN-N

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Executive Summary

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Pollinators are vital to our wellbeing and the survival of nature. By helping plants reproduce, pollinators support a steady supply of healthy and economically valuable food for humans and prop up entire ecosystems. However, we are at risk of losing these benefits, and many others, with the ongoing and dramatic decline of pollinators witnessed around the world.

This brief highlights the importance of pollinators for food production and nature, covering pollination of both crops and wild plants. It also explores the drivers of pollinator decline and the role of monitoring in driving the actions to reverse it. The report is written in the context of the EU Pollinators Initiative, a strategy for the EU and its Member States to address the decline of pollinators.

Three quarters of the world's main crop plant types need pollinators to at least some extent. Pollinators are not just responsible for boosting the yield of these crops and supporting food security: they also enhance crop quality and, in turn, their economic value. Many of these fruit, vegetable, nut and oil crops are essential to human health, supplying key nutrients for a balanced diet and helping prevent many serious diseases, including cardiovascular diseases and cancer.

Pollinators and the plants they pollinate form an intimate and intricate web of relationships that helps bind ecosystems together, create healthier plants and build a bedrock for the survival of other species. Reductions in plant health and diversity stand to have a domino effect that ripples throughout ecosystems, affecting and threatening other plants and animals through the tangled web of interactions between organisms.

Pollinator loss will also erode valuable ecosystem services for humans, beyond pollination. A resultant loss of pollinator-dependent plants will reduce the ability of ecosystems to store carbon and protect against floods, for instance, while the loss of certain pollinators themselves can also take away their pest control services. We also stand to lose the social and cultural values that many pollinating species provide to society.

A large number and diverse array of pollinator species is needed to provide effective and sustainable pollination of crops and wild plants into the future. Diversity ensures that pollination can occur under a range of conditions, for instance, at night-time, during different weather conditions or if the environment changes significantly. Different animals are also better suited to pollinating different plants. This pollinator mix should, therefore, include rare species to ensure a broad spectrum of pollination services.

Many people think of pollinators in terms of bees (and especially of honeybees), but flies, butterflies, moths, wasps, beetles and other insects are also important pollinators, particularly in Europe and most other temperate regions, with birds, bats and lizards also playing pollination roles around the world. Within each of these species' groups, a wide array of individual species is needed for high-quality and resilient pollination services. The full breadth of species diversity in existence is surprising; there are around 2000 bee species in Europe, for instance, and over 20,000 worldwide.

The reasons for wild pollinator decline are multiple, interacting and complex. However, we can identify the main drivers of pollinator loss as: land-use change, intensive agricultural management and pesticide use, environmental pollution, invasive alien species, pathogens and climate change. Of these drivers, evidence suggests that land-use factors, including the use of pesticides and fertilisers, have had the greatest impact on pollinator numbers and diversity by leading to the loss of food and nesting resources through habitat loss, deterioration and fragmentation. This is especially the case in highly simplified, farmed landscapes. Land-use change and management will continue to be influential in future, but we can also expect climate change to have much more of an impact on pollinator habitats in coming decades.

We need urgent measures to address wild pollinator decline. Understanding the status of pollinator populations, which plants they pollinate, and drivers of change can point to appropriate solutions to address pollinator decline. To achieve this, monitoring is critical – that is, systematic censuses of wild pollinators that provide robust data on their population numbers, diversity and impacts (e.g. pollination activity, response to environmental change). This needs to be done across different habitats and geographic regions and repeated over time to help reveal the causes and effects of their decline or recovery. After all, we cannot protect what we do not understand.

Furthermore, we cannot understand what we cannot identify. To this end, more support and regard must be awarded to taxonomy, the discipline of identifying and classifying organisms, which has declined over recent decades. Citizen science also has a critical and increasing role to play in monitoring. Its large, voluntary workforce can enable far more data to be collected than would otherwise be possible within available budgets. In many cases, volunteer expert naturalists also provide valuable taxonomic expertise.

Technological methods, namely DNA barcoding and some applications of artificial intelligence, are also likely to play an increasingly valuable role in monitoring, supporting the work of scientists, including taxonomists and citizen scientists.

Greater coordination and collaboration between new and strengthened networks of actors is needed to enhance the quality of pollinator research. Bringing together researchers from different fields, with public institutions, NGOs and businesses, would help to provide the broad range of perspectives needed to solve challenges in pollinator protection. Combining our understanding of drivers of pollinator population change with data on abundance and diversity is crucial, as is assessing and improving the resilience of pollinators to future environmental change.

Introduction

Pollinators provide many significant benefits to humankind and the environment. However, there is an ongoing and dramatic decline in the number and diversity of pollinating species in Europe and around the world. Pollinating species include bees, hoverflies, butterflies and moths, and some vertebrate species such as birds and bats. Many pollinator species are extinct or threatened with extinction.

This brief from Science for Environment Policy presents an overview of research into the benefits of pollinators for food production and security, the essential role of pollinators in nature, the drivers of change in pollinator populations and the importance of monitoring for pollinator protection. It is largely based upon peer-reviewed research, but also presents case studies that illustrate the nature and significance of pollinators, as well as the work that goes into investigating and supporting these essential creatures. The brief draws on evidence from around the world.

This brief is written in the context of the EU Pollinators Initiative,[1] which presents strategic objectives and a set of actions to be taken by the EU and its Member States to address the decline of pollinators in the EU and contribute to global conservation efforts. The Initiative's priorities are to:

- improve knowledge of pollinator decline, its causes and consequences;
- tackle the causes of pollinator decline;
- raise awareness, engage society-at-large and promote collaboration.

Pollinator decline raises issues that cut across a host of policy areas, including agriculture, management of rural and urban land, biodiversity, food, health, energy (biofuel crops), research and innovation.

At an EU level, relevant legal acts include:

- Birds and Habitats Directives;[2]
- Pesticides legislation (Directive 2009/128/EC, Regulation (EC)[3] No 1107/2009[4]);
- Common Agricultural Policy;[5]
- EU cohesion policy (including its urban dimension);[6]
- EU Framework Programme for Research and Innovation and LIFE.[8]

Relevant policies at a global level include:

- the UN Sustainable Development Goals (SDGs)[9] – especially regarding food security ('zero hunger') and biodiversity ('life on land'). Pollinator research also helps develop monitoring indicators, which can help measure progress towards meeting the SDGs;
- the CBD's International Pollinator Initiative[10] – with recently updated Plan of Action 2018-2030.[11]

1. https://ec.europa.eu/environment/nature/conservation/species/pollinators/index_en.htm
2. https://ec.europa.eu/environment/nature/legislation/index_en.htm
3. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A32009L0128
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10. https://www.cbd.int/agro/pollinator.shtml
11. https://www.cbd.int/doc/recommendations/sbstta-22/sbstta-22-rec-09-en.pdf

BOX 1.

What is pollination?

Pollination is the transfer of pollen between male and female parts of flowers enabling plant fertilisation and reproduction. Pollination can occur via wind and water, but animals are often crucial to the process: nearly 90% of the world's flowering plants require animal pollination (Gill *et al.*, 2016; IPBES, 2017). Most animal pollinators are insects such as bees, flies and butterflies, but there are also many other pollinator species (see Box 2: Know your pollinators).

Pollen carries the male reproductive cells, or sperm, of a plant. The transfer of pollen from one plant to another often involves a pollinator – such as a bee – visiting a flower to collect nectar or pollen for food (Nieto *et al.*, 2014). Whilst doing this, pollen from a male part of the flower (the anther) also sticks to the pollinator's head, foot or other body part (Nowakowski and Pywell, 2016). When the same pollinator visits either another flower on the same plant or on another plant of the same species, the pollen on its body sticks to a female part of the flower (the stigma, which is on the tip of a larger female reproductive part called the pistil) (Meeuse, 2018) (see Figure 1).

Once the pollen is stuck onto the stigma, a pollen tube grows inside the pistil, which allows the male reproductive cells to reach the female reproductive cell (an egg known as the ovule). This enables fertilisation and reproduction to take place and produces seeds from which new plants can germinate (IPBES 2017).

Pollinators benefit plants because they can travel some distance, even between countries in cases such as migratory hoverflies (Wotton *et al.*, 2019). This transfers pollen to another, separate population of plants of the same species, enabling cross-pollination. Cross-pollination helps maintain genetic diversity and species health (Wietzke *et al.*, 2018). Furthermore, some plants cannot self-pollinate (a form of asexual reproduction where pollen falls from the anther onto the stigma of a flower on the same plant) or are not adapted for wind pollination, so animal-mediated pollination is their only method of reproduction.

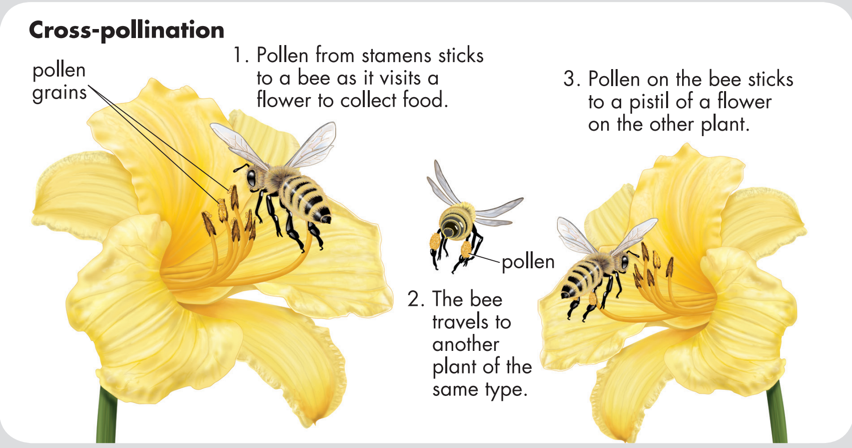


Figure 1. Illustration of a bee cross-pollinating flowers. The pollen is transferred from the male anther of one flower to the stigma on the female pistil of a flower on another plant. (Source: Meeuse B.J.D., 2018 by courtesy of Encyclopædia Britannica, Inc., copyright 2006).

BOX 2.

Know your pollinators: not just a honeybee

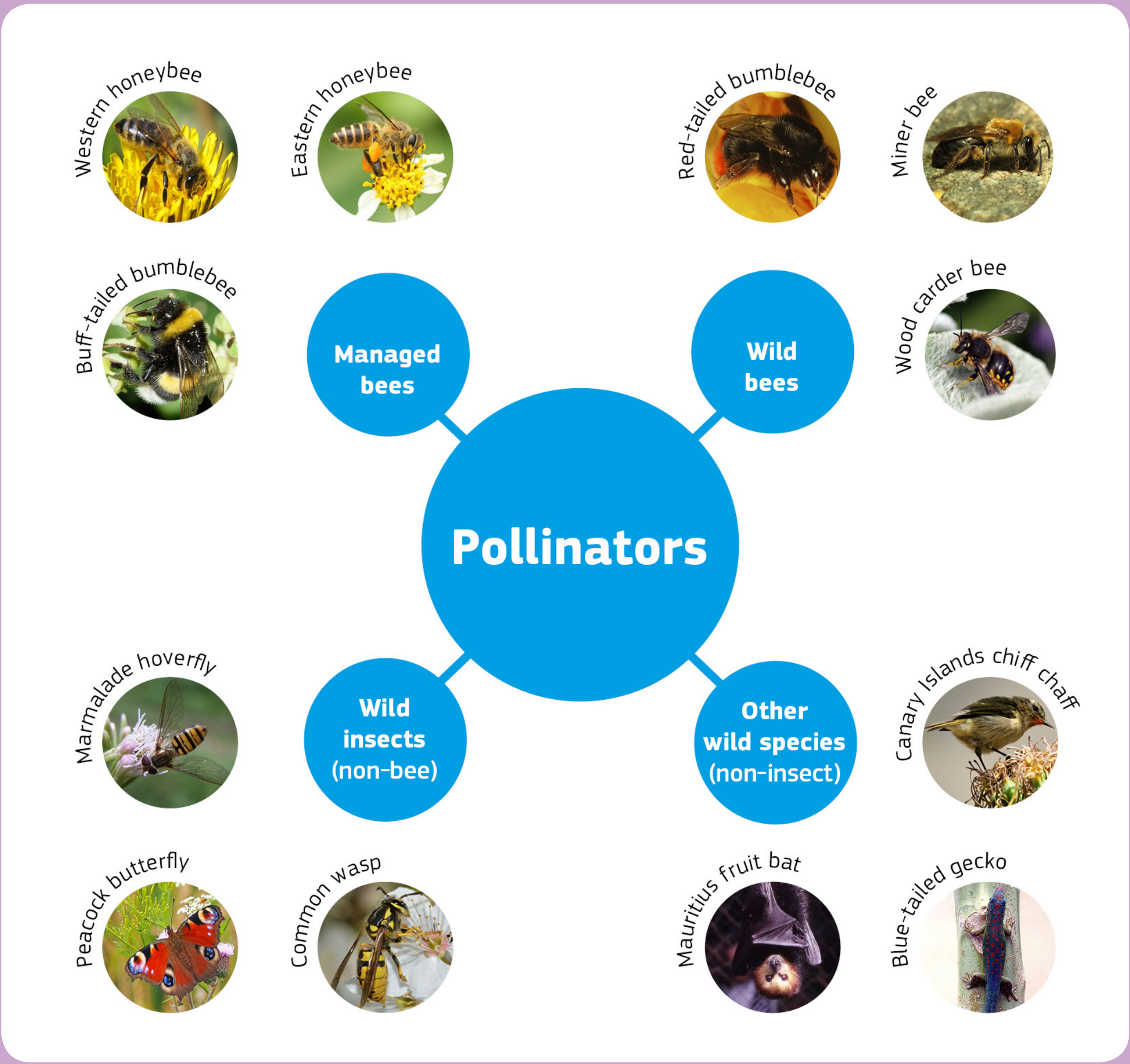


Figure 2. This tiny example of wild and managed species helps illustrate the diversity of pollinators.

Most people associate pollination with bees – honeybees in particular. There are actually 20 000 species of bee globally, and nearly 2 000 in Europe alone (IPBES 2017).

However, bees are only part of the pollinator picture. In truth, a diverse array of species pollinates plants. In Europe, insects are by far the most important type of animal pollinators, with bees, hoverflies (and other less well-studied flies like midges), butterflies, moths, thrips and beetles contributing to the pollination of both crops and wild plants. Despite their poor public image, wasps are also valuable pollinators.

Know your pollinators: not just a honeybee – *continued*

Vertebrate pollination in Europe is unusual, but some bird species (both native and introduced) contribute to pollination services. Globally, there are some fascinating examples of pollination services provided by birds, bats, lizards and mammals (Klein *et al.*, 2018), which are important for pollination in sub-tropical and tropical regions (IPBES 2017). Some of these species can be found in the EU's Outermost Regions and Europe's Overseas Countries and Territories – which include areas that host over 70% of the EU's biodiversity (Nieto *et al.*, 2014). The EU Outermost Region of French Guiana, for example, has many species of rainforest flower that are pollinated by a nectar-drinking bat species. For a number of plant species in tropical and sub-tropical habitats, less well-known pollinators have also been reported, such as cockroaches and snails (IPBES, 2017).

Bees are nonetheless considered the most important pollinator group and are known to visit 90% of the leading 107 global crop types (Klein *et al.*, 2007). They are large and hairy, so can carry high numbers of pollen grains as they fly from flower to flower. They rely completely on floral resources for food, and social bees – such as bumblebees and honeybees – occur in very high numbers, which makes them perfect for pollinating large numbers of flowers (Klein *et al.*., 2018).

Despite bees' significance, a diverse array of pollinator species is essential to high-quality, sustainable pollination (Rader *et al.*, 2016; Garibaldi *et al.*, 2016). Additionally, although other species may not transfer as much pollen per visit to a flower as a bee does, they may make more visits overall (See **Section 1.4** for more information on pollinator diversity).

Managed or wild?

Nearly all pollinators are wild. Of over 20 000 bee species worldwide, only 50 are managed by beekeepers (for purposes including honey production). Just 12 managed pollinator species (all of them bees) are commonly used by farmers to help pollinate their crops. The western honeybee (*Apis mellifera*) is the most commonly managed bee in the world, but others include the eastern honeybee, some bumblebees, stingless bees and solitary bees (Potts *et al.*, 2016). There are indications that wild honeybees are rare in Europe, although 'feral' populations (escaped from managed hives) do occur, and managed honeybees also have a large potential to share their gene pool with wild populations, and vice versa (Moritz, Härtel and Neumann, 2005; Jaffé *et al.*, 2010).

