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# The pollination services of forests

## A review of forest and landscape interventions to enhance their cross-sectoral benefits

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# The pollination services of forests

## A REVIEW OF FOREST AND LANDSCAPE INTERVENTIONS TO ENHANCE THEIR CROSS-SECTORAL BENEFITS

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**Cover photo:** Male *Xylocopa frontalis* pollinating a *Moringa oleifera* tree, Peru.
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## CASE STUDIES

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# Acronyms

| | |
|---|---|
| CWD | coarse woody debris |
| FAO | Food and Agriculture Organization of the United Nations |
| NWFP | non-wood forest product |
| USD | United States dollar(s) |

# Executive summary

Pollination is the process of transferring pollen from a male part of a flower (anther) to the female part (stigma) to enable fertilization and the production of seeds. Most flowering plants, including wild species and many food crops, are pollinated by animals, which are vital, therefore, for biological production and the maintenance of biodiversity. Pollinators benefit from diverse natural habitats for forage and nesting, especially when these are limited in plant production systems. Landscape and forest management practices can help ensure the continued availability of pollinators and thereby increase resilience and the productivity of forestry and agriculture.

This working paper, which is aimed at forest practitioners, landscape planners and land-use decision-makers, reviews published literature on the impacts of forest and landscape management practices on pollinators. It also addresses the implications of climate change, collates 36 case studies, and makes recommendation on measures for maintaining pollinator diversity and abundance in forests and landscapes.

**Pollinators in fragmented forest landscapes**

A decline in pollinators due to habitat degradation and climate change is likely to have major consequences for natural forest regeneration, for example by reducing the genetic diversity of forest trees and therefore their resilience and adaptive potential.

Land-use change and land management practices can fragment and degrade pollinator habitats and affect the connectivity of pollinator communities, which could, in turn, affect pollinator breeding success and thus population size. Meta-analyses of plant species have found a negative effect of fragmentation on pollination and plant reproduction. Connectivity among fragmented habitats promotes the movement of pollinators between patches and may help reduce the impacts of fragmentation.

Many wild pollinators depend heavily on forests for nesting and forage, and the extent of forests and other natural habitats in a landscape plays a role in determining the species composition of pollinators. Agricultural lands adjoining forests or natural areas benefit from pollinator services, and animal-pollinated crops therefore achieve higher fruit set. The proportion of wild habitat required to provide such additional pollination services for crop plants may differ by crop type and other landscape variables. Invasions by alien plants not only alter the diversity of pollinator species available for native plants but could also affect plant–pollinator networks.

Habitat heterogeneity is a significant driver of pollinator abundance and diversity. Consequently, the composition of a landscape is likely to have significant implications for the floral and nesting resources of pollinators and therefore their presence and abundance.

Urban habitats are known to harbour a high diversity of pollinators. Urban gardens, forest patches and semi-natural green spaces in the rural–urban interface can be particularly important in providing pollination services in rural and peri-urban areas.

There is evidence of pollen limitation in several plant species due to recent climatic changes. Given the crucial ecological role of pollination services in landscape resilience, food security and livelihoods and the likely increasing impacts of climate change on such services, understanding the ways in which forest management practices can benefit pollinator communities is imperative.

### Pollinators and forest management

Forest management practices can have significant effects on pollinator abundance and diversity. The harvesting of trees affects forest variables such as structure, species composition, soil dynamics, hydrology and light availability, all of which can affect pollinator species composition and diversity and plant–pollinator networks.

Intensive grazing by livestock reduces pollinator diversity compared with traditional systems. Mowing can affect plant species composition, which might influence pollinator diversity and abundance. Studies have shown that heterogeneous mowing times in grasslands can enable staggered flowering and thus increase the duration of available resources for pollinators. The mowing of semi-natural habitats, however, can have negative impacts on pollinator populations, especially when they are in the egg and larval stages.

Fire is a natural and important disturbance in many forest ecosystems. It may have immediate adverse effects on pollinators, but subsequent regeneration and changes in land use will determine future pollinator species composition, abundance and diversity. Mosaics of burned and unburned habitat recover faster than large tracts of burned habitats.

Indigenous and local knowledge can contribute to the conservation of pollinators through traditional management practices that encourage the sustainable production of honey and other forest products and which have been adapted over time in light of ecological change. Such intrinsic knowledge on the behaviour, biology and ecology of pollinators can increase understanding of management practices that encourage pollinator diversity and abundance. The maintenance of pollination services is crucial for the long-term productivity of many non-wood forest products that are important for local livelihoods and for local to national economies.

### Measures for land and forest managers

This, review, especially the case studies, gives rise to a range of measures that forest and land managers could take to help safeguard pollinators in forests and landscapes (see Chapter 4 for a full list of indicative measures).

At the **landscape scale**, such measures address, among other things, landscape-scale planning to maintain key landscape components on which pollinators depend; ensuring habitat connectivity, including through agroforestry, creating biological corridors or stepping stones, and retaining native vegetation; enhancing the density of floral resources; maintaining or increasing landscape heterogeneity and patchiness to increase the diversity and connectivity of floral and pollinator-nesting resources; maintaining large riverine buffers; and undertaking long-term studies to understand the impacts of natural disturbances on pollinator communities over time.

At the **forest management scale**, the measures may include establishing baselines of pollinator diversity and abundance and monitoring these over time; where fire is used as a management tool, maintaining a mosaic of burned and unburned pollinator habitat; developing field guides for pollinator management based on knowledge of the biological attributes of pollinator species in an area and flowering phenology and synchrony; drawing on and learning from indigenous and local knowledge about pollinators and phenologies; employing forest management practices such as selective logging, thinning, prescribed burning, mowing and coppicing in ways that increase the heterogeneity of tree communities; in forest management planning, allowing temporal (as well as spatial) habitat heterogeneity; retaining dead standing and lying wood in forests and ensuring sufficient bare ground for cavity-nesting and ground-nesting bees; regulating the grazing of domestic and wild ungulates in forests to minimize competition for floral resources between those ungulates and wild pollinators; and, in restoring degraded forests, establishing tree species at densities sufficient to enable their effective pollination.

### Knowledge gaps

There has been little systematic research on the role of forest management practices in maintaining wild pollinators. An important knowledge gap exists on relationships between pollen limitation and forest plant recruitment (i.e. the addition of new individuals to populations) as a result of reduced seed set. There are also large gaps in understanding on metapopulation dynamics, functional diversity and pollination networks of pollinators at the landscape scale across diverse management regimes. Few long-term studies exist that could provide data for projecting the impacts of climate change on forest pollinators. Inventories and quantitative data are lacking on pollinator-dependent forest species that produce wood and non-wood products and on the economic value of pollination services related to these. Indigenous and local knowledge is still undervalued and underused in scientific research.

### Priority areas for action

The impacts of forest management on pollinators should be addressed multisectorally, with the involvement of farmers, pastoralists, indigenous peoples, local communities, forest managers, beekeepers and other land custodians and stakeholders. Policy instruments are needed that encourage practices in the forest and agriculture sectors to help maintain and increase pollinator services, especially given the potential impacts of climate change. These may include mechanisms to facilitate exchanges of knowledge among stakeholders in the forest and agriculture sectors and to help determine trade-offs between interests and ecosystem services; payments for pollination services and other economic incentives to support pollinator-friendly landscape management; and comprehensive guidelines for ensuring the maintenance of pollination services in forests and landscapes.

## Moving forward

Farmers, pastoralists, commercial beekeepers and forest managers are all important actors in the management of forest-based pollination services. Each requires tailored communication tools to raise awareness of the importance of landscape diversity for pollination services and to reduce negative impacts and enhance conditions that benefit pollinators. A review of existing national-level policy instruments would be useful, as would consolidating the evidence base for best practices. Several ongoing initiatives, such as the International Pollinator Initiative 2.0, as adopted by the Conference of the Parties to the Convention on Biological Diversity in November 2018, offer potential opportunities for further addressing the role of landscape and forest management in pollination services.

# 1. Introduction

Pollination[1] is the process of transferring pollen from the male part of a flower (the anther) to the female part of the same or another flower (the stigma) to enable fertilization and the production of seeds. An estimated 87.5 percent (94 percent in the tropics and 78 percent in the temperate zones) of wild flowering plants globally are animal-pollinated (Ollerton, Winfree and Tarrant, 2011), and more than 70 percent of global food crops benefit from animal pollination (with dependence for fruit set or seed set ranging from 1 percent to 100 percent) (Klein *et al.*, 2007).