Section 1. The value of pollinators for food production and food security

Pollinators play a critical role in ensuring that key crops provide us with a sufficient, high-quality supply of food and a diverse range of essential nutrients. This section explores research into the role of pollinators in global and European food supply, including the economic value of this contribution. It also looks at the importance of pollinator diversity in maximising pollinators' benefits for food production, and in ensuring the long-term resilience of pollinator communities.

1.1 Agriculture's dependence on pollinators

Pollinators are especially important to the growth and/or quantity and quality of yield for most fruit, nut and oil crops, including high-value crops such as coffee and cocoa. They are also important in providing seeds for many vegetables, such as carrots and leeks. Around 75% per cent of the main crops grown globally for human consumption rely to at least some extent on pollinators for growth, quality and/or seed production (Klein *et al.*, 2007). These include crops grown in Europe, such as apples, berries, watermelons, tomatoes and oilseed, but also imported crops that form part of modern European diets, such as coconut, mangos, soybeans, cocoa beans and coffee. Additionally, 84% of the 264 crop species grown in Europe benefit at least partly from animal pollination (Williams, 1994). While only 15% of total EU crop production involves crops needing animal pollination, these generate around 31% of income from crop production. (Schulp, Lautenbach and Verburg, 2014). It is also important to note the human health benefits and economic significance of these crops (see **Sections 1.3** and **1.5**), which include pulses, soya, rapeseed, sunflower and some vegetables. Cereals, which generally count for 30% of the utilised agricultural area of the EU (European Commission, 2016), are generally wind pollinated rather than animal pollinated.

Furthermore, global agriculture's dependence on pollinators has rocketed by 300% over the past half-century (Aizen and Harder, 2009). Socio-economic and political factors, such as globalisation in food trade and increasing prosperity in developing countries, are causing the human diet to become more diverse with increased consumption of high-value crops, including those that depend on pollinators (Aizen and Harder, 2009; Gallai *et al.*, 2009). This dependence is also growing with the rapid expansion of insect-pollinated crops grown for biofuels, such as oilseed rape (Ouvrard and Jacquemart, 2019).

Animal-pollinated crops vary in their level of dependence upon animal pollinators; some can only be pollinated by animals, whereas others can be partly self- or wind-pollinated (IPBES, 2017). Around 10% of 87 globally important crops depend fully on animal pollination to produce fruits and seeds consumed by humans (Aizen *et al.*, 2009). At a minimum, Aizen *et al.* (2009) estimate that pollinators are responsible for 5% of the crop yield in developed countries, and 8% in developing countries.

Whilst these figures may appear relatively low, they only consider the direct role of pollinators in producing fruit and seeds that we directly consume. They do not consider pollinators' indirect roles in producing seeds used for growing and breeding many vegetables, or in producing crops grown for fibre or fuel. A European study estimates that pollinators are directly responsible for 7% of crop yield in the EU, including oilseed which has fuel applications (Schulp, Lautenbach and Verburg, 2014). Moreover, it is important to note that pollinator-dependent crops are generally much richer in nutrients than non-pollinated, staple crops and are thus essential to human health (see **Section 1.3**).

Pollinators also indirectly support meat, dairy and fish farming by pollinating crops used to feed animals: these include alfalfa, peas and soya used in feed for cattle, sheep, poultry and pigs, plus sown clover and legumes, and soya, lupin and oilseed rape used to feed farmed fish (IPBES, 2017; Api:Cultural, 2018). The contribution of pollinators to the production of crops for animal feed requires urgent research, according to Klein *et al.* (2018).

Degree of food crop dependence on pollinators	Area km^2	% of pollinator dependent food cropland in EU	Dominant regions of occurrence
Little	18,066	16%	All over Europe
Modest	69,233	61%	Central Europe
Great	22,458	20%	Spain, western Italy, Eastern Europe, Rhine valley
Essential	3794	3%	Eastern Spain, western Italy, Eastern Europe

Table 1. Distribution of pollinator-dependent food crops in Europe. Adapted from Schulp, Lautenbach and Verburg (2014).

Crop group	Dependency level, defined as % of yield loss that would occur in absence of pollinators			
	Little dependency (5% yield loss in pollinator absence)	Modest dependency (25%)	Great dependency (65%)	Essential (95%)
Fruits	0.1%	11%	77%	12%
Vegetables	10%	6%	6%	4%
Citrus fruit	100% of crop area			
Pulses	14%	82%		
Rapeseed		100%		
Soya		100%		
Sunflower		100%		

Table 2. Dependency of crops on pollinators by percentage of crop area in Europe. This shows, for example, that an absence of pollinators would lead to a 95% drop in yield across 12% of cropland for fruits. It is important to note that, even where the percentage of pollinator dependence is 'little', the overall size of the area that this accounts for may be significant. Table adapted from Schulp, Lautenbach and Verburg (2014).

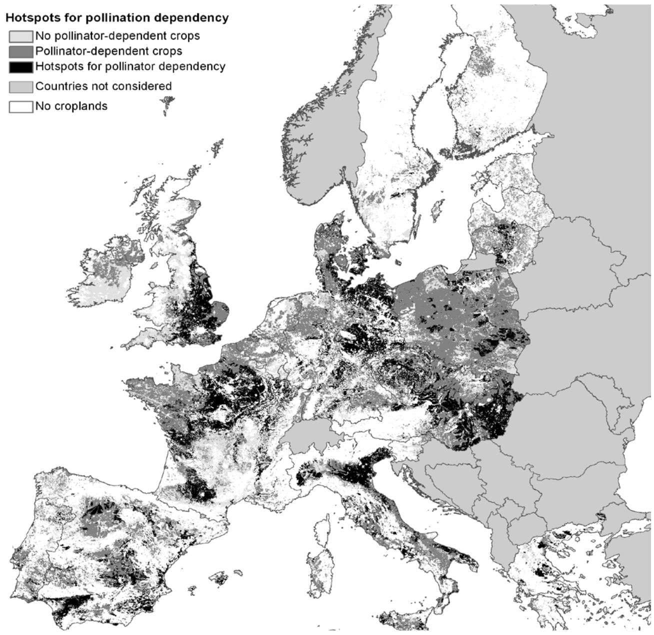


Figure 3. Hotspots for pollinator dependency in Europe. From Schulp, Lautenbach and Verburg, 2014. This shows that pollinators are especially important in large parts of France, eastern Germany, Poland, Czech Republic, Hungary, eastern UK, northern Italy and scattered areas in southern Europe. Many of these areas are used for growing rapeseed in high densities, and for fruit and vegetables that completely depend on pollinators.

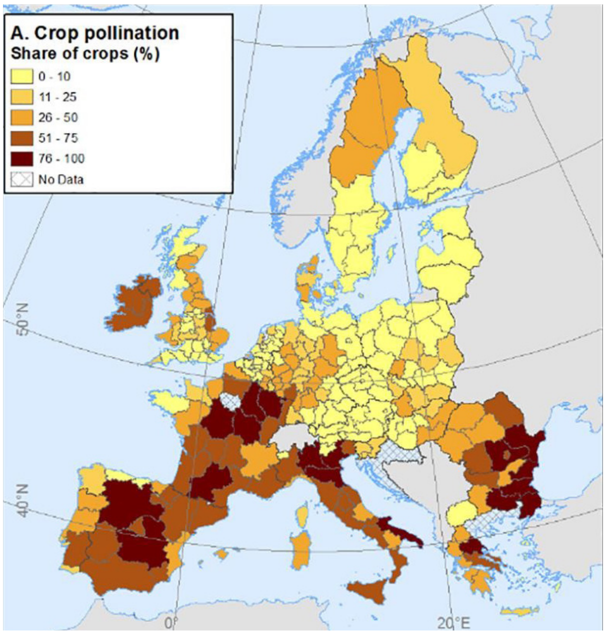


Figure 4: Unmet demand for crop pollination ecosystem services in 2012. From Vallecillo *et al.*, 2019. This shows that, for crop pollination there is a very low percentage of unmet demand in several areas of north and central Europe, due to high environmental suitability to support pollinators (bumblebees and solitary bees) in these areas. The authors posit that regions with higher unmet demand for crop pollination should be prioritised for restoration of pollinator-friendly habitats.

BOX 3.

When pollinators disappear

Cacao or cocoa is one of the most important commercial crops in the world and depends entirely on pollination by insects (Claus *et al.*, 2018). As demand grows, but supply stagnates, cocoa production is facing challenges worldwide – one being pollination.

In Côte d'Ivoire, the largest cocoa producer in the world, a mix of degrading landscape, agricultural management practices, and chemical pest control has led to falling numbers of one of the most important cocoa pollinators: the ceratopogonid midge (order Diptera, genus *Forcipomyia*) (Claus *et al.*, 2018). These midges are the perfect size to pollinate the cocoa tree's small, hooded flowers; however, they love damp, shady conditions with plenty of moist leaf litter for their larvae to bury into. Much cocoa is now produced on ever-expanding plantations that have been cleared of trees and used solely for cocoa, removing much of the shade and moisture (Osterloff, 2018).

When pollinators disappear – *continued*

These challenges are faced by cocoa pollinators the world over. Droughts driven by our changing climate have affected the breeding patterns and habitats of cocoa-pollinating insects in Brazil (Gateau-Rey *et al.*, 2018). In Indonesia, scientists have found that changing the number of tiny, pollinating mosquitos has a far greater effect on the yield of a cocoa tree than altering factors such as lighting, fertiliser and water (Groeneveld *et al.*, 2010).

In the apple and pear orchards of China's Sichuan province, reductions in wild bee numbers have made hand pollination necessary (Partap and Ya, 2012). Farmers in the area have responded by planting crops that do not require insect pollination. However, these provide less nectar and nutrient-rich pollen, increasing the likelihood of further population decline among remaining insect pollinators in the region (Gill *et al.*, 2016). During the annual springtime almond bloom in California, USA, up to three-quarters of the country's commercial honeybee hives are imported to the state to provide temporary pollination services. In 2012, this cost American almond growers nearly US$300 million (€272 million) in beehive rental costs to farmers (Bond, Plattner, and Hunt, 2014).

Oil palm (genus *Elaeis*), the source of palm oil, is also heavily dependent on pollinators. It is pollinated by weevils (*Elaeidobius kamerunicus*), which are one of the most active and important pollinators for oil palm in West Africa and South America (Kalidas, Rajasekhar and Lalitha, 2008). They are so important that when farmers in Malaysia attempted to produce the crop without weevils they saw huge yield losses and large-scale crop failure (Siti Khadijah, 2013).

Be it chocolate or palm oil, midge or weevil, the impact of struggling pollinators is global, and highlights the importance, vulnerability and irreplaceability of insect pollinators worldwide.

1.2 Pollinator benefits for crop quality

Pollinators improve not only the yield of many crops, but also their quality. This has been shown for a wide range of crops and their seeds, including apples, oilseed rape, blueberries, cucumbers, leeks, kiwi, sunflowers and coffee (Klein, Steffan-Dewenter and Tscharntke, 2003; Isaacs and Kirk, 2010; Gajc-Wolska *et al.*, 2011; Bommarco, Marini and Vaissière, 2012; Bartomeus *et al.*, 2014; Garratt, Breeze, *et al.*, 2014; Garratt *et al.*, 2016; Fijen *et al.*, 2018; Perrot *et al.*, 2019; Sáez *et al.*, 2019).

These benefits are exemplified by the large body of research into the effects of animal pollination on the quality of strawberries. Insect-pollinated strawberries are bigger, redder, firmer and more flavoursome than strawberries that have been wind- or self-pollinated. They also have a longer shelf life and smoother shape (see Figure 5) (Wietzke *et al.*, 2018; Castle, Grass and Westphal, 2019; Klatt *et al.*, 2014). These pollinator-derived improvements increase the commercial grade of strawberries, and were found to raise their value by 92% (Wietzke *et al.*, 2018).

Castle, Grass and Westphal (2019) found that the weight of strawberries from self-pollinated plants is 56.2% lower than for strawberries grown next to hedgerows that benefit from enhanced insect pollination. Pollinators may also reduce food waste by increasing the shelf life of fruit. According to Klatt *et al.* (2014), the longer shelf life awarded by bee pollination reduces strawberry fruit loss by at least 11%. Food waste is a pressing issue for industrialised countries where 30–50% of all crops are thrown away by retailers and consumers (Gustavsson *et al.*, 2011; Tscharntke *et al.*, 2012).

Insect pollination brings about these beneficial effects by supporting hormonal processes in strawberries. Bees are naturally good at evenly spreading pollen across a strawberry's achenes (the yellow 'seeds' on a strawberry, which are actually the true fruit). This pollen fertilises the achenes, which then produce auxin. Auxin is a hormone that encourages even and strong growth, as well as the production of acids that slow down softening processes and which promote higher levels of pigment, and also boosts yield (Klatt *et al.*, 2014; Wietzke *et al.*, 2018).

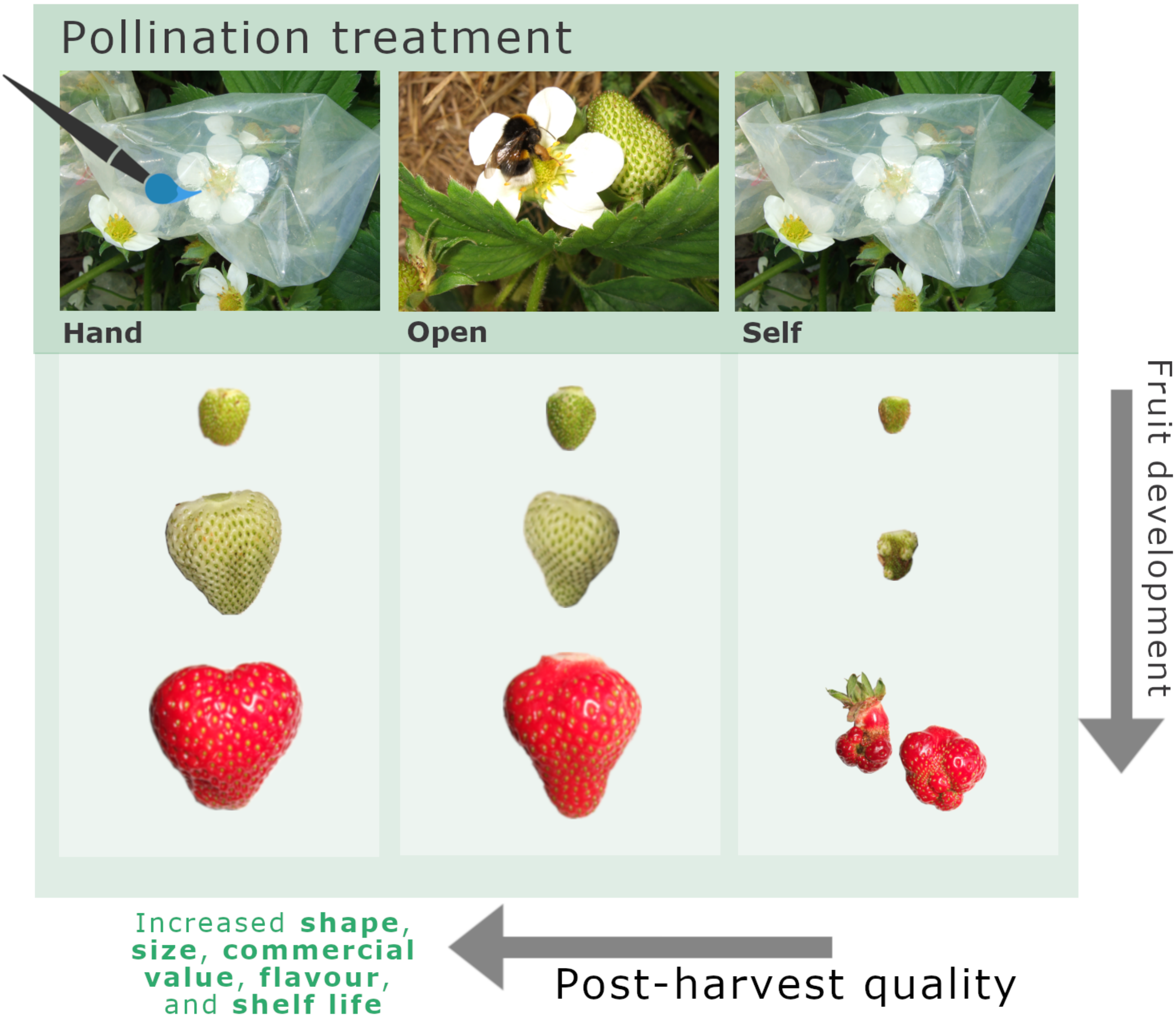


Figure 5. Impacts of different forms of pollination on factors that affect commercial value of strawberries, as shown by Wietzke *et al.* (2018) (redrawn figure). While this study found no difference between the effects of open (insect) and hand (human) pollination on value, it noted the high labour intensity of hand pollination.

1.3 Pollinator benefits for nutrition and human health

Without pollinators, our diets would be short of, or even completely lacking, many of the micronutrients essential for health, including vitamins A and C, calcium and fluoride. Animal-pollinated crops – fruit and nuts, for example – are generally much richer in essential nutrients than staple crops that are mostly wind- or self-pollinated (such as wheat, rice and potatoes). The grains and starchy crops that provide the majority of calories in our diet are poor sources of most nutrients, particularly when processed (into white flour or white rice, for instance) (DellaPenna, 1999).

> *Animal-pollinated crops – fruit and nuts, for example – are generally much richer in essential nutrients than staple crops that are mostly wind- or self-pollinated (such as wheat, rice and potatoes)... pollinators benefit human health by pollinating crops that are high in nutrients, reducing the risk of many serious human health conditions.*

Vitamin and nutrient supplementation and fortification may be insufficient as alternative sources of pollinator-supported nutrients. An increasing body of research questions some of the purported health benefits of supplements (Bazzano *et al.*, 2006; Jenkins *et al.*, 2018) – and many supplements themselves are made using pollinator-dependent flowering plants that would be negatively affected by pollinator decline (Eilers *et al.*, 2011).

Crops that depend either fully or partially on animal pollinators contain over 90% of the vitamin C found in the world's 150 leading crops. They also contain all available lycopene, nearly all of the antioxidants b-cryptoxanthin and b-tocopherol, the majority of lipids, vitamin A and related carotenoids, calcium and fluoride, as well as a large portion of folic acid (Eilers *et al.*, 2011).

Insufficient consumption of the key foods affected by pollinator species – fruits, vegetables, nuts and seeds – increases the risk of many diseases, including cardiovascular diseases, diabetes, oesophageal cancer and lung cancer. Vitamin A and folate are also vital for children and pregnant women (Lim *et al.*, 2012).

Smith *et al.* (2015) calculate that a complete loss of pollinators, a worst-case scenario, could reduce global supplies of fruit by 22.9%, vegetables by 16.3%, and nuts and seeds by 22.1%. The health impacts of the resulting dietary change would be substantial, increasing global deaths yearly from non-communicable and malnutrition-related diseases by 1.42 million (an increase of 2.7%) and disability-adjusted life-years (DALYs)[12] by 27 million (a 1.1% increase). A 50% loss of pollination services would be associated with 700 000 additional annual deaths, and 13.2 million DALYs.[13]

1.4 The importance of pollinator species diversity for crops

Research shows that a diverse range and high number of pollinator species (including both common and rarer species) has a positive effect on crop yield and quality. Managed bees – usually honeybees or bumblebees – are being increasingly used to pollinate crops; the global population of managed honeybee hives increased by around 45% between 1961 and 2007, in concurrence with a 300% rise in demand for pollinator-dependent crops (Aizen and Harder, 2009).

12. A DALY indicates the impact of illness and injury on the loss of healthy years of life. It combines the number of years lived with a disability with the number of healthy years lost due to premature death.
13. For more on DALYs see the Science for Environment Policy Brief What are the health costs of environmental pollution? https://ec.europa.eu/environment/integration/research/newsalert/pdf/health_costs_environmental_pollution_FB21_en.pdf

BOX 4.

Pollinators: looking after your 5-a-day and coffee-break treats

Animal pollinators play an important role in ensuring that farmers can produce a good supply of fruits, vegetables and nuts, which help keep us in good health. Here are just a few examples of nutritious foods that depend upon pollinators:

Almonds	Brazil nuts	Kiwi fruit	Peaches
Apples	Courgettes	Mangos	Squashes
Avocados	Cucumbers	Melons	Strawberries

Animal-pollinated plants provide us with high levels of important nutrients, including Vitamin C, Vitamin A and antioxidants. Losses in pollinators could lead to the decline of many of these plants, with potentially major effects on our health. If we were to lose all pollinators, Smith *et al.* (2015) predict that there would be a global increase in serious health conditions such as heart disease, which could lead to many deaths. See **Section 1.3** for more information.

Pollinators also help fuel us in other ways – by providing us with chocolate and coffee. Cacao, from which chocolate is made, is pollinated by insects including midges, wasps and ants (Toledo-Hernández, Wanger and Tscharntke, 2017). Coffee, on the other hand, is highly dependent upon bees for pollination (Ngo, Mojica and Packer, 2011).

White flowers of arabica coffee by Riza Azhari, Indonesia @Getty/ IStock.

Globally, the western honeybee is widely found and used for its hive products – it is one of the very few species to produce honey, and visits all of the top 15 pollinator-dependent crops (by area), including apples, cucumbers and pears (Klein *et al.*, 2018). However, in the face of shocks (climate change, habitat loss, diseases and pests) that could wipe out a species, it is risky to depend on honeybees – or any single species, for that matter – for crop pollination. It is crucial to have a richly diverse pollinator community that can absorb such shocks. Both wild and managed pollinators are threatened by a number of factors; threats to managed bees include poor nutrition, pests and diseases (Rader *et al.*, 2016) (see **Section 3** for more information on threats to pollinators). It is also important to note that managed honeybees can only be used in a complementary role to wild species, and not as a substitute (Garibaldi *et al.*, 2013).

Moreover, research shows that wild bees often provide better pollination services than managed honeybees. For instance, Garibaldi *et al.* (2013) studied 41 crops grown globally and found that those pollinated by wild bee species produced an average of twice as much fruit as those pollinated by honeybees (both managed and feral). Wild species can also affect crop quality: MacInnis and Forrest (2019) found that strawberries pollinated by wild species were 42% bigger, on average, than strawberries pollinated by honeybees.

> *In the face of shocks (climate change, habitat loss, diseases and pests) that could wipe out a species, it is risky to depend on honeybees – or any single species – for crop pollination. It is crucial to have a richly diverse pollinator community that can absorb such shocks.*

Only a minority of species currently pollinate agricultural crops. Just 2% of all wild bee species account for almost 80% of all global crop visits by wild bees, for instance (Kleijn *et al.*, 2015). However, benefits for crop production increase with pollinator species diversity (Hoehn *et al.*, 2008; Brittain *et al.*, 2013; Garibaldi *et al.*, 2016). For example, a US study found that the number of apple seeds per pollinated flower nearly triples when the number of wild bee 'functional groups' (i.e. groupings of species that perform different ecological roles) increases from less than two to more than four (Blitzer *et al.*, 2016).

Species diversity supports effective pollination services by allowing for a greater number of these functional groups – i.e. greater functional diversity. Different functional groups may forage at different heights or in different parts of a field, in different sorts of weather, at different times of the year or day, or be better at pollinating certain types of crop (Hoehn *et al.*, 2008; Fründ *et al.*, 2013; Rader *et al.*, 2013; Garratt, Coston, *et al.*, 2014; Martins, Gonzalez and Lechowicz, 2015; Fijen *et al.*, 2018).

A large number of species are also needed to ensure high levels of pollination across a region, to account for 'species turnover': the variation in species between sites. This becomes particularly apparent in large, landscape-scale studies, which can provide a more realistic picture of pollination activity than small-scale controlled experiments. In a US study of 48 watermelon, blueberry and cranberry farms in the same region, common species of bee contributed to pollination at every farm (Winfree *et al.*, 2018). However, these species alone could not provide high levels of pollination for every single farm. Other, rarer, species were often also needed to meet pollination thresholds, even though rare species may make only small contributions to pollination on an individual farm (see Figure 6). Naturally, these rarer species were not present across all farms, and so only a high number of species (both rare and common) across the region could ensure high pollination at every site. An average of 5.5 wild bee species at a single farm provided 50% of pollen levels currently provided by wild bees across all sites. Across 16 farms, 55 bee species were needed to deliver 50% of pollen, while 79 species (i.e. most of the bee species who visit the crops) were needed for 75% of pollen delivery (Winfree *et al.*, 2018; Kremen, 2018a).

Furthermore, although only a minority of pollinator species pollinate crops (Kleijn *et al.*, 2015), more species bring more resilience (Garibaldi *et al.*, 2011). A greater diversity of species can counter the loss of dominant species caused by environmental changes, such as changes in weather, for instance (Senapathi *et al.*, 2015a). Moreover, crop-pollinating species also need wild plants for nesting and food resources – and these wild plants often rely upon a range of other species for pollination. In this way, species that do not pollinate crops still offer significant indirect benefits for agriculture by supporting crop pollinators, also helping to sustain healthy ecosystems and wider biodiversity (Senapathi *et al.*, 2015a).

It is also important to remember that pollination is not just conducted by bees. While the majority of recognised pollinators of important food crops grown globally for humans are types of bee (honeybees, bumblebees, stingless bees and solitary bees) (Klein *et al.*, 2007), non-bee pollinators, including flies, beetles, moths, butterflies, wasps, ants, birds and bats perform an average of 39% of flower visits worldwide (Rader *et al.*, 2016). Although they are less-effective pollinators than bees per visit, their higher visit rates mean that, overall, they can provide comparable levels of pollination.

BOX 5.

Pollinator case study: Plants and wasps give and take

Flowering plants and their pollinators have co-evolved over long periods, producing some interesting mutually beneficial relationships. Animals visit flowers for rewards, and not expressly to pollinate the plants. Flowering plants therefore use all kinds of enticing methods to attract pollinators – often forms of deception. These include colourful petal colours and structures, which lure in males by mimicking females of the pollinator species, as well as smelly chemicals that mimic prey species of carnivorous pollinators or the female of the pollinating species (again, to attract the males). Nectar rewards are another enticement for many animal species, including bees, bats and birds such as the hummingbird.

One interesting example of plant deception involves the social wasps Vespidae, such as *Vespula vulgaris* and *V. germanica*. These are opportunistic foragers who use the nectar or honeydew of flowers as a source of energy, but also hunt for carrion, fruit and arthropods, including caterpillars. The flowers of the orchid *Epipactis helleborine* emit compounds that are normally released by leaves when they are being eaten by a caterpillar – this scent lures the Vespidae wasps over to the flower in search of a prey reward. The caterpillar-eating wasp is rewarded with orchid nectar and, in turn, inadvertently pollinates the plant (Brodmann *et al.*, 2008).

Vespula germanica **by Line Sabroe from Denmark @Wikimedia Commons CC BY 2.0**

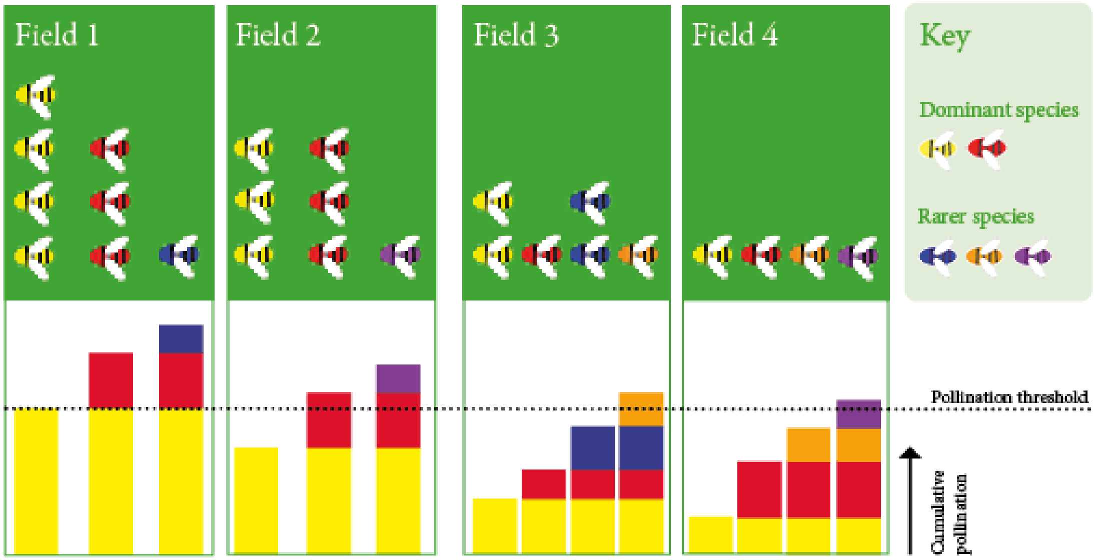


Figure 6: Bee diversity needed for pollination. (Source: Kremen, 2018) (redrawn). Dominant species contributed most to pollination function at sites 1 and 2, where only one or two species are needed to surpass the threshold required for full pollination. Because of the lower abundance of dominant species at sites 3 and 4, more species are needed for full pollination. Species turnover between such sites means that most species in the species pool are needed to supply pollination function across the entire array of sites.

1.5 The economic value of pollinators to agriculture

Pollinators have important consequences for livelihoods and national economies. Animal-pollinated crops provide employment and income for millions of people around the world. In the EU, agriculture and food-related industries and services provide over 44 million jobs, including regular work for 20 million people within the agricultural sector itself.[14] The EU agricultural sector produces a total output value of over €400 billion a year; half of this value comes from crops, including a high share of animal-pollinated crops.[15]

Various studies have estimated the economic value of pollinators (see Table 3 below), but it is difficult to compare the values calculated by these studies as they use different assumptions and methods. Economic analyses are also limited by gaps in ecological and economic data. However, all existing studies point to the economic importance of pollinators. Not only could a loss in pollinators lead to a decline in crop yield and quality, it could also incur costs if, for instance, animal pollination was replaced by hand pollination. Pollination by hand has been practiced for millennia in the production of dates in the Middle East (Zaid and de Wet, 2002) and in the production of vanilla (Fouche and Coumans, 1992). However, hand pollination on a large scale for less lucrative crops is likely to be unfeasible and uneconomic particularly in Europe and parts of the world that have high labour costs.

In a comprehensive global assessment, Lautenbach *et al.* (2012) estimated the economic benefits of global pollination services at c.€190 billion to €467 billion in 2009, based upon the market price of crop production that can be directly attributed to animal-mediated pollination. The same study estimated that 9.4% of agricultural GDP depends upon pollinators.

14. https://europa.eu/european-union/topics/agriculture_en
15. https://ec.europa.eu/agriculture/sites/agriculture/files/statistics/facts-figures/agricultural-farm-income.pdf

Poppies and cows, France by Nicolas Garrat @Getty/IStock.

In Europe, the ecosystem service of crop pollination has been valued at €3 billion for the year 2006, with €2.1 billion of this coming from fresh fruit (JRC, 2018). These figures are also based upon the share of crop yield that depends upon pollinators. Some of the studies estimating the value of pollination services for Europe are summarised in **Table 3** below (p. 18-19). The spatial analysis required for the accounting of crop pollination could be a useful tool to identify priority areas for ecosystem restoration and other nature-based solutions. Increasing the 'pollination potential' (environmental suitability to support wild insect pollinators) in those areas where there is high unmet demand for pollination services (e.g. via creating green infrastructure) would increase the benefits to food production generated by pollinators (JRC, 2018).

Such figures highlight the economic impact of pollinators in terms of market values, crop production or actual crop quantities, but, as discussed in **Section 1.2**, pollinators also increase the value of some crops by enhancing their quality (Klein, Steffan-Dewenter and Tscharntke, 2003; Isaacs and Kirk, 2010; Gajc-Wolska *et al.*, 2011; Bommarco, Marini and Vaissière, 2012; Bartomeus *et al.*, 2014; Garratt, Breeze, *et al.*, 2014; Garratt *et al.*, 2016; Fijen *et al.*, 2018; Perrot *et al.*, 2019; Sáez *et al.*, 2019). As discussed in **Section 1.3**, pollinators benefit human health by pollinating crops that are high in nutrients, reducing the risk of many serious human health conditions (Smith *et al.*, 2015; Eilers *et al.*, 2011). However, these aspects of crop quality improvement and disease prevention are hard to capture in current economic assessments of pollination and have yet to be conducted beyond crude and static estimates (Melathopoulos *et al.*, 2015).

> *Even if pollinators only modestly impact yields of a farm, that contribution can still decide its economic viability.*

It is also important to note that a 20% decline in yield, for example, would not necessarily translate to a simple 20% decline in income. Farmers may respond by switching production to another crop that is not dependent on animal pollination (IPBES, 2017), which may lead to shortages or price changes in certain commodities. However, for many farmers, whose alternatives are limited by economic or environmental constraints, what may appear a relatively small decline in productivity could lead to the closure of their business. Thus, even if pollinators only modestly impact yields of a farm, that contribution can still decide its economic viability.