Scientists globally have been raising concerns about declines in pollinator populations for more than three decades (Buchmann and Nabhan, 1996; Kearns, Inouye and Waser, 1998 ; IPBES, 2016b), although most evidence for the loss of wild pollinators is available for North America (National Research Council, 2007; Koh *et al.*, 2016) and Europe (Potts, Biesmeijer, *et al.*, 2010). Declines in honeybee populations have been recorded in North America (Currie, Pernal and Guzmán-Novoa, 2010; Ellis, Evans and Pettis, 2010); parts of South America (Maggi *et al.*, 2016); Europe (Potts, Roberts, *et al.*, 2010); Japan and the Middle East (Neumann and Carreck, 2010); and parts of Asia (Theisen-Jones and Bienefeld, 2016).

Wild pollinators – insects, birds and mammals – provide important pollination services, not only for cultivated plants (often complementing managed pollinators) but also for wild plants, and they are imperative for the conservation of biodiversity and the maintenance of associated ecosystem services. The pollination services of wild animals can be crucial for increasing the genetic diversity of plant offspring and reducing the potential for inbreeding depression in outcrossing plant species (Kearns, Inouye and Waser, 1998). Improvements in seed quality and quantity, and the enhanced performance of offspring, have been observed when self-compatible species are cross-pollinated, with cross-pollination increasing genetic variability in progeny and thus the ability of species to adapt to environmental changes and pathogens (Jump and Peñuelas, 2005; Morran, Parmenter and Phillips, 2009).

Among pollinators, bees (of which there are 20 000 species, mostly pollinators) are the most frequent flower visitors, followed by flies, butterflies and moths (Winfree *et al.*, 2007). Although social bees are relatively well researched, there are far fewer studies on solitary bees and other pollinators. A main drawback is a lack of long-term data on pollinator populations, although several key pollinators, including certain insects, birds, arboreal mammals and bats, are known to be affected by habitat loss, forest management and land-use change (Winfree, Bartomeus and Cariveau, 2011; Regan *et al.*, 2015; Korine *et al.*, 2016; Volpe *et al.*, 2016). Additionally, information on the

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[1] Terms in orange are defined in the glossary on page 51.

status, diversity and ecology of pollinators (including plant–pollinator interactions) is lacking in many regions (Winfree *et al.*, 2007; CBD, 2018). Such primary information is imperative for developing effective measures aimed at sustaining pollination services in forest landscapes.

The majority of wild plants are pollinator-dependent for fruit and seed set (Ollerton, Winfree and Tarrant, 2011). Pollen limitation in plants has been reported in many species (62 percent of 285 species and 73 percent of 82 case studies), and changes in pollinator abundance and diversity are expected to affect seed production (Burd, 1994; Ashman *et al.*, 2004); few studies, however, have investigated trends in plant reproduction over time. Fruit set has been shown to be correlated with pollinator diversity (Albrecht *et al.*, 2012). Globally, 16.5 percent (192 species) of known vertebrate pollinators are threatened with extinction, and the plants pollinated by them (a total of 16 800 plants are known to be vertebrate-pollinated), therefore, face population declines (Aslan *et al.*, 2013). There has been a shift in community composition from plants that are pollinator-dependent towards plants that can reproduce vegetatively – for example in Cape Town, South Africa, over a span of 180 years (IPBES, 2016b; Pauw and Hawkins, 2011) – and from outcrossing plants to self-fertilized and wind-pollinated plant species, for example in the Netherlands and the United Kingdom of Great Britain and Northern Ireland (Biesmeijer *et al.*, 2006). Vegetative propagation can lead to the reproduction of genetically identical individuals, which are more prone to pathogens (for example, this has been shown in the case of *Agave* cultivation; López-Hoffman *et al.*, 2010).

### This report

Despite evidence suggesting declines in pollinators in many parts of the world (FAO, 2019a), with consequent direct and indirect negative effects on biodiversity conservation and food security, few attempts have been made to investigate the role of forest management practices in maintaining wild pollinators.

This report reviews and synthesizes existing knowledge of the impacts of forest management practices, landscape-scale changes and climate change on the provision of pollination services and makes recommendations for ensuring the maintenance of such services and thereby their contributions to food security, sustainable livelihoods and sustainable forest management. The report also identifies knowledge gaps in this field of study and priority areas for future research, drawing on the literature and the inputs of a wide range of experts to ensure broad coverage of disciplines, expertise and geographies.

In conducting the review, relevant studies were located using Google Scholar and the ISI Web of Science for the period 1999–2019. Use of the search terms "forest management" AND "pollination services" identified 1 125 publications in Google Scholar and 425 publications in the ISI Web of Science. The focus was on peer-reviewed publications, book chapters, dissertations, theses and reports published in English, but searches were also conducted in French and Spanish. The review concentrated on studies that addressed the impacts of forest management practices on pollinators, with a preference for those on which the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem

Services (IPBES, 2016b) based its pollination assessment. Case studies were selected from the reviewed literature on the basis of their clarity, with a view to including a diverse range of pollinator taxa and geographies.

A questionnaire was distributed to 25 global experts, research scientists, non-governmental organizations and forest managers to obtain perspectives on current knowledge and gaps in knowledge relevant to the impacts of forest management on pollination services. A workshop involving about 40 expert participants was convened, and additional interviews were conducted, to explore existing expert knowledge, identify knowledge gaps, and propose ways forward.

This report has four chapters. Chapter 2 presents a discussion, drawn from the literature, of the landscape-scale roles of forests in the provision of pollination services and the impacts of forest fragmentation and other landscape changes on such services; it also addresses the implications of climate change. The chapter features 12 case studies on landscape-scale factors in forest pollination and provides key findings.

Chapter 3 discusses the role of pollination services in forests and reviews the impacts of forest management practices on these; it also examines interactions between pollinators and the management and harvesting of non-wood forest products (NWFPs). The chapter includes 24 case studies and draws key findings.

Chapter 4 explores knowledge gaps and priority areas for follow-up research; provides a set of initial measures that forest and landscape managers should consider taking to help safeguard pollinators in forests and landscapes; and outlines some of the initiatives underway to help in moving forward. A glossary defines some of the key terms used in this report.

# 2. Pollinators in fragmented forest landscapes

The loss and fragmentation of natural habitats due to urbanization, land-use change, climate change and agricultural intensification have major implications for biodiversity (Tilman *et al.*, 2001; Foley *et al.*, 2005; Tscharntke *et al.*, 2005; Elmqvist, Zipperer and Güneralp, 2016), including pollinators (Girão *et al.*, 2007; Marini *et al.*, 2014; Senapathi *et al.*, 2015). The land area under cropland is increasing (e.g. from 10.3 percent of the land area in 1961 to 12.0 percent in 2017; FAO, 2019a), often at the expense of natural habitats. The loss of nesting and forage for pollinators is concerning (Aizen *et al.*, 2009): for example, it could reduce pollinator diversity and abundance (Ollerton *et al.*, 2014; Senapathi *et al.*, 2015), with studies showing a decrease in the diversity and abundance of pollinator groups and changes in species composition due to habitat conversion (Potts, Roberts, *et al.*, 2010; Bommarco *et al.*, 2014).

Land-use change and land management practices can fragment and degrade pollinator habitats and affect the connectivity of pollinator communities, which could, in turn, affect pollinator breeding success and thus population size. Smaller populations lead to lower

**A landscape mosaic comprising forests, human settlements and agricultural fields in the Western Ghats biodiversity hotspot, India**

genetic diversity, decreasing the general fitness of populations and their capacity to adapt to stochastic events, including those associated with climate change. Additionally, low genetic diversity could lead to inbreeding depression (Hartl and Clark, 2006), making populations more vulnerable to local extinction. Meta-analyses of plant species have found a negative effect of fragmentation on pollination and plant reproduction (Aguilar *et al.*, 2006), with indications that fragmentation leads to pollen limitation, particularly in self-incompatible plants (Vranckx *et al.*, 2012); Aguilar *et al.* (2019) found that the progeny vigour of outcrossing plant species experienced stronger negative effects (compared with mixed-mating species) of habitat fragmentation due to restricted pollen dispersal, except for vertebrate-pollinated species, which presumably could move more freely across landscapes. Thus, a decline in pollination and thereby fruit and seed set is likely with a decline in pollinator habitats (Aguilar *et al.*, 2006), which would reduce regeneration. Additionally, fragmentation has a negative impact on the diversity of pollen received (Breed *et al.*, 2015), thereby affecting the genetic diversity of the plant species (Aguilar *et al.*, 2008).

Pollinators are mobile, and they often use certain habitat patches while residing in another. It is difficult to isolate the impacts of management in one land use from those associated with adjoining land uses. With an increase in human-modified landscapes, studies on the responses of pollinators to land-use change and their implications for pollination services for crops and wild plants are imperative (Winfree, Bartomeus and Cariveau, 2011). Such studies should include nesting habitats as well as their interactions with foraging habitats. The importance of forage in agricultural landscapes for the survival of wild pollinator populations is not well understood, and nor are the effects of agrochemical use on wild pollinators in agriculture, specifically regarding toxicity, the extent of exposure, interactions with other variables, and the risks for pollinators posed by genetically modified crops (IPBES, 2016b).

Plant reproductive success depends on pollination, flowering, fruiting and seed dispersal, as well as germination and seedling establishment. Plant mating systems (e.g. outcrossing and self-fertilization) strongly affect pollen dispersal and pollen-mediated gene flow and are in turn affected by factors such as population density, floral synchrony and post-pollination mechanisms. The survival and viability of seedlings may depend on pollen flow, and disruptions could affect species survival (White, Boshier and Powell, 2002; Mariot *et al.*, 2014; Ratnam *et al.*, 2014; da Silva *et al.*, 2018; Ebrahimi *et al.*, 2018).

## 2.1 VARIED RESPONSES TO LAND-USE CHANGE AND FRAGMENTATION

Habitat loss and fragmentation have negative effects on pollinator diversity, abundance and richness (Kearns, Inouye and Waser, 1998), although some land-use changes may have positive effects on certain pollinators (Hadley and Betts, 2012).

The impacts of land-use change and fragmentation are contingent on the quality of the intervening land matrix (Williams and Jackson, 2007). The response of pollinators is also likely to be species- or taxa-specific (Brosi *et al.*, 2008; Krishnan, 2011; Medeiros, 2019), with generalists advantaged over specialists (Winfree, Bartomeus and Cariveau, 2011). Above-ground nesters are more vulnerable than below-ground nesters to the loss of natural and semi-natural habitats (Williams *et al.*, 2010). Studies have shown that moderate amounts of disturbance that increase the quality and availability of habitat can have a positive effect on pollinator diversity (IPBES, 2016b); for example, negative impacts on bees are evident only in situations of extreme fragmentation (Winfree *et al.*, 2009). Flies are more resilient to habitat change and loss (Winfree, Bartomeus and Cariveau, 2011), with certain species increasing in number with land-use change (although some decrease). Community composition is more sensitive to land-use change than abundance and pollinator richness (Winfree, Bartomeus and Cariveau, 2011) and thus might be a better measure for understanding the impacts of land-use change.

Many wild pollinators depend heavily on forests as primary nesting habitats and forage sites, and the extent of forests and other natural habitats in a landscape plays a role in determining the species composition of pollinators. An increase in tree cover (i.e. mixed-tree agroforestry instead of monocrops of rice paddy fields) maintained 93 percent of the crop pollinators found in natural forest in West Java, Indonesia (Barrios *et al.* 2018). A decrease in habitat size is likely to reduce the availability and diversity of forage resources, with negative impacts on specialists and possibly benefits for generalists (Burkle and Knight, 2012; Marini *et al.*, 2014). Plant–pollinator networks are more likely to be robust and resilient in larger interconnected patches (IPBES, 2016b) due to higher ecological redundancy (Moreira, Boscolo and Viana, 2015).

A meta-analysis by Winfree, Bartomeus and Cariveau (2011) found that the responses of insect pollinators to fragmentation and habitat loss were more often negative than positive. Bees were found to be most negatively affected by these pressures, followed by butterflies and hoverflies; conversely, there was a positive effect on vertebrates such as birds and bats (Table 1), possibly due to the ability of some vertebrate pollinators that are habitat generalists to travel relatively large distances between habitat patches or use the intervening matrix (Winfree, Bartomeus and Cariveau, 2011). Other studies indicate that larger species are less sensitive to changes in habitat area (Marini *et al.*, 2014), thus supporting this view (Greenleaf *et al.*, 2007; Garibaldi *et al.*, 2011). This may not always be the case, however, because some large vertebrate species (e.g. insectivorous bats) may not move easily across fragmented landscapes (Juliani Shafie *et al.*, 2011).

Although ecotones between two habitats often support high pollinator diversity, such diversity mainly comprises common species (IPBES, 2016b). Agricultural landscapes adjoining fragmented forests and natural areas benefit from pollinator services (spillover effect) and thus animal-pollinated crops achieve higher fruit set (Krishnan *et al.*, 2012; Cunningham *et al.*, 2013). The proportion of wild habitat required and the distance within which it should be present to provide such additional pollination services for crop plants vary by crop type and other landscape variables (Westphal, Steffan-Dewenter and Tscharntke, 2003; Morandin and Winston, 2006; Winfree *et al.*, 2009). Among farming systems, agroforestry can be relatively biodiverse and can act as a link between natural and semi-natural areas (Perfecto and Vandermeer, 2008). Bentrup *et al.* (2019) synthesized the following benefits of trees and shrubs for insect pollinators and pollination services

**Table 1. Directionality of pollinator response with increasing human land-use change**

| Group | Directionality of pollinator response (% studies) to increasing human land-use change | | |
|---|---|---|---|
| | Negative | Neutral | Positive |
| Bees | 40 | 47 | 13 |
| Butterflies | 39 | 39 | 22 |
| Flies (Syrphids) | 40 | 30 | 30 |
| Birds | 32 | 27 | 41 |
| Bats | 22 | 29 | 49 |

*Note*: Human land-use change involves the conversion of natural ecosystems to agriculture, urban or other land uses.

*Source*: Modified from Winfree, Bartomeus and Cariveau (2011).

in temperate agroforestry: providing forage, nesting and egg-laying habitats; enhancing site and landscape connectivity; and mitigating pesticide exposure (e.g. by providing no-spray zones and reducing spray drift and runoff, although accumulations may occur close to treated fields).

Connectivity among fragmented habitats promotes the movement of pollinators between patches. Even small, early-successional forests in a fragmented landscape can harbour pollinators and be of conservation value (Taki *et al.*, 2018). Island-dwelling species are at high risk, with about 30 percent of island-based pollinators under threat (Aslan *et al.*, 2013).

Habitat heterogeneity is a significant driver of pollinator abundance and diversity. Consequently, the composition of a landscape (i.e. the type and frequency of different land uses) is likely to have significant implications for the floral and nesting resources of pollinators and therefore their presence and abundance.

## 2.2 BENEFITS OF FOREST POLLINATION SERVICES FOR SURROUNDING FOREST FARMS

Animal pollination enhances fruit set in about 70 percent of tropical crops (Roubik, 1995), 85 percent of European crops (Williams, 1994) and 70 percent of the world's leading crops (Klein *et al.*, 2007). Many important cash crops are fully or partially pollinator-dependent for fruit set. Animal pollinators increase total production by an estimated 8–10 percent (by weight) (Aizen *et al.*, 2009). A decline in pollinator diversity and abundance negatively affects fruit set in a number of crops, and the yields of pollinator-dependent crops are less stable than those of pollinator-independent crops.

Indications of declines in wild pollinators have been noted in Europe (Potts, Biesmeijer, *et al.*, 2010) and America (National Research Council, 2007; Koh *et al.*, 2016), with associated declines in wild plant pollination and seed set and in the diversity of pollinator-dependent wild plant species (Biesmeijer *et al.*, 2006). Large declines (associated with habitat loss) were observed in clover fields in Scandinavia between 1930 and 2009 in the abundance and species richness of long-tongued late-emerging bumblebees. Cameron

**Apis dorsata (Asian wild social bee) visits coffee flowers in India**

*et al.* (2011) reported a 96 percent decline in populations of four bumblebee species in the previous 20 years in North America. Sinu and Shivanna (2007) reported a decline in the yield of large cardamom in India due to low visits by bumblebees, leading to reduced fruit set.

Despite indications of declines in pollinators worldwide, however, the yields of some commonly cultivated pollinator-dependent crops doubled between 1961 and 2006 (Aizen *et al.*, 2008; IPBES, 2016b).

Pollinator diversity and abundance are often higher in farmlands that adjoin areas with forage and nesting sites for pollinators (IPBES, 2016a). Forests harbour wild bees that provide wild and crop plants with important pollination services, and pollination services for crop plants decline with increasing distance from natural and semi-natural habitats (Ricketts *et al.*, 2008), with reduced fruit set (Garibaldi *et al.*, 2011). The role of forested and semi-natural habitats in crop pollination services has been demonstrated in a number of agroecosystems (Kremen *et al.*, 2004; Greenleaf and Kremen, 2006; Klein, 2009; Carvalheiro *et al.*, 2010; Bailey *et al.*, 2014). Wild bees, butterflies, hoverflies, wasps, non-*Apis* bees and other pollinators provide crop plants with important pollination services, and the contributions of such wild pollinators to crop production cannot be substituted by managed bees (Garibaldi *et al.*, 2011). A number of studies have demonstrated the importance of wild pollinators in increasing crop fruit set (IPBES, 2016a).