Study	**Gallai *et al.*, 2009**	**Bauer and Sue Wing, 2016**	**JRC, 2018**
Estimated value of insect pollination for Europe for one year	€14 200 000 000 (€14.2 bn) (2005)	€17 700 000 000 (€17.7 bn) (2004)	€3 100 000 000 (€3.1 bn) (2006)
Geographical range	EU25	Europe – i.e. EU 27 plus Albania, Belarus, Norway, Russia, Switzerland, UK and Ukraine	EU28
Approach	Partial equilibrium estimates, of contribution of insect pollination to the economic value of agricultural output. Applies a crop pollination dependency ratio to the market value.	Partial equilibrium estimates of production loss in the event of complete pollinator loss. Applies a crop pollination dependency ratio to the market value.	Experimental ecosystem account of crop pollination, combining biophysical flows with monetary valuation, before presenting via accounting tables. Estimates contribution of pollination, using actual flow of met demand multiplied by dependency ratio, to measure how much of total production depends on pollination.
Factors considered	Considers crop quantity produced, quantity consumed dependence ration of crop on insect pollination, European price of crop per unit produced.	Considers the pollinator-dependent share of agricultural revenue as well as the loss of consumer surplus (CSL) in crop markets.	Considers actual production flows, records of pollinator presence, and agricultural economic accounts; uses constant monetary values rather than current prices; and considers how much of the crop demand for pollination is actually met.

Study	**Gallai *et al.*, 2009**	**Bauer and Sue Wing, 2016**	**JRC, 2018**
Assumptions/limitations	Focuses on individual markets without looking at potential linkages between them; ignores multi-market interactions. Assumes that the whole extent of crop demand is covered by the pollination potential. Only considered crops used directly for human consumption as reported by FAO and crops for which there were data available. Loss increases with the size of the affected economy.	Focuses on individual markets without looking at potential linkages between them; ignores multi-market interactions. Assumes that the whole extent of crop demand is covered by the pollination potential. Consider only losses that occur in pollinator-dependent crop sectors within the region experiencing the shock. Ignores potential increases in the prices of crop producers' outputs and underestimates the total impact on the economy by not accounting for concomitant changes in the value of non-crop sectors' outputs. Opportunity cost increases with the size of the affected economy.	Only considers pollinator-dependent crop production covered by pollination service (met demand, which depends on the actions of wild pollinators). For pollinator-dependent crops, about 66% of production depends on the service of crop pollination. The actual flow is then only processed for the 66% of the production rather than the 100% of production. Lack of local data on pollinator presence and abundance. Assessment of actual effective pollination is limited. Lack of disaggregated data prevents integration of information on specific crops with costs incurred by farmers during production. Only considers simplified base prices rather than market prices.
Source data	2005 production data from FAOSTAT database; Klein *et al.*, 2007.	2004 production data from FAOSTAT database; Gallai *et al.* 2009; Klein *et al.*, 2007.	Official agricultural statistics from ESTAT; spatial data from CAPRI model; dependency ratios from Klein *et al.*, 2007; economic account reported for agriculture within the SNA.

Table 3: Comparison of estimates of economic value of pollination services for Europe. Sources: Gallai *et al.*, 2009; Bauer and Sue Wing, 2016; JRC, 2018.

An alternative strategy could be to use knowledge about the profitability impact of losses of pollinators to invest in measures to mitigate loss (such as flower strips) (Wratten *et al.*, 2012; Garibaldi *et al.*, 2014).

It is also important to remain aware that an increase in research that shows the economic value of species conservation – and the rising apparent value of pollinator services – has not yet coincided with a marked improvement in healthy, diverse and resilient wild pollinator populations, but instead has coincided with their further deterioration (Melathopoulos *et al.*, 2015; Spangenberg and Settele, 2010; Fischer *et al.*, 2007).

1.6 Pollinator benefits for pest control

While larvae of some pollinators are crop pests themselves, research suggests that other pollinating species could contribute to the important ecosystem service of pest control in agriculture. The larvae of some hoverfly species, for instance, prey upon aphids, insects that are particularly economically damaging pests. This natural form of pest control could reduce farmers' reliance on chemical methods, according to Hatt *et al.* (2017), who studied Belgian wheat fields and found that aphid numbers dropped as hoverfly numbers increased. The hoverflies were attracted to the fields by strips of wildflowers. This study demonstrates that pollinating insects can also have benefits for non-pollinated crops (in this case, wheat) through pest control. It supports a range of other studies that show that wildflower strips on farmland and semi-natural or natural habitat in the surrounding landscape may reduce pest numbers by attracting natural predators, such as aphid-eating species of hoverfly and parasitoid wasps (Lindgren, Lindborg and Cousins, 2018; Woodcock *et al.*, 2016; Schirmel *et al.*, 2018; van Rijn and Wäckers, 2016; Tschumi *et al.*, 2016; Ramsden *et al.*, 2017; Moquet *et al.*, 2018).

Hover fly larva consuming an aphid by Scot Nelson @Flickr, public domain

Hoverfly (Syrphidae) egg found on a Centaurium leaf close to an aphid colony, Jambes, Belgium, by Gilles San Martin @Wikimedia Commons [CC BY-SA 2.0]

Wasp-mimicking hoverfly (Ceriana vespiformis) by Alvesgaspar @Wikimedia Commons [CC BY-SA 3.0]

BOX 6.

Other benefits of pollinators

- Pollinators provide many benefits to people beyond food. These include medicines (e.g. allopathic and traditional herbal remedies), biofuels (e.g. canola and palm oil) and materials (e.g. cotton, linen and wood) (Gutiérrez-Ibáñez *et al.*, 2014). These benefits often have significant economic values.

Some specific medicinal benefits provided by pollinators include:

- medicinal properties of mānuka honey to help wound healing (Klein *et al.*, 2018);
- anti-cancer properties of propolis, a compound produced by bees (Xuan *et al.*, 2014);
- bee venom used in medicine (Klein *et al.*, 2018);
- antimicrobials produced by bacteria living on ants (Rader *et al.*, 2016); and
- reproduction of flowering traditional medicinal herbs such as black cohosh (Forester, Creek and Farm, 2007).

Pollinators are also significant in art, literature and even engineering; there are many examples of pollinating species appearing in cultural contexts from around the world.

- For instance, sacred passages about bees can be found in all major religious texts, highlighting their significance to human societies over millennia (Gutiérrez-Ibáñez *et al.*, 2014). Van Huis (2019) notes that the Bwa people of Burkina Faso use seven-foot-wide butterfly masks to symbolise fertility, whilst in Senegal, the butterfly or moth is called 'déftèle-allah' (paper of God) by the Halpulaar, or 'Bedèllel Allah' (God's fan) in Fula. Pollinators are also often important national symbols: examples include the hummingbird in Jamaica, the birdwing butterfly in Sri Lanka and the sunbird in Singapore (IPBES, 2017a).

Image of the Praenomen of Senwosret I, containing a Bee by Captmondo@ Wikimedia Commons

- Honeybees have also provided inspiration to NASA scientists working on bio-inspired engineering of exploration systems (BEES). Pollinator-inspired concepts include: navigation by the Sun (inspired by bees' use of ultraviolet skylight polarisation as a direction reference for the Sun's position); and searching Mars for caves, based on the swarming behaviour of honeybees establishing new hives (Levine *et al.*, 2015).

Other benefits of pollinators - *continued*

Butterfly Mask, Nuna peoples, Burkina Faso) (National Museum of African Art) by catface3 @Flickr, CC BY-NC-SA 2.0. This large mask is one of a cast of masquerade characters and is a representation of a bush spirit. Butterflies signal the coming of the rain and the start of the planting season. It was created by the Nuna people who live in Burkina Faso near the border with Ghana. The patterns – zigzags, bulls eyes, and triangles in alternating colors – are a visual code known to the Nuna peoples.

Biocultural diversity – biological and cultural diversity and the links between them – is important for the protection of threatened species and languages. Indigenous peoples often have multiple local names for pollinator species, and favour diverse land management and farming systems that protect many pollinators (IPBES, 2017).

Pollinators can also have huge aesthetic appeal: just think of the beauty of butterfly wings. By supporting floral diversity, these beautiful species also make landscapes more aesthetically appealing and contribute to cultural recreation (Gill *et al.*, 2016).

Section 2. Pollinators, an essential element of nature

This section explores research into the essential role that pollinators play in supporting the survival of global biodiversity and the health of nature worldwide. It examines the interlinked role pollinator and plants have in each other's survival in a changing climate, as well as case studies of pollinator loss and the cascading effects that occur when pollinator numbers decline or are lost completely in an ecosystem.

Nearly 90% of wild flowering plants depend at least to some extent on animal pollination (IPBES, 2017) – and around 50% of flowering plants are completely dependent on animal pollination, as they cannot self-pollinate (Potts *et al.*, 2016; CBD, n.d.). By supporting the health and reproduction of wild plants pollinators play a role in providing food and shelter for many other invertebrates, mammals, birds, reptiles and other species connected to one another in the food web (Gutiérrez-Ibáñez *et al.*, 2014). Furthermore, the ecological impacts of animal pollinators mean that they play a valuable role in providing ecosystem services. These include the direct provision of ecosystem services, mainly for crop pollination (see **Section 1**), but also the indirect provision of services, such as flood protection and climate regulation, which arise as a result of pollinators' role in supporting plant communities and their role in soil formation (also directly via soil nesting pollinator species). The loss of wild plant diversity and wild fruit yields due to pollination deficit is one of many risks to human happiness, quality of life and well-being identified by Potts *et al.* (2016).

In the absence of pollinators, there is a risk that many plants would not be able to adapt their reproductive methods, and would thus disappear (Settele, Kotarac and Grobelnik, 2010). This would cause cascading effects within ecosystems and habitats worldwide, given the dependence of other animal species on the plants and habitats that pollinators help create (Christmann, 2019).

Grasslands are an important example of a valuable habitat where pollinators have a crucial ecological and evolutionary role. These habitats occur worldwide and are often used for grazing and livestock production (Bendel *et al.*, 2019). They host high levels of biodiversity and species richness, and provide pollinating species with many resources (Faber-Langendoen and Josse, no date). Johnson, Harris and Procheş (2009) studied South African grasslands, and found that the majority of the wildflower plant species present were self-incompatible (that is, they could not adapt to rely upon self-pollination) and were thus entirely reliant upon a diverse range of pollinators: bees, flies, wasps, butterflies, hawkmoths, beetles, sunbirds and more.

Mangroves also rely upon pollinators. These habitats are largely comprised of plants that need to be cross-pollinated, and are vital in preventing coastal erosion, providing resources for fisheries, protecting land against flood and salt intrusion, and providing wood for fuel and timber. Mangroves also provide habitat and food for bees and many other species (e.g. birds and mudskippers) (Mukherjee *et al.*, 2014) under environmental conditions that would kill most other plants.

Forests are another example, which contain many plants that need pollinators to reproduce. Ecosystem services provided by forests include climate regulation, disease regulation, and the provision of food for both humans and other forest-dwelling species (CBD, no date; S. Díaz *et al.* 2019).

BOX 7

Pollinator case study: The fig and the wasp

Figs (genus *Ficus*) are not fruit, but 'inflorescences': clusters of flowers and seeds packed inside a bulb-shaped stem (Jousselin and Kjellberg, 2001). Because of this unusual structure, they need a specialised pollinator: the fig wasp. To pollinate, a fig wasp queen wriggles through a small opening in the fig to access the florets inside and sheds the pollen she has collected. She then lays eggs, dies, and is digested by the fig.

When these eggs hatch, the young wasps mate before the females leave – collecting pollen on their way out to continue the cycle of pollination. The males stay, remaining within the fig for their entire few-day lifespan (Kline, 2011; Cook and West, 2005). Commercially cultivated fig trees are often bred to be seedless, and so do not rely on pollinator wasps (Stover *et al.*, 2007). However, there are roughly 750 fig species, each fertilised by at least one specialised species of wasp (Cook and West, 2005).

This fig-wasp pairing is an ancient and diverse 'mutualistic' relationship: non-sterile figs rely entirely on their wasp pollinators to produce fruit, while these wasps rely entirely on the fig to host and protect their offspring (Jandér and Herre, 2010). Fig trees produce fruit throughout the year when other trees do not, making them an important food source for many animal species worldwide – monkeys, birds, bats, and more (Cook and West, 2005), which then spread fig seeds via their droppings.

Wasps inside the figs, Singapore by Jnzl's photos @Flickr, CC BY-SA 2.0.

2.1 Pollinators and plants support each other's survival

Insect pollination maintains genetic diversity in plant populations. This increases fruit quality, quantity, seed production, and plant fertility, leading to a fitter next generation and healthy wild plant communities. Pollinators thus underpin the successful functioning of terrestrial ecosystems (Gill *et al.*, 2016; IPBES, 2017).

Sexual reproduction and cross-pollination via pollinators ensure that plants remain genetically robust and better able to adapt and evolve in response to environmental pressures, such as climate change and disease. Pollinators are crucial for sexual reproduction in nearly 90% of wild flowering plants (IPBES, 2017), and many species of plant have evolved in tandem with a specific group or species of pollinator, for example, the fig—wasp relationship (see Box 7). If that pollinator species disappears, it is unlikely those plant species would continue to thrive or survive.

Habitat disturbance and loss can reduce the flowering density of plants, lowering pollinator attraction and potentially leading to deficits in the amount and quality of pollen. As this leads to limited opportunities for cross-pollination, plants come to self-pollinate more frequently and 'selfing syndrome' evolves, resulting in the de-selection of flower traits, like the provision of nectar, as these are resource-intensive for the plant and no longer useful (Eckert *et al.*, 2010). At the same time, the loss of flower resources will adversely impact the health and survival of pollinator populations and species (IPBES 2017, Baude *et al.*, 2016).

In such a manner, the fate of bee pollinators and wild plants are tightly linked. Evidence from the Netherlands and the UK revealed parallel declines in native plants and their bee pollinators during the late twentieth century (Biesmeijer, 2006). The absence of bees may be causing a decline in plant reproduction, and a resultant fall in numbers of both bees and plants (Biesmeijer, 2006). While correlation is not the same as causation, the greatest declines in bee species are found for those that depend on plant species most negatively affected by climate change (Klein *et al.*, 2018; IPBES, 2017). Separate research found that 76% of plant species foraged by bumblebees declined in frequency across Britain between 1978 and 1998, including some species of particular importance to threatened bumblebee species. This may have contributed to their scarcity, suggest Carvell *et al.* (2006).

***Bombus cullumanus*, a critically endangered bumblebee, Netherlands by Natuurbeleven @ Wikimedia Commons, CC BY-SA 4.0.**

BOX 8.

Pollinator case study: Deceived by orchids

Orchids are masters at deceiving and luring in animals to carry out pollination. They also offer one of the few examples of ant pollination. The hare orchid, *Leporella fimbriata*, for example, has evolved specifically to be pollinated by just one species of ant found in southern Australia. Not only does it look like the female bulldog ant, *Myrmecia urens*, but it also emits a smelly chemical that is attractive to males. The male bulldog ant is tricked into mating with the flower, covering itself in pollen in the process, which it then spreads to other plants (Tautz, 2011).

As seen with the hare orchid, the bee orchid (*Ophrys apifera*) combines both visual and scent-based deception. The lip of this orchid flower resembles a particular kind of female solitary bee, tempting male bees into mating with it and transferring pollen as it does so (Ray and Vendrame, 2015; Lane, 2017). The bee orchid mimics not only the look but also the scent of a female bee – as do Bucket orchids (genus *Coryanthes*), which fill their bucket-shaped lips with a pungent oil that is highly attractive to male orchid bees. Bees become stuck in this lip and can only escape by wriggling through a small part of the plant that temporarily traps them and deposits pollen onto their backs. The bees then fly off to pollinate another flower (Ray and Vendrame, 2015). The bee—orchid relationship is highly specialised, with particular orchid species producing fragrances that attract only one or a few species of orchid bee – even if dozens exist in the habitat (Milet-Pinheiro *et al.*, 2015).

Ophrys apifera - Mirador El Collado, Camijanes, Herrerias, Cantabria, Spain by Bernhard Dupont @ Wikimedia Commons, CC BY-SA 2.0.