## 2.3 IMPACTS OF URBANIZATION

Urban populations are growing rapidly globally. Although it has been reported that urbanization has led to declines in pollinators (Gómez-Baggethun *et al.*, 2013) (especially specialist species – see Potts, Biesmeijer *et al.*, 2010), urban habitats are also known to harbour a high diversity of pollinators (especially generalist species), at times at even higher diversities than elsewhere (Sirohi *et al.*, 2015). Urban gardens, forest patches and semi-natural green spaces in the rural–urban interface can be particularly important (Pereira-Peixoto *et al.*, 2014) in providing pollination services in rural and peri-urban areas.

Studies have shown that urbanization can have both positive and negative impacts on pollinators (IPBES, 2016b). Parks and semi-natural areas in urban areas are usually managed in ways that provide a diversity of floral resources throughout most of the year. Moreover, there is likely to be less pesticide use – one of the main reported causes of pollinator decline in agricultural areas (Hall *et al.*, 2017) – in urban landscapes (although the home-based and horticultural use of pesticides may be widespread in some urban areas). The quality of urban habitat, the surrounding landscape composition, habitat connectivity (Braaker *et al.*, 2014) and the "hostility" of the matrix between pollinator habitats are all likely to play important roles in determining the status of pollinator communities (Antonini *et al.*, 2013). Bee species richness is positively correlated with landscape heterogeneity (Sattler *et al.*, 2010), suggesting that urban forest management can play an important role in sustaining pollinator communities in peri-urban environments – synergistically with other benefits of urban forestry, such as urban cooling, biodiversity conservation and sustainable food systems.

## 2.4 GENETIC ENGINEERING

The genetic engineering of plants to remove or modify reproductive structures (e.g. to achieve fruit set without pollination) may become more common as a means to increase production (at least in the short term), but there is a lack of scientific study on the impacts of genetically engineered plant reproductive modification on pollinators. It could create ecological traps for pollinators that make habitat selections in forests based on structural cues and not resource availability, especially where such cues were previously reliable but have become maladaptive due to anthropogenic interventions. There is concern over the transfer of transgenic pollen from genetically engineered to wild trees (Strauss *et al.*, 2017).

## 2.5 NATURAL INSECTICIDES

Basu *et al.* (2016) considered that an increase in the use of insecticides in agricultural landscapes is responsible for declining numbers of bee communities, finding that areas with low pesticide use and more semi-natural habitats had higher bee diversities. Alternatives to pesticides that minimize negative impacts on pollinators are needed, therefore; several studies have explored the use of natural insecticides and their impacts on bees (Elzen, Elzen and Lester, 2004; Xavier *et al.*, 2010; Aliakbarpour, Salmah and

Dzolkhifli, 2011; Pestana, 2011; Patnaik *et al.*, 2012; Al-Alawi, 2014; Naik and Hugar, 2015), although there is a lack of studies on the impacts of pesticide use in forestry, on pollinators.

## 2.6 INVASIVE AND ALIEN SPECIES

Invasive plants are often insect-pollinated, with the ability to self-pollinate in the absence of insect visitors (Pyšek *et al.*, 2012). Invasive species can compete with native species for pollinators, thus affecting the reproduction of native plant species (Morales and Traveset, 2009). In a meta-analysis of 143 studies, Montero-Castaño and Vilà (2012) showed that habitat modification and invasive species had similar effects on pollinators. Pollinators adapted to plants at risk of replacement by invasive non-native plants might be severely affected if they are specialists and cannot adapt to the new species composition of the invaded habitat (Stout and Morales, 2009). Invasions by alien plants alter the diversity of pollinator species available for native plants (Traveset and Richardson, 2014) and could also alter plant–pollinator networks (Giannini, Garibaldi *et al.*, 2015). Invasive plants have been shown to both compete with and facilitate the pollination of native plants (Bartomeus, Vilà and Santamaría, 2008).

The introduction of alien bee species to perform crop pollination services can lead to competition with natives for forage and nesting resources and may eventually replace native crop pollinators (Laport and Minckley, 2012). Badano and Vergara (2011) found that the honey bee (*Apis mellifera*) can reduce native pollinator diversity and that, in shade coffee plantations in Mexico, an increased abundance of *Apis mellifera* was correlated with a decrease in fruit production. Cairns *et al.* (2005) observed aggressive competitive behaviour involving physical attacks by *A. mellifera* on stingless bees in highly human-disturbed environments in Mexico and with increasing *A. mellifera* population size. Studies have shown that pathogens carried by introduced bee species can infect native bees not adapted or equipped to handle new diseases, thus decimating native bee populations (Goulson, 2003). Introduced invasive alien predators and herbivores can alter pollinator networks, predate on pollinators and affect visitation to plants. Few studies exist, however, on the effects of invasive plant species on the pollination of crops and co-flowering native species. Forest managers should consider the potential impacts on local pollinator species of the introduction or expansion of non-native species.

## 2.7 INCREASING DEMAND FOR AND COST OF POLLINATION

There has been an increase in demand for pollinator-dependent crops (such as almonds, avocados and mangos) worldwide due to their higher nutritional value (Eilers *et al.*, 2011; Brittain *et al.*, 2014; Chaplin-Kramer *et al.*, 2014; Ellis, Myers and Ricketts, 2015), leading to a substantial increase (>300 percent) in area and production (Aizen and Harder, 2009). The increase in the rate of dependency on pollinator-dependent crops has been much higher in developing countries. The resilience of pollinator-dependent food systems depends on stable pollinator communities.

Many farmers (e.g. almond growers in the United States of America) now rent honeybee colonies to ensure the availability of pollination services (IPBES, 2016a). In regions where this is not an option, some farmers have resorted to hand pollination to facilitate fruit set (e.g. for apples in China) (Partap and Ya, 2012). Moreover, plant breeding programmes to develop crops that are pollinator-independent have been promoted worldwide, with successful examples including tomato (*Solanum lycopersicum*) (Peralta and Spooner, 2007) and almond (*Prunus amygdalus*) (Kodad and Socias i Company, 2008); this approach is not viable for many crops, however. An electrical apparatus has been used to pollinate date palms (IPBES, 2016a). Ultimately, the costs and benefits of developing and using alternatives to animal pollination should be weighed against the costs and benefits of encouraging natural pollination, including through the retention of forests and other natural habitats in the vicinity of agricultural areas and by modifying land management (including forest management) practices.

Arguments about biodiversity conservation, ecosystem resilience and food security might not always be sufficient to ensure that actions are taken to improve pollination services. Evaluations of the economic benefits of wild pollination, the economic consequences of its decline and the cost of pollination management could help. Nevertheless, in their review, Breeze *et al.* (2016) found that the estimated benefits of studies were difficult to exploit and more integrated work was needed. Such benefits are highly heterogeneous (due to differing methods or neglected factors); biased towards the developed world, whereas costs differ according to country; and rarely well suited to decision-making.

## 2.8 CLIMATE CHANGE

The initiation of many plant phenological events, such as leaf-unfolding, flowering and fruit maturation (Cleland *et al.*, 2007), relies on climatic cues such as temperature and rainfall. Changes in climate, therefore, may alter the time, quality and duration of phenological events, and it is likely that phenological mismatches in plants and pollinators will increase in the future due to human-induced climate change (Thomson, 2010; McKinney *et al.*, 2012). Asynchrony in plant–pollinator interactions could be disastrous, especially for specialists. Migratory pollinators could also be significantly affected by climate change.

Spring phenology has advanced by 2.5 days per decade in 78 percent of plant species in Europe due to climate change (Hoffmann *et al.*, 2019), and early flowering and fruit-ripening due to higher temperatures has also been reported in Nepal (FAO, 2019b). Fewer phenological studies have been conducted in the Southern Hemisphere than in the Northern Hemisphere (Hoffmann *et al.*, 2019). There are also few studies in the tropics on the effects of climate change on plant–pollinator interactions (Giannini, Acosta, *et al.*, 2013).