Another UK study found that fluctuating levels of nectar resources in the twentieth century appear to somewhat mirror levels of pollinator diversity (Baude *et al.*, 2016). Nectar resources declined between the 1930s and 1970s, stabilised, and then increased between 1998 and 2007. In separate research, pollinator diversity declined in the middle of the century in north-west Europe, but has stabilised more recently (Carvalheiro *et al.*, 2013).

2.2 Pollinator loss affects all levels of an ecosystem

Insects act as a food source for animals higher up the food chain – insect-eating birds, for instance – and provide fruits and seeds via pollination services, which are eaten by a range of animal groups, and have a different nutritional composition when animal-pollinated (Klein *et al.*, 2018). Pollinator loss, therefore, can lead to the loss of other species in the food chain in what are described as 'cascading effects'.

> *Pollinator loss... can lead to the loss of other species in the food chain in what are described as 'cascading effects'.*

An indication of a possible cascading effect comes from Bowler *et al.* (2019) who found that insect-eating bird numbers declined by 13% between 1990 and 2016 across 27 countries of the EU (excluding Croatia), whereas omnivorous bird populations remained stable. Insect-eating birds that were particularly noted to be in decline were farmland-dwelling (especially grassland), ground-feeding, and cold-adapted species. Species that migrate long distances were overwhelmingly insectivores, and these insect-eating migrants showed significant declines. This study suggests that the decline in insect-eating birds is largely due to agricultural intensification and loss of grasslands, which are both feeding and breeding habitats for birds. It raises the question of whether bird declines are related to changes in insect populations.

Similar cascading effects across different levels in the food chain have been observed when bird pollinators are removed from an ecosystem. A New Zealand study found the extinction of bird pollinators on the mainland to reduce pollination, seed production and plant density in the shrub *Rhabdothamnus solandri* (Gesneriaceae). The seed production per flower on the mainland was reduced by 84%, demonstrating a cascading effect of bird pollinator loss on the plant community (Anderson, 2011).

Birds that specialise in pollination, such as hummingbirds, feed on flower nectar, and are present in all continents bar Europe and Antarctica. However, there are several European bird species (e.g. tit groups *Cyanistes* and *Sylvia* and warblers *Phylloscopus*) that, although they are generalist feeders, sometimes play a role in plant pollination. Bird—flower visits in Europe are slightly more common in the Mediterranean basin where many nectar-eating migratory species, particularly warblers, stop off during their migration. Migratory species such as the warblers potentially affect plant health by increasing pollen genetic flow over great distances (da Silva *et al.*, 2014).

2.3 Night-time pollinators

Night-time pollinators, such as moths, are often overlooked by researchers (Macgregor *et al.*, 2015). Moths are an important group to study: there are thought to be 160 000 moth species – compared with 17 500 butterflies – living in a wide range of habitats. Studies show that moths are in decline, something that is likely to have cascading effects across the ecosystems they live in given their position as a food source for foxes, insectivorous birds, bats and other small mammals (Butterfly Conservation, 2002; Conrad *et al.*, 2006; Groenendijk and Ellis, 2011). Of particular significance for pollination are nectar-eating moth species from the families Sphingidae, Noctuidae and Geometridae (Winfree, Bartomeus and Cariveau, 2011) and potentially the newly defined Erebidae (LeCroy, Shew and VanZandt, 2013).

Hummingbird hawkmoth (*Macroglossum stellatarum*) feeding, by Yusuf Akgul @Wikimedia Commons, CC BY-SA 4.0. This species can be seen feeding on plants including honeysuckle.

Moths pollinate a wide range of plant species: at least 289 species from 75 different plant families can be either partially or exclusively pollinated by moths. Recent work indicates they may perform an important role in maintaining botanical biodiversity – for instance, 23% of moths collected in a UK study were found to be carrying pollen from a total of 28 different species of plants (Macgregor *et al.*, 2017). However, little is known about the scale and importance of their function as pollinators, and further monitoring and data collection is needed. The importance of monitoring night-time pollinators is becoming more pressing; artificial light pollution is a growing problem globally, and moths are declining in numbers. Their decline is going largely unrecorded (Macgregor *et al.*, 2015, 2017), and, given moths' position as significant pollinators, is likely to have detrimental impacts that may trigger cascading effects across habitats (Knop *et al.*, 2017) (see **Section 3.5** on the effects of artificial light pollution).

Other important nocturnal pollinators include some bats, beetles and flies (Willmer, 2011). Bats, for instance, are important pollinators in both tropical forests and drier areas (IPBES, 2017). Species of the small bats Microchiroptera are thought to pollinate at least 500 species of plants in Central and South America, a well-known example being the genus *Leptonycteris*: the main pollinators of the agave plant in Mexico, from which tequila is made (Hutson *et al.*, n.d.). A number of pollinating bat species are known to be threatened. The Thomas's yellow-shouldered bat, *Sturnira thomasi*, for instance, is endemic to Guadeloupe (an Outermost Region of the EU) and currently vulnerable due to habitat loss.

In the forests of Africa, Eurasia and Australia, around 289 species of plants rely to some degree on large populations of the 200 species of flying fox bats for propagation – these plants contribute to 448 economically valuable products. French Guiana, an

EU Outermost Region, hosts species of flying fruit bat important for seed dispersal in tropical forests (Fujita and Turtle, 1991). In Réunion, another Outermost Region of the EU, the fruit-eating pollinating bat species *Pteropus niger* was thought to be locally extinct on the island since the early eighteenth century. However, more recent reports suggest a colony has re-established itself (O'Brien, 2011).

Lesser long-nosed bat *Leptonycteris yerbabuenae* **or 'tequila bat' covered in pollen by US National Park Service @Wikimedia Commons, public domain.**

2.4 Island ecology and pollinator loss

Understanding pollinators' precise contributions to nature is challenging when looking at large, complex ecosystems. However, isolated island communities can provide important clues. Islands where native pollinators have been removed – due to the introduction of invasive alien species, for example – provide a 'microcosm' view of the benefits that pollinators confer to an ecosystem. The detrimental impacts of their absence are often more apparent in these simpler, more isolated ecosystems. Extrapolation from these microcosms can provide an impression of the potential global benefits pollinators contribute to larger, more complex ecosystems, which are typically harder to study.

For example, the impacts of introduced cats, rats and stoats on pollinators and pollination are very notable in vulnerable island ecosystems. These introduced species exert a top-down pressure on plant pollination and fitness as they eat pollinators such as birds, lizards, bats and other small mammals (Vanbergen, Espíndola and Aizen, 2018).

In the Ogasawara archipelago of Japan, invasive alien lizards wiped out endemic bee species through predation, leaving only the introduced western honeybee species, which came to dominate the pollinator community. The western honeybee also prefers flowers of invasive alien plants on these islands. Thus, the ecosystem shifted to a state where invasive alien pollinators and plant species thrive, while endemic plant species decline in number (Vanbergen, Espíndola and Aizen, 2018).

In Hawaii, the invasive alien predatory wasp Vespula pensylvanica out-competed for nectar resources both the native *Hylaeus* bees and the purposefully introduced western honeybee. Both *Hylaeus* bees and western honeybees are the principal pollinators of the native tree species *Metrosideros polymorpha*, which consequently produced less fruit due to lower rates of pollinator visitation. This lack of fruit may mean that other species in the food chain, which eat the fruit, will decline in number due to a lower availability of this food source (Vanbergen, Espíndola and Aizen, 2018).

Section 3. Drivers of change in pollinator populations

There is no single overriding cause of wild pollinator decline. This section explores the multiple – likely interacting – factors that are driving changes in pollinator abundance, distribution, range and diversity. The focus here is on the main, direct drivers of overall decline. These can broadly be summarised as: land-use change, intensive agricultural management and pesticide use, environmental pollution, invasive alien species, pathogens and climate change. Land-use and land-management factors are especially significant as they remove or reduce the quality of habitats (destruction, fragmentation or degradation). This includes the influences of conventional, intensive agriculture, such as the increase in monocultures – which homogenise and simplify the landscape – and high use of pesticides and fertilisers. Understanding the drivers of population change can point us towards appropriate solutions to address pollinator decline, such as how to adapt habitats and their management or reduce harmful impacts of pesticides on pollinators.

Current scientific opinion is that land-use change and land-management issues appear to be the most influential drivers of historic and ongoing pollinator biodiversity changes. It is important to recognise, however, that the importance of a particular driver varies with geographical and ecological context, and with the pollinator species in question (IPBES, 2017). This makes it very hard to universally rank the drivers on a quantitative basis. For instance, disease is a particular problem for honeybees (see **Section 3.6**) but is less well documented for other pollinator groups. Invasive alien species can be especially impactful in island ecosystems, while climate change is expected to become a more important influence on biodiversity and ecosystem services in the near- to medium-term (decades), either alone or in interactions with other drivers such as land-use change (IPBES, 2019).

It is important to also be aware of indirect drivers of biodiversity decline – the broader, systemic issues behind the direct drivers (IPBES, 2017; 2018; 2019). For instance, population growth, increasing wealth and technological development have knock-on effects for the direct drivers of land-use change, agricultural intensification, climate effects and the spread of invasive alien species.

3.1 Figures of decline

Numerous studies have highlighted a decline in wild pollinating species in Europe and around the world, producing some very stark figures. For instance, Sánchez-Bayo and Wyckhuys (2019) estimate that half of the world's insect species, including many pollinators, are rapidly declining, and a third are threatened with extinction. There has been a 76% fall in the biomass of flying insects (again, including pollinators) in protected areas in Germany between 1989 and 2016, suggest Hallmann *et al.* (2017). The Netherlands has experienced an 84% decline in butterfly species since the late 19th century (van Strien *et al.*, 2019), while 70% of western Mediterranean butterfly species declined between 1994 and 2014 (Melero, Stefanescu and Pino, 2016). In the UK, the range sizes for a third of wild bee and hoverfly species contracted between 1980 and 2013 (Powney *et al.*, 2019). These figures are largely the results of volunteer-collected data (see **Section 4.2**).

It is not yet possible to put precise and overall figures on levels of decline; there are major knowledge gaps concerning abundance, and the extent and causes of population decline in wild pollinator species owing to patchy, insufficient monitoring systems (Goulson *et al.*, 2015) (see **Section 4**). Data are very sparse for regions beyond Europe and North America, and for non-bee species (IPBES 2017). The available evidence, however, is more than sufficient to trigger major concerns and urgent conservation action, given the critical role that pollinators play in supporting food production and underpinning ecosystems (see **Sections 1** and **2**). These concerns are acknowledged in a number of significant initiatives, including the EU Pollinators Initiative, IPBES, the Convention on Biological Diversity (CBD),[16] and many national initiatives.

BOX 9

The 'windscreen phenomenon' and the shifting baseline

The decline in wild insect pollinators has been going on largely unnoticed for many decades, as has a decline in most insect groups globally. The 'windscreen' phenomenon is a term referring to adults' memories of there being more insects when they were children – notable after driving a car, when they remember seeing bugs splattered all over the windscreen. Today, in contrast, windscreens after a drive are reported as clean (Jarvis, 2018). As we only have recent data regarding the population size of many pollinator species, the baseline from which we measure decline today is somewhat skewed. The 'shifting baseline' concept refers to the likely possibility that the baseline of 50 or 100 years ago was much higher for insect pollinators. Thus, monitoring data today that cites a 10% decline over the course of a few years needs to be set in the context of a much higher baseline for that group only 50 years ago; such a comparison would likely show a much more shocking trend. The children of today may be liable to see the present-day, already reduced, abundance of pollinators as normal (Soga and Gaston, 2018).

Bugs on the windshield, Montana by D. Garding @Flickr, CC BY-NC-SA 2.0.

Road and windshield by Hans @Pixabay, public domain.

16. https://www.cbd.int/

3.2 Land use, land management and agricultural inputs

These drivers of change cover a range of influences on pollinators, including land-use change, land management practices and agrochemical use (pesticides and fertilisers).

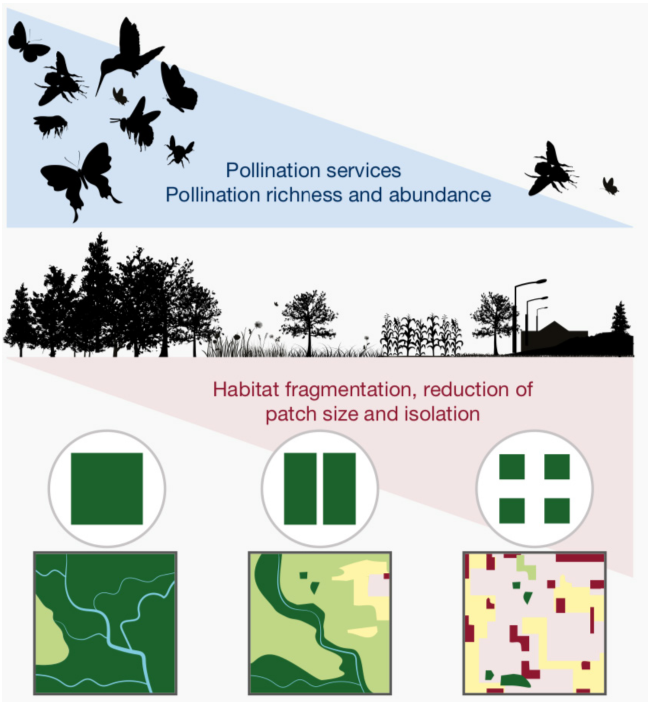


Figure 6: Increasing fragmentation of habitats reduces levels of pollination, the diversity of pollinator species and numbers of individuals. Source: IPBES, 2017.

3.2.1 Land-use and land-use change

Land-use change can destroy and reduce the quality of habitats for nesting pollinators, and remove sources of food (i.e. flowers). It can also fragment habitats, meaning that pollinators must travel further to forage (IPBES, 2017).

Many pollinator species need abundant and diverse sources of pollen throughout the year for sufficient intake of nutrients (van der Sluijs and Vaage, 2016). However, the simplification of landscapes is reducing the supply of these food resources. This simplification has arisen through factors including the rise of conventional intensive agriculture, which is characterised by monocultures dominated by one or a few crops, the use of insecticides and herbicides that destroy wildflowers, and which is often accompanied by deforestation and/or urbanisation.

Large monoculture systems reduce foraging resources for pollinators by removing flowering weeds and native plants and reducing crop diversity. For example, Senapathi *et al.* (2015b) concluded that the reduced diversity of forage plants associated with monocultures is likely to be behind reduced bee and wasp pollinator richness and composition in England. Some mass-flowering crops provide large amounts of foraging resources for some pollinators, namely nectar and pollen, but these resources are only temporary, and cannot support most pollinators throughout their life cycle (IPBES, 2017).

Monocultures also reduce the availability of nesting resources and micro-habitats – undisturbed soil patches, hollow stems, shrubs, trees and dead wood – and this has also contributed to global wild insect pollinator decline (Pisa *et al.,* 2015; IPBES, 2017). For instance, the loss of host plants over the winter for moth eggs, larvae, pupa and adults has been linked to declines in moth abundance and distribution (Fox, 2013).

Genetic diversity among bees is much lower in landscapes that have been simplified by high proportions of agricultural cover (Grab *et al.*, 2019). Such results suggest that agricultural land favours species with certain traits, such as the ability to fly long distances; larger species that traverse greater distances may be less sensitive to changes in habitat area, for example (Bommarco *et al.*, 2010).

Agricultural intensification can lead to wild pollinator decline through the high use of agrochemicals (see **Section 3.2.2**), but also through land management


Rows of green maize sweetcorn crop ripening, fotoVoyager @Getty/IStock. Aerial drone image of fields with diverse crop growth based on principles of polyculture and permaculture – a healthy farming method for ecosystems yuelan @Getty/IStock.

practices such as over-grazing by livestock or intensive mowing and tillage, which worsen the quality of grassland (IPBES, 2017). For instance, in northern Germany, changing grazing regimes have been shown to alter plant—pollinator communities, leading to fewer pollinator species (Kruess and Tscharntke, 2002). Also, in Germany, Hallmann *et al.* (2017) postulate that a major cause of a 75% decline in flying insects in protected areas is the surrounding farmland, which is intensively managed. Similarly, Senapathi *et al.* (2015b) saw a greater decline in bee and wasp species richness in the UK since 1921 on natural sites surrounded primarily by arable expansion than on sites that were not. These results demonstrate how the influence of habitat loss on agricultural land may spill over into natural areas.