Early spring flowering (Cleland *et al.*, 2007) in response to warmer temperatures could have a negative impact on pollination if pollinators do not also respond to early-spring cues (IPBES, 2016a). For example, a decrease in synchrony between the unfolding of leaves in a host plant and the larvae of a herbivore pollinator may reduce the density of the pollinator population (van Asch and Visser, 2007). In some cases, advances have been observed in both plants and pollinators, thus maintaining synchrony; in other cases, this has not occurred, leading to mismatches (Xu *et al.*, 2019). Shifts in plant phenology and the associated responses of pollinator communities could alter the composition of plant and pollinator communities. Changes in rainfall patterns can influence flowering times and pollinator activity. Specialized plant–pollinator interactions in the tropics are expected to be much more vulnerable to climate change than generalized interactions (Ramírez and Kallarackal, 2018).

Evidence suggests that, as temperatures have increased, there has been a shift in the ranges of plants and animals towards the poles (Settele, Bishop and Potts, 2016), and extinction may be imminent for organisms unable to make the shift (Kerr *et al.*, 2015). Projections have been made on plant and pollinator distributions using current trends and existing climate prediction models (Schweiger *et al.*, 2008; Settele *et al.*, 2008; Rasmont *et al.*, 2015; Miranda, Imperatriz-Fonseca and Giannini, 2019), but few predictions have been made on plant–pollinator interactions (Giannini, Chapman, *et al.*, 2013; Imbach *et al.*, 2017), and few studies exist on the impacts of phenological shifts or shifts in the habitats of plants and pollinators (Giannini, Tambosi, *et al.*, 2015). Climate change may lead to increases in the incidence of pollinator diseases, pests and predators, but this is not well addressed in the literature, and there has been little attention on the implications for forest management. There seems little doubt that, in managing landscapes, more attention is needed on the impacts of climate change on pollination services.

## 2.9 CASE STUDIES

Case studies 1–10 illustrate the impacts of landscape-scale changes and management on forest pollinators and pollination services. Case studies 11 and 12 address the implications of climate change for pollinators.

**Case study 1.**

### Impact of landscape attributes on the diversity of bees and flower flies in Brazilian coffee landscapes

In a study of the impact of landscape attributes on the alpha and beta diversity of bees and flower flies in Brazilian sun-grown coffee landscapes, Medeiros (2019) found that bee richness was positively correlated with forest cover but the richness of flower flies did not respond to any landscape variable. The beta diversity of bees was positively affected by the extent of forest cover, and that of flower flies was affected by edge density and landscape diversity. The study suggests that bees in these landscapes are highly dependent on forests for resources; for flower flies, the driving factor may be the availability of larval host plants, which are weedy plants that increase in density with increasing landscape diversity and edge density in agricultural landscapes. The study indicates a need for management practices that help maintain key landscape components, such as specific species and habitat types, on which pollinators depend. This, in turn, requires knowledge of existing pollinator presence and the habitat requirements of individual pollinator species.

**Case study 2.**

## Influence of land use and land cover on bumblebee assemblages in Vermont, United States of America

Richardson *et al.* (2019) found that land use and land cover strongly influenced the diversity and abundance of bumblebee assemblages in Vermont, United States of America. A positive association of bumblebee abundance with forest cover was observed specifically in evergreen (spruce, fir and hemlock) forests, although forests dominated by conifers have a low diversity of flowering plants. The authors attributed this effect to factors such as the presence of nesting and forage resources in wetlands and edges associated with these forests. Bumblebee abundance was negatively associated with deciduous forests that were heavily managed for timber extraction and with the presence of wild game species, possibly because of an associated reduction in the diversity of floral resources in the understorey. The extent of croplands as a proportion of land use appeared to have a negative effect on bumblebees, but the presence of grasslands was the most important determinant of species diversity and predictor of individual species. Although "developed lands" (i.e. all human-developed areas) were negative predictors for certain species, they were positive for others; thus, pollinator responses to land use is often species-specific. Management measures should take into account species-specific responses to land use. Maintaining sufficient areas of forest and diverse understoreys may be important measures for maintaining pollinator diversity.

**Case study 3.**

## Social and solitary bees have differing responses to local forest and landscape attributes in southern India

Krishnan (2011) identified the variables that influence the abundance and richness of the social giant Asian honey bee (*Apis dorsata*) and solitary bees in remnant forests in a coffee-growing landscape mosaic in southern India. Specifically, the study explored the influence of forest size and quality and the role of surrounding landscape features (i.e. forest cover, coffee agroforestry, human settlements, water bodies and distance from the nearest contiguous forests) on bees. Forest size had a positive influence on the abundance of colonies of *Apis dorsata*, which preferred forests with relatively open edges. The richness and abundance of solitary bee species were negatively influenced by forest size when the forest edge had a high density of large trees. The extent of cover of *Lantana camara*, an exotic invasive species, on forest edges was also negatively correlated with solitary bee richness. The density of *Apis dorsata* colonies was influenced by the surrounding matrix habitat, with a coffee–forest matrix preferred over a rice paddy–forest matrix. Coffee agroforests feature various native shade trees that provide bees with forage resources; nevertheless, the presence of such agroforests had no apparent effect on the abundance of solitary bees, possibly because they obtain their forage resources in the forests in which they nest. Differences in nesting and forage preferences at multiple scales are possible reasons for differences in responses to local and landscape attributes by social compared with solitary bees.

**Many *Apis dorsata* (Asian wild social bee) colonies nesting on a single tree.**

**Case study 4.**

### Trees as stepping stones for nectariferous birds in human-modified landscapes in Brazil

Studies have shown that the abundance of nectariferous birds (many of which are important pollinators) decreases along a forest–agriculture gradient, declining with reducing area of natural forest in landscapes (Baudron *et al.*, 2019). In São Paulo, Brazil, however, the presence of rural homesteads with trees that provide forage for nectariferous birds in otherwise homogenous farmland appears to enhance landscape connectivity for these species. In highly fragmented landscapes, such biological stepping stones can facilitate forest regeneration (Barros *et al.*, 2019). The quality of the matrix habitat in fragmented landscapes, therefore, can be important in harbouring pollinators and connecting habitat fragments. Ensuring sufficient numbers and diversity of bird-pollinated tree species (i.e. feeder trees) in rural landscapes may be an important management practice.

Case study 5.

## Effects of tropical forest fragmentation on bee communities in Costa Rica

Brosi *et al.* (2008) evaluated the overall and individual responses of bee tribes to tropical forest fragmentation in Costa Rica. They found that overall bee abundance and diversity were not influenced by the size of forest fragment, but some individual bee tribes were significantly affected. For example, among the bees present in the forest exterior, stingless cavity-nesting bees had the strongest positive response to increasing forest fragment size and extent of forest in the landscape, but the feral European honey bee (*Apis mellifera*) was negatively affected. Stingless (*Meliponini*) and orchid (*Euglossini*) bees were the dominant tribes in the forest interior (>90 percent of individuals), but the size of forest fragment did not influence their abundance.

Community composition was not affected by fragment isolation because most fragments were within the flight range of bees. There was a difference in the tribal composition of bees between the forest interior and exterior, however. Although no individual of an orchid bee species was captured in pastures, they comprised about 15 percent of bees captured in forest interiors. Orchid bees are specialized, and their preference for forest habitats may be attributed to the availability of forage such as Orchidaceae and Araceae and of nesting materials and sites for thermoregulation.

Some bee species were found only in forested habitats, indicating the importance of native forests in maintaining bee diversity within a landscape. The response to landscape variables is often species-specific, and management measures should be planned accordingly.


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**The inflorescences of Brazil nut trees constitute a forage resource for various large-sized bees in Madre de Dios, Peru**

**Case study 6.**

### Effect of urbanization and management practices on pollinators in tropical Africa

Guenat *et al.* (2019) investigated the effect of urbanization (rural, urban and peri-urban) and vegetation management practices (amenity lands, which are green spaces managed for aesthetic purposes; farmland; and informal green spaces) on pollinator abundance, bee diversity, community structure and functional traits. They found that, in medium-sized tropical African cities, overall bee diversity and abundance were unaffected by urbanization; wasp abundance decreased with urbanization but was unaffected by vegetation management practice; beetle abundance was lower on amenity lands than on farmland and in informal green spaces and negatively affected by urbanization; and non-fruit-fly abundance was unaffected by vegetation management practice and urbanization. Although, overall, bee diversity and abundance were unaffected by urbanization and vegetation management practices, there were differences among species in their responses based on body size, tongue length and foraging behaviour, with the diversity and abundance of cavity-nesters and long-tongued bees decreasing with increasing urbanization. All farmlands had lower bee abundances across a rural–urban gradient, possibly because of pesticide use. Amenity lands had highly disturbed soils and thus fewer ground-nesting bees; the high level of disturbance also explains the reduced abundance of beetles in amenity lands. Other pollinators were unaffected by management practices but decreased with increasing urbanization. Urban green spaces can harbour a wide diversity of pollinators. Nevertheless, urbanization can modify pollinator community composition based on resource availability, habitat connectivity and management.

**Case study 7.**

### Long-distance pollen dispersal is required to prevent inbreeding in a tropical timber species

Ismail *et al.* (2012) studied the consequences of a reduction in population density of *Dysoxylum malabaricum* (Meliaceae) that produces valuable timber and medicinal products, due to habitat fragmentation. They found that, in low-density stands, there was an increase in the frequency of short-distance pollen transfer, leading to an increase in the relatedness of offspring, although isolated single trees received pollen from long distances and benefited from a diverse pollen pool. More-intact forests had more pollen donors from fewer related trees. High-density stands, therefore, are important for the long-term fitness of *Dysoxylum malabaricum*, although single isolated trees may also play important roles in species conservation.

**Case study 8.**

## Riverine forests play an important landscape role in pollination services

Santos *et al.* (2018) tested whether land-use and land-cover change in riverine areas of the River Minho, Portugal, affected habitat suitability for insect pollinators. The floodplains in the study area are occupied by a complex land-use matrix dominated by small-scale agriculture, orchards, vineyards and scrublands, and in nutrient-poor soils by forests of maritime pine (*Pinus pinaster*) and eucalypt (*Eucalyptus globulus*). Since the 1950s, emigration, rural exodus and low birth rates had caused overall agricultural land abandonment, followed by a general increase in woodlands, scrublands and exotic stand plantations. Santos *et al.* (2018) developed a pollination suitability index for riverine landscapes by assessing the capability of different riverine land uses (in a 300-m buffer surrounding the River Minho) to support pollination services. They found that the abundance of pollinators differed significantly among land-use classes: the highest number of insects was recorded in riparian forest, followed by broadleaved forest. *Eucalyptus* forest had the lowest number.

There are records of unique mutualistic relations between riparian host plants and insects – such as the valley elderberry longhorn beetle (*Democerus californicus dimorphus*) (Collinge *et al.*, 2001) – that provide pollination services to host plants. Elderberry (*Sambucus* spp.) is an important nectar source for many pollinators in riparian forests in California, United States of America (Wojcik, undated). Goodding's willow (*Salix gooddingii*), a riparian species, is a host plant for the larvae of Western viceroy butterfly (*Limenitis archippus obsoleta*) in southwestern United States of America, and adults provide pollination services to this and other riparian tree species (Nelson, 2003).

In their study in Portugal, Santos *et al.* (2018) concluded that near-natural land-use classes, such as riparian scrublands, riparian forests and broadleaved forests, had a higher capacity to support pollination services than agricultural or other forest land uses, even in proximal fluvial territories (the 300-m buffer surrounding the river). Riverbanks and side bars were also found to be important for supporting pollinators. Management, therefore, should be targeted at improving landscape heterogeneity and patchiness in riverine areas to increase floral and nesting resource diversity and connectivity. Protection buffers in riverine areas should be enlarged and include measures that restrict access to the riverine areas, sand extraction from riverbanks and side bars, and clearcuts of riparian vegetation. Riparian forests harbour unique flora and fauna and are important in providing various ecosystem functions. Management measures should aim to maintain large riverine buffers of near-natural habitat and reduce disturbances in them.

**Case study 9.**

### Bats have important landscape pollination and seed-dispersal functions

The pollination services of mammals are poorly documented, including in forests. Bats are pollinators of wild species, including the wild relatives of certain important commercial crops, such as *Agave* and *Musa*; they are also pollinators of the long-lived iconic baobab, which has more than 300 known uses by humans (Buchmann *et al.*, 2010). Several species of hemi-epiphytic cactus, tree beans and durian are bat-pollinated (Aziz *et al.*, 2016; Williams-Guillén *et al.*, 2016). Bats play important role as pollinators in tropical forests, including for *Syzygium cormiflorum* (Meyer, Struebig and Willig, 2016), a rainforest tree species native to northern Queensland, Australia. No studies appear to have been carried out on the economic value of fruit bats as pollinators of timber trees, although many are bat-pollinated (Aziz *et al.*, 2016). Fruit bats are not just important pollinators but also seed dispersers. Their ability to travel (and thereby carry pollen) over long distances enables greater genetic variability among the plant species they pollinate. The protection of these important species primarily involves conserving their roosting sites, which may not be confined to forests. In many regions, bats are hunted for their meat, making them vulnerable (Ibouroi *et al.*, 2018).

Bats seem to prefer riparian habitats due to the ready availability of water and the greater abundance of food resources such as insects. Lactating females require access to water and visit water bodies frequently through the night during nursing. Several bat species prefer to roost close to water bodies. The loss of water sources or their pollution by toxins associated with mining operations and agricultural run-off has been shown to threaten bat populations; artificial water sources may benefit bats in arid regions (Korine *et al.*, 2016).

**Case study 10.**

### Invasive pollinators are detrimental to native biota and agriculture in Argentina

Invasive flower visitors such as *Apis mellifera scutellata* and *Bombus terrestris* introduced for honey production and crop pollination have been more successful in new areas than in their native ranges (Aizen *et al.*, 2014). Most studies show that fruit set increases with increasing pollinator visits; however, a study by Sáez *et al.* (2014) on raspberry (*Rubus idaeus*) in north-west Patagonia, Argentina, found that fruit set declined with increasing visits by *Bombus terrestris* and, to a lesser extent, by *Apis mellifera* due to the damage caused to the pistils by excessive visits from the invasives. This suggests that there is an optimum for honeybee densities; thus, management recommendations should be based on studies that evaluate optimum populations for high crop yields (Rollin and Garibaldi, 2019).

**Case study 11.**

### Climate change threatens crop pollination services in Brazil

Using climate models, Elias *et al.* (2017) predicted a decline in tomato yields due to a reduction in the suitability area for pollinators. Magrach and Ghazoul (2015) predicted a reduction in the suitability area for coffee; however, the implications of this for crop pollination and therefore yield are yet to be ascertained. Giannini, Acosta, *et al.* (2013) predicted a shift in the suitability area for passionfruit pollinators (*Xylocopa* spp.) from the southern and central-eastern areas of the Brazilian tropical savanna to its northern areas. Although the distribution range of the pollinator is predicted to increase, its forage resources in the passionfruit non-flowering season could be limited, potentially diminishing the pollinator population. Climate change is also predicted to affect larger (mammalian) pollinators; a study of bats in Brazil by Costa *et al.* (2018) predicted that the suitability area of nectarivorous bats will decline by 28 percent, which could have major impacts on bat-pollinated plants.

**Case study 12.**

### Climate change could disrupt fig pollination

Fig trees – which are important species in tropical rainforests – depend on fig wasps for pollination and fruit set. Fig wasps are small and short-lived and potentially vulnerable to climate change. An increase in temperature could decrease the lifespan of fig wasps and thus disrupt their role in the fig-tree reproductive cycle. Fig trees, in turn, are an important food source for many animals (Harrison, 2000, 2003; Jevanandam, Goh and Corlett, 2013). A disruption in the mutualistic relationship between wasps and fig trees, therefore, could have cascading effects on myriad organisms dependent on this keystone species. The local extinction of pollinator fig wasps in northern Borneo because of a gap in the availability of floral resources caused by a drought (induced, in turn, by an El Niño–Southern Oscillation event) (Harrison, 2000) is an example of the impact that an extreme climatic event can have on plant–pollinator interactions.

## 2.10 SUMMARY OF CASE-STUDY FINDINGS

The findings of these case studies on promoting pollinator communities in landscapes can be summarized as follows:

- Management practices should help maintain key landscape components, such as specific species and habitat types, on which pollinators depend. This requires knowledge of existing pollinator presence and the habitat requirements of individual pollinator species.
- Maintaining sufficient forest areas in landscapes, and diverse understoreys, may be important measures for maintaining pollinator diversity.