The loss of traditional, extensively managed forms of farmland contributes to the decline of many wild pollinator species. Farmland abandonment, which is driven by economic and social factors (Benayas *et al.*, 2007), often sees high-quality habitats for open-habitat species, such as meadows and grasslands, turn into forest – particularly in southern Europe. Conversely, this conversion of land could benefit several other pollinators that need woodland habitats, such as hoverflies. This land-use change can negatively impact species that have evolved to thrive on traditional low-intensity farmland. For example, Herrando *et al.* (2016) found that while a minority of butterfly species benefited from the newly increased forest cover in Catalonia, the majority of butterfly species studied were negatively affected by farmland abandonment (see **Box 13** for more information on butterfly monitoring in Europe). However, in some intensively farmed western European landscapes – where only isolated fragments of forest remain – these islands of forest habitat, benefit bees and hoverflies, which favour old forest remnants with a herb layer (Proesmans *et al.*, 2019).

Research from tropical rainforests, such as those in Brazil and Australia, shows how forest loss and fragmentation is negatively affecting wild bee abundance and diversity (Newton *et al.*, 2018; Smith and Mayfield, 2018; Ferreira *et al.,* 2015). In Illinois, USA, Burkle, Marlin and Knight (2013) found that the quantity and quality of pollination services has declined since the late 19th century, correlating with a shift from a continuously forested landscape to a fragmented landscape with a mixture of agricultural, commercial and residential land uses. Overall, a mosaic of natural and semi-natural habitats across a landscape, which includes woodlands, agroforestry, grasslands, hedgerows and wetlands, will support diverse pollinator communities and networks (IPBES, 2017).

> *A mosaic of natural and semi-natural habitats across a landscape, which includes woodlands, agroforestry, grasslands, hedgerows and wetlands, will support diverse pollinator communities and networks.*

Urban areas account for 22.5% of the EU's total area (EuroStat, 2016). While not as significant a factor as agriculture or forestry, urbanisation can also contribute to habitat and floral losses in some cases. However, in other cases, the valuable habitats provided by gardens and allotments in urban areas have been shown to offer refuges from agricultural monocultures (see **Box 10**). The benefits or negative impacts vary by species. For instance, hoverflies appear to be more negatively affected by urban development than bees (Baldock *et al.*, 2015), and pollinator species that have more specific habitat or food needs – long-tongued bumblebees adapted to particular flower species, for example – are particularly vulnerable to land-cover changes that alter the availability of food or nesting resources. This can lead to less diverse pollinator communities dominated by common generalist species that are more able to adapt to altered conditions (discussed in IPBES 2017).

3.2.2 Pesticides and other biocides

Pollinating insects are often chronically exposed to pesticides during their development and adult life. Landscape-scale surveys of wild bees and butterflies show that species richness tends to be lower where both pesticide and exposure levels are high (Brittain *et al.*, 2010). Most research into the effects of pesticides on pollinators has been conducted on bees – and in recent years, neonicotinoids are the group of insecticides most strongly implicated in their decline (Pisa *et al.*, 2015). These insecticides are used as a seed dressing on crops that becomes incorporated in all the plant's parts as it grows and are thus often found in pollen and nectar, thereby providing an exposure pathway to bees and other pollinators (Blacquière *et al.*, 2012; Goulson, 2013).

Neonicotinoids can have significant negative effects on the neurological systems of both wild and managed bees; they impair bees' foraging and navigational abilities, reduce their fertility, and increase susceptibility to disease (see **Section 3.6**). A key emerging issue with these neurotoxins is that they are highly persistent in soil and soil water, and have been found at biologically relevant concentrations in the pollen and nectar of wildflowers ('non-target' plants) near, and well beyond, crops (Krupke *et al.*, 2012, 2017; Botías *et al.*, 2016). Pesticide concentrations in Europe are often below those that would cause immediate death to pollinating insects (acute toxicity), but can have sub-lethal or chronic effects, which affect behaviour or lifespan. These effects may interact with other stressors (such as disease) acting on pollinators at the same time or location (Godfray *et al.*, 2014).

Most studies on the toxicological effects of neonicotinoids have been conducted in laboratory settings, which has intensified the debate on their actual impact in the real world. However, field studies are now starting to appear. A notable study conducted in Sweden found that, when applied to oilseed rape seeds, the neonicotinoid clothianidin and the non-

> *Pesticide concentrations in Europe are often below those that would cause immediate death to pollinating insects (acute toxicity), but can have sub-lethal or chronic effects, which affect behavior or lifespan.*

Oilseed rape (rapsflower) blossoms by Moinzon @ Pixabay, public domain.

systemic (i.e. not taken up by the plant and into its leaves) pyrethroid β-cyfluthrin reduced wild bee density, solitary bee nesting, and bumblebee colony growth and reproduction under field conditions (Rundlöf *et al.*, 2015). Further supporting evidence from the field comes from Tsvetkov *et al.* (2017), who found that honeybees near corn crops in Canada were exposed to neonicotinoids for three to four months via non-target pollen. This weakened the bees' immune systems and led to reduced survival, especially when they were co-exposed to a commonly used fungicide. This highlights that, in contrast to laboratory studies, pesticides can often occur in the environment together with other biocides, which can combine to formulate a more lethal 'cocktail' for pollinators.

Furthermore, in field experiments on rapeseed in Hungary, Germany and the UK, Woodcock *et al.* (2017) found neonicotinoid exposure from several non-target sources to reduce winter survival and colony reproduction in wild bees. However, the same study noted that the effect on honeybee hives was more variable with negative effects on colony size found in Hungary and UK in contrast to positive effects during crop flowering in Germany. The effect on honeybees in Hungary persisted throughout the winter resulting in a 24% smaller colony the following spring. Neonicotinoid pesticides (e.g. thiamethoxam) have also been found to prompt addiction in social bees, which preferentially visited pesticide-laced feeders. This maladaptive behavior is likely to lead to greater exposure, and greater risk, over time.

In Europe, the neonicotinoids clothianidin and thiamethoxam are no longer approved for use by the European Commission. The Commission has also not renewed the approval of the neonicotinoid thiacloprid, and imidacloprid can only be used in permanent greenhouses. In 2018, the neonicotinoid acetamiprid was again approved for use until 28 February 2033, given that its risk to bees is deemed low.[17] It is also known that agrochemical stressors do not act in isolation, and their interactions may be difficult to predict; for example, some pesticides alter the effects of other pesticides on bees (Goulson *et al.*, 2015).

> *In contrast to laboratory studies, pesticides can often occur in the environment together with other biocides, which can combine to formulate a more lethal 'cocktail' for pollinators.*

As seen above, fungicides can harm foraging insects, especially in combination with other biocides. Herbicides can also affect forage availability for pollinators, reducing wild plant diversity and thus degrading pollinator habitats. There are also a number of studies that address the direct effects of fungicides and herbicides on bees. The number of studies investigating potential sub-lethal effects of herbicides and fungicides on bees is low, making this an area worthy of further attention (Cullen *et al.*, 2019).

17. https://ec.europa.eu/food/plant/pesticides/approval_active_substances/approval_renewal/neonicotinoids_en

3.2.3 Fertilisers

Leaf fertilisers can input heavy metals into the agricultural ecosystem, such as copper (Cu), iron (Fe), zinc (Zn), manganese (Mn), cobalt (Co), and selenium (Se), all of which can be detrimental for bee health (He *et al.*, 2005, Hladun *et al.*, 2016). Increasing concentrations of the leaf fertilizer CuSO4 were found to increase mortality of the stingless bee *Partamona helleri* in Brazil (Botina *et al.*, 2019). The same researchers assert that research about the effects of fertilisers on the microbiota of bees remains neglected. However, fertiliser treatments at realistic rates have also been found to slightly increase caterpillar abundance in field margins in Germany (Hahn *et al.*, 2015).

A Brazilian study also found that positive effects of native pollinators on crop yield were most accentuated under lower inputs of nitrogen (N) (e.g. equal to or below 72kg ha-1) and effects became negative above 100 kg ha-1, which suggests an alteration of the plant's investment strategy (reproductive versus vegetative development) under high N availability (Ramos *et al.*, 2018). It has also been shown that the effects of nitrogen fertilisers can combine with the effects of pesticides to amplify a delay in flowering for tansy (*Tanacetum vulgare*), for example (Dupont, Strandberg and Damgaard, 2018).

In Europe, it has been shown that increasing the amount of fertiliser decreased total and small bee abundance in winter cereal fields in Hungary, and posit that reduced application of fertiliser and a cessation of insecticide application might lead to high bee species richness and abundance (Kovács-Hostyánszki, Batáry and Báldi, 2011).

While fertilisers seem to produce lesser effects than pesticides, it is clear that pollinating species can be affected by the application of agricultural chemical fertilisers. It has also been found that increases in pollinator visitation rate and decreases in pest pressure enhanced yield more than increase in fertiliser supply (van Gils, van der Putten and Kleijn, 2016).

3.3 Climate change

There is evidence that changes in climate have led to shifts in range for some pollinators. Range shifts in response to climate have been seen in butterflies in Europe and North America, for example (Devictor *et al.*, 2012; Forister *et al.*, 2010), and some mountain-dwelling species of bumblebees have shifted uphill in Spain (Ploquin, Herrera and Obeso, 2013). However, some species cannot shift range at all; for instance, bumblebees in North America and Europe have not moved northwards as the climate has warmed, although the southern ends of their range are shrinking (Kerr *et al.*, 2015). This makes bumblebees particularly susceptible to rapid climate change. Furthermore, climate change can affect the timing of key life stages. For example, butterflies are emerging earlier in the year as average temperatures rise (Robinet and Roques, 2010).

Such results have led to concerns around a mismatch between the location and timing of pollinators and their plants given that, in many cases, these elements are not all shifting at the same pace. For instance, climate change could shorten the bumblebee foraging season by reducing the availability of early- or late-season forage (Memmott *et al.*, 2010). Such mismatches could potentially lead to population declines and local extinctions (Burkle, Marlin and Knight, 2013), and there are concerns that, even where species are

Wildflowers, by jacquesvandinteren @Getty/IStock.

shifting their range, they might not be able to keep pace with climate change and may therefore struggle to adapt to evolving habitat conditions. For example, while the rate of climate change in Europe from 1990 to 2008 was equal to a 249-kilometre northward shift, butterflies only made an average northward shift of 114 kilometres (Devictor *et al.*, 2012).

Climate change is also expected to increase the frequency and severity of extreme weather events such as storms, floods, and droughts – something that is likely to have major ecological impacts on a local scale. For example, floods are likely to harm many bee species that nest or hibernate underground (Goulson *et al.*, 2015), and hot, dry conditions have been shown to kill the eggs of some butterfly species (Klockmann and Fischer, 2017).

Climate change is likely to be a growing source of stress in the future that exacerbates the impact of other factors, such as habitat loss (Goulson *et al.*, 2015; IPBES, 2019). For instance, widespread extinctions of drought-sensitive species of butterflies could occur in the UK as early as 2050, according to Oliver *et al.* (2015) – but these could be mitigated by improving their habitat. Conversely, habitat loss and fragmentation could compound the damaging effects of climate change on pollinator populations or diversity by limiting the amount of available habitat for species to migrate to as the climate shifts (Vanbergen *et al.*, 2013).

BOX 10.
Urban pollinators

Surprisingly, towns and cities often provide valuable habitats for pollinators. Research in the UK, for example, found that urban green networks formed by roadside strips, allotments, gardens, roundabout planting and parks are a valuable source of insect biodiversity – including pollinators. In fact, the researchers found that cities contain more bee species than some agricultural landscapes (Baldock *et al.*, 2015).

Other studies point to the remarkably wide array of pollinator species found in cities. For example, 35% of UK hoverfly species were recorded in a single urban garden (Owen, 2010), and half of German bee species have been recorded in Berlin (Saure, 1996).

Urban areas offer a patchwork of habitats that can benefit some pollinators. They also offer a refuge from insecticides. Brownfield sites in cities – developed land not currently in use – can provide nesting materials for some species, and gardens with exotic species provide a year-round and plentiful source of nectar to pollinators. However, not all species benefit, which may be partly due to differences between urban areas. More research is needed, especially in cities in the Neotropical (Central and South America) and arid areas where data are currently lacking (IPBES, 2017)

Furthermore, pollination provides cities with many ecosystem services. Wild plants in towns and cities support human health and wellbeing by filtering air, trapping carbon and cooling temperatures. Green spaces in cities promote outdoor activities, provide scenic beauty and can have a calming effect (Klein *et al.*, 2018; 2018a).

Dandelion on a road by Pezibear @Pixabay, public domain. Native pollinators often prefer native flowers, which are often thought of as weeds.

Urban pollinators - *continued*

Litchi tomatoes and white-tailed bumble bee with pollen sacks, by BarbeeAnne @Pixabay, public domain.

Get planting

There is much urban gardeners can do to help pollinators – and stay healthy themselves in the process. Native pollinators' favourite flowers are often those thought of as weeds by gardeners – such as buttercups, common hogweed, ox-eye daisies, dandelions, creeping thistle and brambles. Urban gardeners could let parts of their gardens grow longer to let these plants thrive.

Gardens and allotments contribute to pollinator abundance in cities; gardens do so by their extensive area, but allotments give the biggest boost to pollinator diversity and numbers per unit area (Baldock *et al.*, 2019). Allotments also supply healthy fruit and vegetables, cut food miles, and encourage people to socialise and stay active (Carrington, 2019).

3.4 Invasive alien species

Increasing global trade is facilitating the spread of exotic species around the world. This may negatively affect pollinators in at least four key ways:

1. Introduced species may be in the form of parasites and pathogens, such as the *Varroa destructor* mite and its associated viruses, which, following the global translocation of honeybee colonies, have become major pressures affecting the western honeybee (see **Section 3.6** on disease);
2. Invasive alien plants may outcompete native plants favoured by local pollinator species, or lead to a lower diversity of food resources;
3. Invasive pollinator species may outcompete native pollinator species;
4. Invasive predators, such as cats and rats, may eat certain pollinator species, such as birds and lizards – and disrupt ecosystems as a result.

There are still large gaps in our understanding of the risks of invasive species to pollinators, but evidence suggests that the risks are complex, substantial, and vary greatly by the ecosystem and species involved (Vanbergen, Espíndola and Aizen, 2018).

Invasive alien plants

While invasive alien plants can provide a substantial food resource for pollinators able to exploit them, pollinator diets may suffer if local floral resources become dominated by an invasive alien plant species that does not provide the optimal balance of nutrients (IPBES, 2017; Vanbergen, Espíndola and Aizen, 2018). Bees, for instance, are very sensitive to nutrient combinations, such as the ratio of different essential amino acids to carbohydrates, and may suffer poor growth and survival if they consume a monotonous or nutritionally sub-optimal diet (Vaudo *et al.*, 2016; Stabler *et al.*, 2015).

Invasive alien pollinators

Documented cases of invasive alien pollinator species outcompeting native species include those of introduced bumblebee species, which have similar needs to native bees in terms of nesting and floral resources. This can lead to the alien species becoming dominant and outcompeting natives. A notable example is the local extinction of the Patagonian giant bumblebee *Bombus dahlbomii* from most of its range in Argentina, following the introduction and establishment of European bumblebee species (*B. terrestris* and *B. ruderatus*) (Morales *et al.*, 2013).

Invasive alien predators

Invasive alien predators spread by humans such as cats, rats and stoats often consume pollinators such as birds, lizards, bats and other small mammals, with knock-on effects on plant pollination (IPBES, 2017). This is especially true in the simpler food webs of island ecosystems (see **Section 2.4** on island ecology),

The predatory yellow legged hornet, *Vespa velutina*, an invasive species in Europe threatening the populations of European honeybee, by Danel Solabarrieta @Flickr, CC BY-SA 2.0.

but can also be the case in larger-scale ecosystems. For example, the accidental introduction of the yellow-legged hornet (*Vespa velutina*) into Europe from Asia in 2004 represents a direct threat to already stressed western honeybee populations (Monceau, Bonnard and Thiéry, 2014). As well as preying upon honeybees, the hornet prevents honeybees from foraging by hovering in front of beehives, and has been shown to be an important contributor to winter colony collapse among western honeybees in France (Requier *et al.*, 2019).

Bright city: night image of Paris, France from the International Space Station by NASA @Wikimedia Commons, public domain.

3.5 Pollution

As well as chemical pollution in the form of agrochemical biocides and fertilisers (see **Section 3.2**), heavy metals such as lead and cadmium are a potential risk to pollinators. These are well-known to have generally damaging effects on organisms – but their effects have not been widely investigated for pollinators specifically (IPBES, 2017).