- The responses of pollinators to land-use change, including habitat fragmentation and urbanization, are likely to be species-specific and trait-based (e.g. body size, tongue length, nesting and forage preferences).
- Habitat heterogeneity may be beneficial for pollinator diversity if not highly fragmented.
- Differences in nesting and forage preferences at multiple scales are possible reasons for differences in responses to local and landscape attributes by social compared with solitary bees.
- Ensuring sufficient numbers and diversity of bird-pollinated tree species (i.e. feeder trees) in rural landscapes may be an important management practice.
- Riparian scrublands and forests are known to harbour unique flora and fauna and are important in providing various ecosystem functions and services, including pollination. The conservation of such forests and associated pollinators is important for ensuring their continued services.
- Solitary trees, groups of trees and agroforestry can act as biological stepping stones and help increase connectivity between habitat fragments in landscapes, with benefits for some pollinators.
- The effects of fragment size and edge density on pollinators vary by species.
- A higher density of flowering plants may be more attractive to pollinators than a higher diversity of such plants, given already high plant species richness. In habitats with few wild plant species, however, plant diversity matters.
- Urbanization has differing effects on pollinators, depending on taxa; many non-bee pollinators are negatively affected.
- Urban green spaces can harbour a wide diversity of pollinators. Nevertheless, urbanization can modify pollinator community composition based on resource availability, habitat connectivity and management.
- Invasive and alien species can alter plant–pollinator networks.
- Bats enable pollination over large areas and may be important pollinators in some tropical forests.
- Climate change may lead to changes in phenological events, such as leaf unfolding, flowering and fruit maturation, which may, in turn, affect pollinators, habitats and plant–pollinator relationships.
- Climate change may also disrupt synchronies between plant phenological events and pollinators, with impacts on both plants and animals.

# 3. Pollinators and forest management

Although studies have investigated the effects of specific forest management practices – such as logging, grazing and mowing – on pollinator diversity and abundance, most focus on the effects of habitat loss, degradation, fragmentation, ecotones, fire, invasive species, landscape composition and land-use types on pollinator diversity and abundance. The negative effects of forest degradation, habitat loss, isolation, reduction in patch size and fragmentation on pollinator diversity, abundance and richness have been well documented in Europe and North America, but there is a paucity of data for the rest of the world (IPBES, 2016b). Relatively few studies exist of the impacts of forest management practices on wild pollinator species. Some recent research has examined the role of management of semi-natural habitats and croplands in facilitating pollinator services.

Disturbances can have beneficial effects on pollinators (Hanula, Horn and O'Brien, 2015; Rivers, Galbraith, *et al.*, 2018) by increasing habitat heterogeneity (Rodríguez and Kouki, 2017). Severely disturbed habitats, on the other hand, can have negative effects on pollinator communities (Winfree *et al.*, 2009) because of habitat homogenization (Quintero, Morales and Aizen, 2010).

Habitat management is an important driver of pollinator community change. Berecha *et al.* (2014) showed that increasing forest management intensity in coffee–forest systems (from no interventions to far-reaching interventions such as the removal of competing shrubs and the selective thinning of the upper canopy) decreased pollinator richness and potential coffee pollination services. It therefore potentially decreased the resilience of the coffee production system due to the impoverishment of insect communities.

## 3.1 INDIGENOUS AND LOCAL KNOWLEDGE SYSTEMS IN FOREST MANAGEMENT AND POLLINATION

Indigenous and local knowledge may be considered as the knowledge, practices and beliefs that have evolved and been transmitted through cultural and intergenerational processes (IPBES, 2016b). In indigenous and local knowledge systems, "pollination processes are often understood, celebrated and managed holistically in terms of maintaining values through fostering fertility, fecundity, spirituality and diversity of farms, gardens, and other habitats" (Lyver *et al.*, 2015, cited in IPBES, 2016b, p. 336). Such systems might, for example, favour heterogeneity in land use and gardens, conserve nesting trees and flowering resources, distinguish the presence of a wide range of wild bees, and observe pollinator habitats and food preferences (IPBES, 2016b). Indigenous and local knowledge can contribute to the conservation of pollinators through traditional management practices that encourage the sustainable production or gathering of honey and other forest products and which have been modified and adapted over time in light of ecological change. Such intrinsic knowledge – or traditional ecological knowledge – on the behaviour, biology and ecology of pollinators can increase understanding of management practices that encourage pollinator diversity and abundance (IPBES, 2016b; Athayde, Stepp and Ballester, 2016; Jasmine *et al*., 2016; Hill *et al*., 2019). Moreover, indigenous and local knowledge offers a holistic understanding of pollination services, which can assist in the development of pollinator-friendly policies (IPBES, 2016b; Roy *et al*., 2016).

Terms such as biocultural approach have emerged as part of moves to include indigenous and local knowledge in conservation efforts (Hill *et al*., 2019). A biocultural approach is much more inclusive of local cultural perspectives and knowledge in understanding and identifying feedbacks between (and within) ecosystems (Athayde, Stepp and Ballester, 2016) and quality of life. Nevertheless, some efforts to incorporate indigenous and local knowledge in conservation management have been poorly executed (Athayde, Stepp and Ballester, 2016). There remains a tendency to undervalue and poorly document indigenous and local knowledge and traditional ecological knowledge, especially in relation to forest management practices aimed at strengthening pollination services.

## 3.2 LOGGING, GRAZING, MOWING AND FIRE

The harvesting of trees affects forest variables such as structure, species composition (plants and animals), soil dynamics, hydrology and light availability (IPBES, 2016b), all of which can affect pollinator species composition and diversity and plant–pollinator networks (Nielsen and Totland, 2014). Most studies on the impacts of logging on pollinators are in temperate regions.

The impacts of grazing by livestock on pollinator diversity and abundance are contingent on factors such as type of land cover, plant species composition, season of grazing, grazing intensity, land-use history and climate. Intensified grazing (e.g. involving the high use of fertilizer, cutting and silage before flowering in legumes) reduces pollinator diversity compared with that in traditional systems (IPBES, 2016b). On the other hand, there has been little research on the impacts of wild herbivore grazing on wild pollinators due to resource limitation.

Mowing can affect plant species composition, which might influence pollinator diversity and abundance (Humbert *et al*., 2012). Studies have shown that heterogeneous mowing times in grasslands can enable staggered flowering and thus increase the duration of available resources for pollinators. The mowing of semi-natural habitats, however, can have negative impacts on pollinator populations, especially when they are in the egg and larval stages (Di Giulio, Edwards and Meister, 2001). Huge bee losses have been observed in clover fields subjected to mowing during flowering, but this can be mitigated to a certain extent by leaving uncut refuges within the landscape and by delaying mowing (Humbert *et al*., 2012). Forest managers should consider the potential negative consequences of alternatives to mowing, such as herbicide application, as management options for weed control.

Fire is a natural and important disturbance in many forest ecosystems. It may have immediate adverse effects on pollinators, but subsequent regeneration and changes in land use will determine future pollinator species composition, abundance and diversity. The availability of soil nutrients often increases following fire, which leads in turn to an increase in plant flowering, producing an abundance of resources for pollinators (Carbone *et al.*, 2019). Fires in dormant seasons and during nesting and reproduction, however, could be particularly harmful for pollinators and affect future populations (Hopwood *et al.*, 2015). Those at risk may include ground-nesting bees, queen bumblebees overwintering on the ground, solitary bees that nest in twigs and stems, and larvae and pupae that cannot fly or are immobile. Specialists and species that are less mobile are likely to be most affected by fire (Vogel, Koford and Debinski, 2010).

The presence of intact areas close to burned habitats can act as a source population for colonizing burned areas (Swengel, 2001; Panzer, 2002). Burning isolated patches as a whole, however, could destroy entire extant pollinator populations and reduce or eliminate the potential for re-colonization. Although fire can have very strong negative initial effects on pollinator abundance and diversity, recovery is possible given sufficient time (Potts *et al.*, 2003), contingent on the availability of sufficient unburned areas to act as a source of colonizers (Harper *et al.*, 2000; Swengel, 2001; Panzer, 2002) and the frequency of burning. Mosaics of burned and unburned habitat recover faster than large tracts of burned habitats, and the frequency of burning should not exceed the rate of recolonization. The risk of losing certain species due to fire in small isolated forest fragments is higher than in larger contiguous forests (Harper *et al.*, 2000).

## 3.3 FOREST RESTORATION

Pollinators are essential for the reproduction of foundational tree species in a range of ecosystems. Montoya-Pfeiffer *et al.* (2020) found that pollinators were less diverse and abundant, and their functional interactions were lower in restoration plantings than in primary forests but that restored sites were more favourable to bee-community recovery than the other disturbed habitats studied (anthropogenic wetlands and sugarcane fields). The largest bee species, and above-ground bee species, were the most diminished pollinator populations in these restoration plantings, suggesting that those pollinators are highly dependent on mature forest features such as pre-existing cavities in trees. Trees in restoration sites (plantings) may therefore be dependent on pollinators in nearby primary forests to ensure reproductive success.