There is emerging evidence, however, of the damaging effects of artificial light at night. For example, a recent UK study found that street lighting lowered numbers of moths by 50% at ground level, and species diversity by 25%. Twenty-three per cent of moths collected were carrying pollen from a total of 28 species of plants, suggesting they are likely to be significant pollinators (Macgregor *et al.*, 2017).

Artificial light may have potentially far-reaching effects on pollinators and plants. Knop *et al.* (2017) found that fewer night-time pollinator species pollinate plants in the presence of experimentally imposed artificial light (similar to street lights). Pollinator visits to illuminated plants were 62% lower, with 29% fewer species, than for non-illuminated plants. Recorded night-time pollinators included various species of moth, fly and beetle. These reductions in visits and diversity led to a subsequent fall in fruit production in illuminated plants by 13%, and thus reduced levels of plant reproduction – and a likely reduction in food supply for pollinators active during the day. This study illustrates how plants and their pollinators are embedded in a complex network of interactions; disruption to one part of the network can have cascading effects across ecological communities.

3.6 Diseases

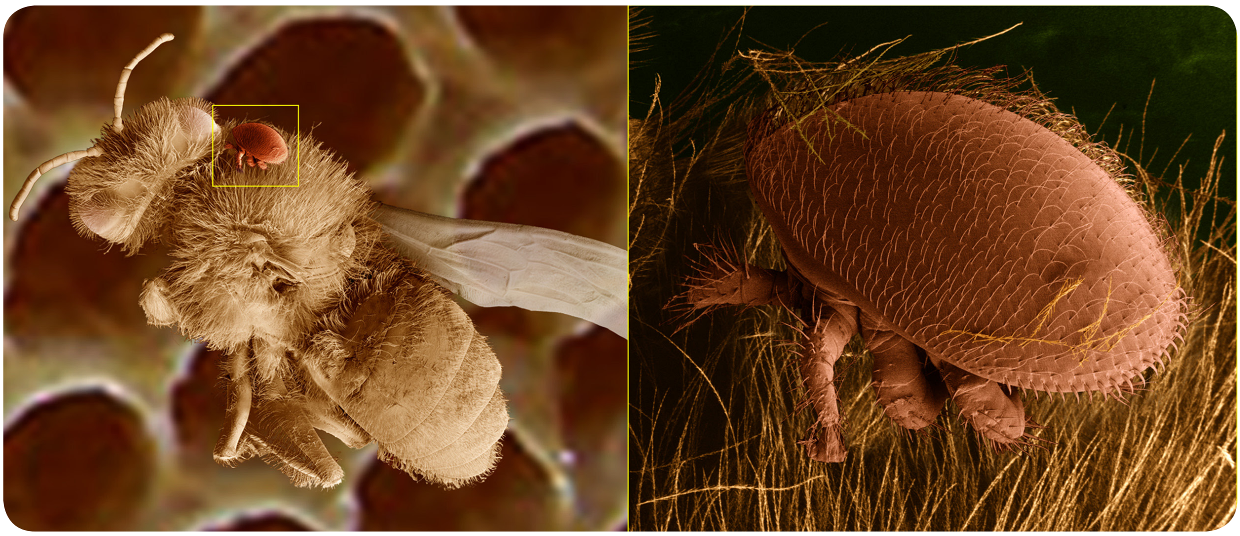
A broad range of invertebrate parasites, insect parasitoids (a kind of parasite that always kill their host) and pathogens (bacteria, viruses, fungi) have contributed to honeybee declines (IPBES, 2017).

It is worth noting that most research has focused on diseases associated with honeybees, with some research into bumblebees. Very little is known about the pathogens of other wild bee species (Goulson *et al.*, 2015).

The most well-known example of pollinator disease is the mite *Varroa destructor.* This affects honeybees (*Apis* spp.), but seemingly not other bee species. It was spread by contact between the original host, the Asian honeybee *Apis cerana*, and the western honeybee *Apis mellifera*, which was translocated for beekeeping purposes and has little resistance to this pest. Since the 1960s, *Varroa* has spread from Asia to Europe, the Americas, and most recently to New Zealand. During parasitic feeding on the bee host, the mite also transmits pathogens such as deformed wing virus (DWV). The combined effect of the mite and the diseases it transmits is a major contributor to honeybee colony losses in North America and Europe (Rosenkranz, Aumeier and Ziegelmann, 2010; Nazzi *et al.*, 2012; IPBES 2017). Travelling in the other direction, drastic declines in the Asian honeybee in China (and subsequent reduction of plant pollination and plant diversity) following the introduction of the western honeybee in the late 19th century may have been in part due to the transfer of disease (Yang, 2005).

Mass breeding and the large-scale transport of managed bees can increase the risk of spreading pollinator diseases from managed to wild bee species. For instance, DWV can spread from managed honeybees to wild bumblebees (Manley *et al.*, 2019; Fürst *et al.*, 2014). This disease spillover presents a potential threat to some wild species and populations, and may diminish rates of naturally occurring pollination: a service that is often already affected by large, monoculture croplands that provide few natural nesting habitats or year-round floral resources for wild bees (IPBES, 2017). It is worth noting, however, that some wild (feral) honeybee populations show resistance to disease; for example, Loftus, Smith and Seeley (2016) suggest that wild colonies of European honeybees see far lower *V. destructor* infestation rates, partly because they nest in small cavities and more frequently swarm.

The lethal effects of pathogens have increased with the rise of bee exposure to pesticide-contaminated pollen and nectar (Long and Krupke, 2016), which weakens their immune system (Tesovnik *et al.*, 2017). In isolation from other stressors on bees, pathogens are less likely to lead to death.



Female of *Varroa destructor* on dead bee, USDA by Pavel Klimov @Wikimedia Commons, public domain.

Section 4. Monitoring pollinators for their protection

This chapter explores opportunities to enhance the monitoring of pollinators – that is, systematic censuses of pollinators that provide us a with a picture of their populations, communities, habitats and impacts, and how these may be affected by changes in the environment such as landscape change or climate warming. This fundamental understanding forms the basis of further (applied) research and enables well-designed policies intended to safeguard pollinators' continued existence. For instance, monitoring helps verify whether policies are having the desired effects, such as whether new protection measures have improved the conservation status of endangered species or whether an agri-environment scheme has led to increased pollinator numbers in croplands. Monitoring can also provide an 'early warning system' that tells us how close we may be to a 'pollination crisis' – the point at which crop yields fall due to pollinator decline.

Monitoring is resource-intensive, however, and current efforts are far from complete. Most pollinator species are not well-monitored and there are currently no global monitoring schemes. Challenges to pollinator monitoring include: i) the large number and diversity of pollinating species; ii) the fact that most of these cannot be easily identified in the field, making it necessary to capture them for analysis in the laboratory; iii) the fact that identifying collected specimens is time-consuming and needs specialist skills; and iv) the fact that, to date, there are comparatively few volunteer recorders or citizen science initiatives focused on pollinating insects (Carvell *et al.*, 2016).

Significant gaps in pollinator data remain. For instance, extremely little is known about pollinator trends and distributions outside northern Europe and the USA, two regions with the most concentrated research efforts (Bartomeus *et al.*, 2019; IPBES, 2017). Even within Europe, the conservation status of over 55% of bee species in the EU could not be assessed as part of the IUCN Red List assessment[18] due to gaps in data. These gaps limit our understanding of the status and trends of pollinator species, and of the potential implications of their declines for our well-being.

Opportunities to fill these data gaps include a strengthened professional taxonomy sector, empowered citizen science, coordinated research infrastructure and the development of novel monitoring technologies.

'Bug hotel' at a nature reserve in Berlin, by ebenart @Getty/IStock.

18. http://ec.europa.eu/environment/nature/conservation/species/redlist/downloads/European_bees.pdf

BOX 11

Pollinator monitoring techniques: a brief introduction

There are various methods used to monitor pollinating insects. Some common methods are:

- Pan traps. Insects are deceived into visiting coloured bowls of water designed to resemble flowers. Trapped in the water, the insects can be counted and identified by experts and/or DNA-based identification technologies (see **Section 4.4** on DNA barcoding).

A pan trap lures in insects for analysis and counting by Frost Museum @ Flickr CC BY 2.0.

Pan traps in situ. © Claire Carvell.

- Transects. Recorders walk a set route: the transect. They record all the species they observe and can recognise by sight along that path (Transects may also be coupled with specimen collection for subsequent expert identification). Typically transects are employed to monitor conspicuous species that are readily recognisable.
- Floral observations. Recorders watch a flower and log all species or broad pollinator group they observe and can recognise by sight during a set amount of time.
- Each method brings different benefits – and limitations. The choice of method depends on the goals and resources of the project, as well as the target species and the location.

For example, transect and floral observation studies can reveal which insects are pollinating which flowers in a given place and time and how they interact with one another, whereas pan trap surveys provide a more detailed snap-shot of the abundance, community composition and species diversity in a locality, often picking up more species than transects/observations. When coupled with expert identification pan traps offer more reliable species identification – although this identification gap can be reduced where recorders on transect or floral observation surveys have high levels of taxonomic expertise (O'Connor *et al.*, 2019).

4.1 Strengthening the professional taxonomy sector

There is an urgent need for reliable taxonomy to understand and help to prevent wild pollinator decline. By providing fundamental information to help define and identify species and their behaviour, taxonomy provides the building blocks for applied and fundamental research (such as ecological research).

Knowing merely the number of species is insufficient. Monitoring and conservation cannot occur without identifying the species themselves. However, correctly identifying species is often very challenging – notably for insects – and the number of skilled taxonomists able to conduct this work is insufficient. This represents both a major bottleneck in monitoring pollinators (Bartomeus and Dicks, 2019) and a limitation in biodiversity research, which tends to focus on easier-to-identify species as a consequence (Halme, Kuusela and Juslén, 2015a; 2015b).

Most research on pollinator decline has focused on bumblebees, for instance. These are relatively easy to identify by sight in the field and in the lab, without the need to dissect the body (as is often required to identify solitary bee species, for example). However, for bees alone there are around 20 000 species worldwide, which often need to be identified by experts. Bumblebees make up a minority of these 20 000 species, and each species may respond differently to environmental change. We thus do not know the extent of decline for most pollinator species, or understand geographic differences in loss (Archer *et al.*, 2014; IPBES, 2017; Potts *et al.*, 2016).

The professional taxonomy sector has been in decline over several decades, as funding has been diverted away from species-level research towards population-level and genetics-based research. There is presently a dearth of taxonomy jobs. Taxonomy has thus been described as a 'science in crisis' (Agnarsson and Kuntner, 2007).

To a certain extent, professional taxonomic expertise can be substituted by amateur expertise (see **Section 4.2**) and can be supported by novel identification technologies such as DNA barcoding (see **Section 4.4**). However, professional and traditional 'morphological' identification is still essential. For many groups of organisms, there may be only a small handful of taxonomists in the world – or even one individual – able to carry out proper identification. For many other groups, expertise is completely lacking. To help prevent the extinction of many species, a new generation of taxonomists is needed to support conservation efforts (Sluys, 2013).

Increased funding could help revitalise the professional base by providing education, jobs and improved career prospects. There also needs to be greater awareness of the far-reaching value of taxonomy to life sciences and policymaking (Ebach, Valdecasas and Wheeler, 2011). To reap the greatest benefits from the taxonomy sector, greater coordination with other sectors is needed (as discussed in **Section 4.3**).

4.2 Citizen science

Professional scientists usually design and manage monitoring programmes and take responsibility for a project's scientific reliability. They also analyse the resulting data for trends in the abundance, diversity or occurrence of species, and identify reasons, or drivers, for these trends where possible (see **Section 3**).

However, citizen scientists also play a valuable and increasing role in monitoring programmes, principally by reporting sightings of species. There is a long tradition of volunteer nature enthusiasts collecting monitoring data; this goes back to the 19th century, long before the term 'citizen science' was coined. These amateur naturalists are now often referred to as citizen scientists and include skilled experts from monitoring societies (often voluntary recording societies, environmental charities or NGOs) as well as enthusiasts without specialist skills.

Catching butterflies @Pixabay, public domain.

Whilst professionals also conduct ecological surveys, there are clear advantages of a monitoring workforce bolstered by volunteers. Citizen scientists can help meet data collection targets when programmes need to monitor a large geographical area or require frequent sampling, for instance, to support early detection of invasive alien species (for example, Pocock *et al.*, 2017; César de Sá *et al.*, 2019; Maistrello *et al.*, 2016). The relevance of citizen science data to environmental policy may be direct, as in the collection of data to support biodiversity indicators (Roy *et al.*, 2012; Chandler *et al.*, 2017; Van Swaay *et al.*, 2019a), or indirect, as when volunteer-collected data have highlighted declines in pollinator species (for example, van Strien *et al.* 2019; Hallmann *et al.*, 2017; Powney *et al.*, 2019; Melero, Stefanescu and Pino, 2016) (see **Section 3.1** on figures of decline). There are also benefits for citizen scientists themselves; participation can provide a sense of community belonging and empowerment, inspire actions and increase awareness of environmental issues (Pocock *et al.*, 2019).

Some volunteers play a significant role beyond data gathering, by providing high-level taxonomic expertise – that is, they are recruited to identify and describe individual species. The past few decades have seen an ongoing decline in the professional taxonomy sector (see **Section 4.1**).

BOX 12.

UK pollinator monitoring scheme brings volunteers and professionals together for national policy

Currently, the UK's Pollinator Monitoring Scheme (PoMS) is the only scheme in the world generating systematic data on the abundance of insect pollinators at a national scale. It aims to provide data on how populations and communities of pollinators are changing to inform government policy, such as England's National Pollinator Strategy[19] and the Pollinator Strategy for Scotland.[20]

The programme is led by academics and brings together a range of partners – including volunteer networks and NGOs. As well as supporting monitoring efforts, taxonomists with high levels of expertise in the target groups (bees and hoverflies) provide a consultative role, and identify species caught by other surveyors.

19. https://www.gov.uk/government/publications/national-pollinator-strategy-for-bees-and-other-pollinators-in-england
20. https://www.nature.scot/pollinator-strategy-scotland-2017-2027

UK pollinator monitoring scheme brings volunteers and professionals together for national policy – *continued*

The programme leaders developed two systematic methods of monitoring to help provide consistent, policy-relevant data. The first uses pan traps (bowls of water that capture insects, see **Box 11**) in a set of 75 one-kilometre squares, which have been randomly allocated within cropped (agricultural) and non-cropped (semi-natural) land across the country. This approach helps avoid some of the biases often found in volunteer-collected data, such as the natural tendency to record less-common species, to focus on more 'scenic' locations or higher recording effort taking place in areas not far from cities or towns where volunteer recorders live.

PoMS 1 km square surveys are conducted by volunteers who are provided with the necessary equipment and offered training and mentoring by professional surveyors from the PoMS team. This mentoring aspect is key in supporting individuals to understand the standardised protocols and put newly acquired insect identification knowledge into practice. In addition, online video guides are provided for all aspects of the survey. During the initial phase of the scheme, PoMS team surveyors have filled in 'gaps' in allocation of squares to volunteers.

Fifty volunteer surveyors have been recruited to cover just over half of the 1 km squares over the first two years (2017-2018), and together with PoMS team surveyors, have collected 1366 pan-trap samples in total.

The second monitoring approach is the FIT Count (Flower-Insect Timed Count), a simpler surveying technique. Volunteers count the number of insects that visit a patch of flowers over a 10-minute period. They identify insects to a broad group level, such as 'bumblebees' or 'hoverflies', and submit the data to a website. Some 14 347 insect visits to flowers have been recorded over two years with this method. The FIT Count approach has been recently transferred to Cyprus as part of the PoMS-Ky project, which has the additional objective of understanding the impacts of invasive plant species on pollinating insects (http://www.ris-ky.eu/poms-ky).

https://www.ceh.ac.uk/our-science/projects/pollinator-monitoring

Additional sources: Claire Carvell, personal communication (2019); Helen Roy, personal communication (2019); Adam Vanbergen, personal communication (2019).

With this decline, there has been increased reliance on amateur expert naturalists from monitoring societies to act as volunteer taxonomic consultants on monitoring schemes. The Pollinator Monitoring Scheme (PoMS)[21] in the UK, for instance, has recruited volunteer experts from the Bees, Wasps and Ants Recording Society[22] and Hoverfly Recording Scheme[23] (see **Box 12** for more information on this project). This expertise complements the data gathering efforts of other volunteers, and the theory and analysis provided by professional scientists.

Digital technologies also create opportunities for volunteers with less taxonomic expertise and bring together disparate sources of taxonomic expertise. Apps and websites, such as iNaturalist and eBird, provide a central portal for a broad public to submit wildlife sightings – the identity of which can then be verified by experts (Chandler *et al.*, 2017). An analysis published by the European Commission in 2018 on the use of citizen science for environmental monitoring shows that projects that have high scientific standards and are endorsed by professional scientists tend to serve more phases of the environmental policy cycle. An easy engagement process for volunteer participants (requiring limited efforts and a priori skills) facilitates the project's policy uptake (Bio-Innovation Service, 2018).

The full power of citizen science is 'still to explode', however, according to Bartomeus and Dicks (2019). A large number of local citizen science projects exist in various locations, but for their data to be more useful for monitoring pollinators across a large scale they should be openly accessible and share basic protocols in order for data to be compared between projects, say Chandler *et al.* (2017) and Bartomeus and Dicks (2019). However, this would entail overcoming the challenges of agreeing on the 'best' method and, for many, switching from established methods. These

BOX 13

The European Butterfly Monitoring Scheme (eBMS) provides an international picture

The European Butterfly Monitoring Scheme (eBMS) is a network of 16 butterfly monitoring schemes spanning 14 countries in Europe. It is the only transnationally coordinated monitoring scheme on any group of pollinators.

Its thousands-strong, largely voluntary workforce is expert in butterfly identification and records near-weekly sightings of butterfly species, as observed on transects (i.e. whilst walking along a set path, see Box 7). Recorders submit their data to their local monitoring scheme. Data from all these schemes is pooled together once a year to reveal how the numbers and geographic spread of butterflies vary across Europe and over time.

As with other insects, many butterfly populations are in decline. Monitoring helps reveal the causes of their decline to inform conservation actions. Data from the eBMS show, for example, that grassland-dwelling butterflies fell by 39% in number across Europe between 1990 and 2017 (Van Swaay *et al.*, 2019).

21. https://www.ceh.ac.uk/our-science/projects/pollinator-monitoring
22. http://www.bwars.com/home
23. http://www.hoverfly.org.uk/

The European Butterfly Monitoring Scheme (eBMS) provides an international picture - *continued*

Along with the damaging effects of climate change, a key reason for this decline is changes to grassland management – but the data also help to inspect how this specific driver varies by regions. Agricultural intensification is a major factor in butterfly decline in northern Europe, but a major driver in southern Europe is agricultural abandonment, which has led to forests encroaching onto meadows and other types of traditional, butterfly-friendly farmland habitats.

Data from this grassland butterfly work by the eBMS are used to measure the EU's progress towards meeting the UN's Sustainable Development Goal (SDG) 15: to protect life on land (European Union, 2019).

Furthermore, through the EU ABLE project (an extension of the eBMS), butterfly monitoring is being supported and developed in even more countries – 29 in total – and providing results that support EU biodiversity and land use policies (including the Common Agricultural Policy and the EU Pollinators Initiative, as well as aforementioned efforts to meet UN SDG 15). ABLE is expected to launch a data-logging smartphone app in 2020 to help open up monitoring to new audiences.

Compared with other groups of pollinator species, such as bees and flies, butterflies are relatively easy to monitor; recorders need less specialist expertise to recognise species, and it is unnecessary to kill butterflies for identification when contributing to butterfly monitoring schemes. There are also far fewer species of butterfly than bee or fly.

Sources: www.butterfly-monitoring.net and David Roy, Personal communication (2019).

European Swallowtail, Grazelema, Andalucia, Spain by gailhampshire @ Flickr CC BY 2.0.

developments should take place as part of wider efforts to integrate monitoring efforts (see **Section 4.3**). More and better targeted funding is needed for citizen science to contribute to international biodiversity monitoring, argue Chandler *et al.* (2017); while citizen science monitoring is often more cost-effective than paying professionals to do the same data collection job, it should not be misconstrued as 'free', and investment is needed.

4.3 Coordinated research infrastructure

Alongside gathering more accessible and comprehensive data, it is essential to better integrate the various actors involved in monitoring pollinators.

An interdisciplinary approach is needed to protect pollinators, given the multiple and potentially interacting drivers of their decline (see **Section 3**). Accordingly, there are calls for taxonomists and ecologists to work more collaboratively. This could improve the scientific quality of both disciplines through deeper insight, open up potential funding sources, helping to solve the taxonomic 'crisis' (see **Section 4.2**), and balance ecological research towards species that may be harder to identify but nevertheless ecologically important. In turn, this would increase the quality of nature conservation and management plans, with additional benefits for environmental policymaking (Halme, Kuusela and Juslén, 2015).

Two successful examples of funding instruments in Europe that have brought taxonomists and ecologists together, according to Halme, Kuusela and Juslén (2015), are:

- PUTTE. This government programme in Finland funded studies into deficiently known and threatened forest species between 2009 and 2016, at a cost of €400 000 per year. It increased the number of species evaluated in the latest national Red List[24] by 3000 to 4000. www.environment.fi/PUTTE

- Swedish Taxonomy Initiative. Run by the Swedish Species Information Centre (SSIC) and commissioned by the Swedish Parliament in 2002, this initiative provides grants to taxonomic research and inventories of poorly known groups of species. So far, it has led to the discovery of more than 2000 new species in Sweden. https://www.artdatabanken.se/en/the-swedish-taxonomy-initiative/

Taxonomic and occurrence data on pollinators are held in disconnected pockets by a large number of organisations, notably natural history museums and citizen science groups. Bartomeus and Dicks (2019) thus recommend digitising these data for wider use, and storing them in an accessible common repository. Data could include labelled images of specimens from museums to aid identification (Bartomeus *et al.*, 2019). While open ecological data are becoming more common, they are hard to manage as they are not collected or stored in one single format (.xls, .csv, etc.) or unit (e.g. counts, densities). Bartomeus and Dicks (2019) also recommend, therefore, adopting data repository standards to allow data to be easily integrated and researchers to 'connect the dots and see how patterns emerge'.

24. A Red List is a list of species and their conservation status. It helps decision-makers prioritise conservation measures and provides data towards environmental objectives.

BOX 14.

Citizen science: get involved and help understand your local pollinators

There are a number of opportunities across Europe for members of the public to get involved in understanding and protecting pollinators through citizen science projects. Here are just a handful to consider:

Bumblebee Monitoring Scheme (Ireland)
This network of volunteers across Ireland records over 13 000 bumblebees from over 100 sites each year, in support of the Irish Pollinator Initiative. www.biodiversityireland.ie/record-biodiversity/bumblebee-monitoring-scheme/

European Butterfly Monitoring Scheme (eBMS) (pan-Europe)
Thousands of volunteers across Europe regularly head out and log local butterfly sightings. The results are pooled together to reveal important changes in butterfly populations. For more details, see **Box 13.** www.butterfly-monitoring.net

INSIGNIA (Austria, Belgium, Denmark, France, Greece, Ireland, Italy, Latvia, UK)
An innovative project for beekeepers that helps us understand bees' food choices and their exposure to pesticides. Participants collect pollen from their honeybees for analysis of pesticides and botanical origin. www.insignia-bee.eu

Observatoire Bourdons (France)

Organised by the Natural History Museum of Paris, participants in this project count and identify bumblebees in their garden at least once a month. www.observatoire-asterella.fr/bourdons/index.php

Pollinator Monitoring Scheme (Cyprus and UK)
This project provides a systematic means of monitoring pollinators at a national level. For more details see **Box 12**. www.ris-ky.eu/poms-ky (Cyprus) and www.ceh.ac.uk/our-science/projects/pollinator-monitoring (UK)

Solitary Bee Monitoring Scheme (Ireland)
Volunteers in this scheme support the conservation of solitary bees in Ireland by counting nest holes once a year. https://pollinators.ie/record-pollinators/solitary-bee-monitoring-scheme/

SPIPOLL (France)
This project invites you to become a 'paparazzi of pollinators' by taking a photo of each insect that lands on a plant over a 20-minute period. www.vigienature.fr/fr/spipoll-0

X-Polli:Nation (Italy and UK)
Participants are invited to create a small patch of habitat, plant seeds suitable for pollinators, and then record the pollinators that visit www.opalexplorenature.org/xpollination

4.4 Novel identification and monitoring tools: DNA barcoding and machine learning

4.4.1 DNA barcoding

Information and communication technology (ICT) tools have the potential to contribute to monitoring processes. One technology under current intense discussion is DNA barcoding. With this method, captured specimens (e.g. insects caught in a trap) are identified from a short sequence, or 'barcode', of their DNA, which is matched against records in a central database of genetic information.

DNA barcoding has some benefits over traditional standard identification methods. For example, it needs much less taxonomic expertise and can be completed more quickly. This allows more species to be identified within a study area, thus providing high volumes of data and reducing the reliance on a small number of indicator species to infer the effects of environmental change on overall biodiversity (Ji *et al.*, 2013).

DNA barcoding data are now available for many European bee species and are accessible through the global Bee Barcode of Life Initiative (Bee-BOL)[25]. Similarly, there is a well-populated DNA barcode database for butterfly species, the Lepidoptera Barcode of Life campaign.[26] To date there is no complete database for other pollinator groups.

The more 'traditional' and relatively commonplace form of DNA barcoding involves identifying specimens one at a time. Next-generation technologies may be preferable as they are more time-efficient. The most straightforward and cost-efficient of these newer technologies is 'metabarcoding'. This allows researchers to place a large number of specimens (e.g. collected from a pan trap) into a machine, which then picks out the species present. Whilst being quicker than traditional barcoding methods, metabarcoding is less precise, in that it may only offer approximate identifications, i.e. it often works well to recognise a broad species group, but not necessarily an individual species or sub-group (Ji *et al.*, 2013). Encouragingly, a very recent study was able to achieve 97% correct species identification of UK bees using metabarcoding after complicating factors, such as the effects of cross-contamination, had been stringently filtered out (Creedy *et al.*, 2019).

A more accurate next-generation technology is 'mitochondrial metagenomics', which also performs bulk analysis. As well as identifying species, the technology can identify associated organisms within the ecosystem, such as pollen and pathogens.

Illustration of DNA barcoding.

25. http://www.bee-bol.org
26. http://lepbarcoding.org/

It can also provide a picture of the genetic diversity and ecological networks (food web) within local ecosystems from the mixture of samples (Gill *et al.*, 2016; Derocles *et al.*, 2018).

Well-managed and accessible databases are needed in order to advance DNA barcoding; these must be continually expanded with sequence data for more species. Expert 'traditional' taxonomists are still needed to check that DNA barcoding pairs sequences with the correct species (Joly *et al.*, 2014).

Museums potentially have an important role to play. A collection of butterflies by Maky_Orel, Czech Republic @Pixabay public domain

Museums potentially have another important role to play here, in populating these databases with sequence data from preserved specimens in their collections (Gill *et al.*, 2016). Molecular taxonomy techniques also call for greater collaboration between molecular biologists, taxonomists and ecologists.

Artificial intelligence

Artificial intelligence (AI) could support pollinator monitoring and the essential work of experts. While AI-based technologies for monitoring are still in development and prone to some error, they open up a number of future possibilities. For example, machine learning, whereby computers 'learn' to spot patterns and make predictions from repeated analysis of large datasets, has the potential to detect patterns in pollinator trends from widespread, scattered data collected by different groups of people. This in turn could provide ecology with greater predictive powers – for example, rapidly picking up on early warning signals of decline to enable fast and specific conservation actions (Bartomeus and Dicks, 2019).

Artificial intelligence could also be used for automated species identification. This could enable people without taxonomic expertise to identify species and provide new opportunities for continuous and remote monitoring, i.e. monitoring without attending in person. Machine learning could be used to train computers to recognise species from photographs (Wäldchen and Mäder, 2018), their sound – such as a bumblebee's buzz (Gradišek *et al.*, 2017) – or their foraging pattern (Arruda *et al.*, 2018).

Machine learning could also be used to reconstruct ecological networks, potentially based upon DNA samples of animals and plants found in the environment. This could show which species are interacting with each other, or 'who eats whom', revealing changes in ecosystems quickly and cost-effectively (Bohan *et al.*, 2011; 2017)

Concluding remarks: summary and knowledge gaps

Two tortoiseshell butterflies on a flowering linden (lime) tree, Ukraine, by Iryna Chubarova @Getty/IStock.

This brief provides a breadth of evidence that demonstrates the value of pollinators to crop yield and quality, human health, wild plants and other animals. In short, research shows that pollinators play an essential role in underpinning food security and nature as a whole.

Furthermore, by supporting agriculture, human health and the provision of ecosystem services, pollinators are of major economic importance. Their cultural value is also significant; many pollinating species hold special social, artistic and spiritual meaning for societies around the world.

The impetus to support pollinators is very clear. It is not just a matter of boosting pollinator numbers, however. We also need to support pollinator diversity, for research shows that a wide variety of species leads to better, more sustainable pollination of crops and provides a stronger support system for nature.

It is of huge concern that wild pollinator numbers and diversity are threatened, in Europe and around the world, and are declining in many cases. Declines stand to have cascading and damaging effects across nature, which, in turn, compromise pollinators' supply of ecosystem services, including the pollination of agricultural crops.

This brief presents evidence on many of the reasons behind these declines. The reasons are complex and interacting, with many inherent uncertainties. However, land-use change, intensive agricultural management and pesticide use, environmental pollution, invasive alien species, pathogens and climate change are identified as the main drivers of decline. The breadth of these drivers indicates how all sectors of society, including government, land managers, the private sector and the wider public, have a role to play in ensuring the survival of pollinators.

To manage and conserve pollinators, we need to know exactly what is being lost, where, and why, as well as which remedies are likely to be most effective. Much valuable research has been conducted, or is underway, to help us answer these questions. For more comprehensive answers – and thus more effective solutions to pollinator conservation – increased research efforts are needed to overcome some major gaps in our understanding of pollinators and pollination.

This report highlights specific areas of research where increased investment and capacity, and improved infrastructure, would be particularly beneficial to pollinator conservation. Monitoring pollinators and their activities (e.g. which plants do they visit?) is key to filling many knowledge gaps. There is a notable need for increased monitoring in regions outside northern Europe and North America, as well as of non-bee species, for example.

To maximise the quality and value of monitoring, further investment in personnel and expertise is required. This report calls attention to the field of taxonomy as in particular need of support. Enhanced expert capacity of taxonomy, through increased job opportunities and training, for example, would further increase the value of monitoring schemes. In addition, boosting the capacity of citizen science would allow for more cost-efficient, large-scale monitoring, while also helping raise awareness of pollinators among society in general.

Development of technological, as well as human, resources also benefits monitoring. Technologies featured in this report are DNA barcoding and artificial intelligence (AI). These could allow for monitoring programmes to cover more species, at larger spatial scales and, in the case of AI, on a more continuous timescale.

A key theme in this report is interdisciplinary, integrated working. New and strengthened networks of actors will further enhance the quality of pollinator research and its value for policy and conservation. We need to find ways of bringing together and coordinating the work of different fields of research, such as ecology, taxonomy and molecular biology, to improve the quality of pollinator research and species identification powers.

We also need to bring different organisations together. For instance, museums – and the information they hold – are featured several times in this report as valuable to pollinator research, as are citizen science groups. Greater and coordinated collaboration of these organisations with academia, research organisations, NGOs, businesses and policymakers would help form an unprecedented knowledge base and provide the broad range of perspectives needed to solve challenges in pollinator protection.

Combining our understanding of drivers of pollinator population change with data on abundance and diversity is also key. For instance, understanding the impacts of different land management practices on different species and in different locations can help us identify the best conservation actions at a local level – because not all pollinators are the same. More knowledge is also needed to assess and improve the resilience of pollinators to future environmental change, notably in the face of climate change's increasing threats to biodiversity.

A consultation workshop on the EU Pollinators Initiative held in 2018[27] produced an extensive list of specific actions for the EU, its Member States and relevant stakeholders to consider, which could help fill the data gaps highlighted in this report. On 20 May 2020, the European Commission launched the EU Pollinator Information Hive,[28] a web platform which will serve as a central repository of information on actions for wild pollinator conservation across the EU. It is through a strengthened evidence base that we can ensure pollinators continue to deliver their indispensable benefits for society and the environment, well into the future.

27. https://ec.europa.eu/environment/nature/conservation/species/pollinators/documents/consultation_workshop_report.pdf
28. https://wikis.ec.europa.eu/display/EUPKH/EU+Pollinator+Information+Hive

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How to value and account for ecosystems
This video introduces the key debates on valuing ecosystem services such as pollination, and how natural capital accounting could lead to better and more balanced global and local decisions. https://ec.europa.eu/environment/integration/research/newsalert/multimedia/ecosystem_valuation_and_accounting_en.htm

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