Restoration efforts should take into account the nesting needs of bees and address the management and conservation of primary-forest remnants that are sources of habitat. For example, restoration areas may be best sited close to functional habitat areas, or it may be possible to re-create habitat elements with plantings or by improving existing spaces. Restoration plantings should aim to establish tree species at densities sufficient to enable their effective pollination. Few studies exist, however, of the long-term implications of initial restoration plantings on pollination.

Requier *et al.* (2019) highlighted the presence of wild honeybee (*Apis mellifera*) colonies in European forests and the importance of tree cavities as nest sites. Conserving cavity-bearing trees in managed European forest and maintaining a proportion of unmanaged forest areas (that generally host far more tree cavities than their managed counterparts) could contribute to safeguarding and sustaining wild native honeybee populations.

## 3.4 NON-WOOD FOREST PRODUCTS AND LIVELIHOODS

An estimated 300–350 million people worldwide are highly dependent on forests for their survival (Chao, 2012). NWFPs play vital roles in the livelihoods of many forest-fringe communities and may be essential for their subsistence (Msalilwa, Augustino and Gillah, 2013; Mulenga *et al.*, 2014). Many NWFPs are important economically, such as Brazil nuts, latex, açaí and palm fruits (Ibrahim, Abdalla and Fangama, 2015; Shackleton, Ticktin and Cunningham, 2018).

Pollinators are key for maintaining the productivity of many NWFPs in the long term (Thomas *et al.*, 2009). With a loss of pollinators, there is a risk of reducing seed set and therefore fruit production and the plant's natural regeneration (Vance, Bernhardt and Edens, 2004; Rehel *et al.*, 2009; Neuschulz *et al.*, 2016). There is a large knowledge gap, however, on the extent to which NWFP yields are dependent on pollinators (IPBES, 2016b), and existing information is poorly documented (Rehel *et al.*, 2009). Literature on forest management practices and conservation strategies related to NWFPs and their pollinators is scant.

NWFPs are an important resource base, and their use offers a strategy for conserving forest landscapes because they can be harvested in the wild and thereby help ensure the economic viability of natural forests (Shackleton *et al.*, 2008; Msalilwa, Augustino and Gillah, 2013; Ibrahim, Abdalla and Fangama, 2015). There is evidence, however, that NWFP extraction can be unsustainable at certain harvest intensities, leading to cascading effects on surrounding plant and animal communities (da Silva *et al.*, 2018; Shackleton, Ticktin and Cunningham, 2018). Advancing understanding of how pollination and pollinator availability affect NWFP production, and vice versa, is crucial for sustaining national and international markets and for poverty alleviation (da Silva *et al.*, 2018). The harvesting of NWFPs can cause changes in insect pollinator communities and affect the viability of keystone species and plant–pollinator networks (Neuschulz *et al.*, 2013). Few studies have addressed the effects of NWFP harvesting on pollination systems or the possible cascading effects.

## 3.5 CASE STUDIES

Case studies 13–31 illustrate the impacts of forest management on pollinators and pollination services; case studies 32–36 address a subset of forest management pertaining to the role of pollination in the production and management of NWFPs.

**Case study 13.**

### Selective thinning and its benefits for pollinators in the Black Forest National Park, Germany

Eckerter *et al.* (2019) studied the effect of forest management on the pollination and fruit set of bilberry in an unmanaged (80–90 years) forest in the Black Forest National Park in Baden-Württemberg, Germany (bilberry is an important forage plant for capercaillie, *Tetrao urogallus*, a threatened bird species). The forest structure comprised a mosaic of closed canopy (dominated by Norway spruce – *Picea abies*) and smaller gaps (developed through natural causes such as storm events or due to differences in tree species composition; these gaps were 2–5 m in size). A total of 12 50×50 m plots were selected. As part of a restoration effort, selective thinning was carried out in 6 of the 12 plots in which single trees were uprooted and others girdled, with treatments randomly allocated in the plots, thus simulating natural forest disturbance leading to higher forest heterogeneity. All treatments were established in similar vegetation, and they led to an increase in standing and lying dead wood in addition to greater canopy openness (Eckerter *et al.*, 2019) (canopy gaps have been shown elsewhere to have a positive effect on the richness of nectar-rich plant species; Cho, Lee and Bae, 2017). Flower bud abundance increased with canopy openness and increased light penetration, thus providing more forage resources for pollinators, leading to a higher abundance of pollinators at the bilberry flowers. The study by Eckerter *et al.* (2019) indicated that a diverse forest structure had dual benefits by both increasing pollinator diversity and improving the conservation of capercaillie, but the benefits of logging and dead wood for the main pollinator of bilberry were not demonstrated. Forest management practices such as selective logging and coppicing to increase the heterogeneity of tree communities are likely to be beneficial for pollinators as well as other forest biodiversity.

**Case study 14.**

### Benefits of tree mortality caused by a natural disturbance event on bee communities in Idaho, United States of America

Foote (2018) studied the impacts on bee community composition of tree mortality in Douglas fir forests caused by the Douglas fir beetle at sites in Idaho. He found that bee community responses differed according to the severity of tree mortality, with bee diversity decreasing at sites with relatively high tree mortality rates (>90 percent) compared with areas with low tree mortality (<30 percent), possibly due to variations in nesting and foraging behaviours as well as in the relative flight capabilities exhibited by colonizing bees. The study also found that bees were more abundant and species-rich with increasing above-ground nesting resources, more open canopies and higher herbaceous cover (which is important for forage for some bee species). On the other hand, bee species richness decreased with increasing shrub cover and organic matter

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cover, which reduced the extent of herbs present and nesting sites for ground-nesting bees. Foote (2018) suggested that bees can benefit from bark beetle outbreaks, and allowing for such biotic disturbances in certain locations (e.g. wilderness areas) may be an effective and efficient mechanism for promoting and maintaining abundant and diverse bee communities in forested landscapes. Monitoring changes in bee communities following forest disturbances could help in predicting the impacts of climate change and future forest disturbance events on forest-associated bee populations. The data collected through such monitoring could also help guide land management decisions in areas where bee biodiversity is in decline or at risk of decline. Allowing biotic disturbances could promote heterogeneity in habitats and thus promote bee communities in forested landscapes. Long-term studies are required, however, to fully understand the impacts of natural disturbances over time and how associated changes affect pollinator communities.

**Case study 15.**

## Resource accessibility and detectability by small-scale thinning of woody species increases pollinator abundance in Patagonian woodlands

Coulin, Aizen and Garibaldi (2019) investigated the responses of flowers and pollinators to four levels (0, 30, 50 and 70 percent) of woodland thinning intensities (thinning of woody species) in Río Negro Province, north-west Patagonia, Argentina. This forest/steppe ecotone comprises broadleaved mixed shrublands dominated by *Nothofagus antarctica*, a wind-pollinated species, but also includes other animal-pollinated woody species. The shrublands are heterogeneous in species composition, canopy profile, tree height, and slope degree and orientation. The study was carried out in tall (maximum stratum height of 5–8 m), medium (maximum height of 3–5 m) and short (height 1.5–3 m) shrublands with eight 31.5x45-m plots and were randomly assigned to one of the four thinning treatments (two replications of each treatment per shrubland type). The study found that pollinator abundance was higher in the tall shrublands, but pollinator richness was similar at the three sites studied. Pollinator evenness decreased marginally with thinning intensity, due possibly to an increase in the density of one or two species. Pollinator richness increased sharply at all three sites with thinning. Although pollinator and flower abundance and diversity were positively related, the response to thinning differed between flowers and pollinators, at least in the short term. The increase in pollinator density and richness with thinning could be because the response of pollinators is regulated by changes in flower attractiveness due to changes in abiotic conditions (e.g. light and temperature) and vegetation structure. Thus, resource accessibility and detectability might be more important than resource abundance, and an increase in light and temperature could increase pollinator activity and diversity. Vegetation structure and abiotic factors play key roles in determining pollinator community structure. The small-scale thinning of woody species may constitute an effective management approach for enhancing local plant communities and increasing environmental heterogeneity, with benefits for pollinators.

**Case study 16.**

### Soil-nesting bees benefit from the removal of above-ground organic matter following timber harvest in coniferous forests, United States of America

Rivers, Mathis *et al.* (2018) evaluated the impact of removing harvest residues (branches, brash, stumps and non-commercial timber) at varying intensities and levels of soil compaction on the abundance and diversity of ground- and cavity-nesting bees in a coniferous forest in Oregon. Five treatments were tested: 1) tree bole removal + no soil compaction; 2) tree bole removal + moderate soil compaction; 3) above-ground vegetation removal + no soil compaction; 4) above-ground vegetation removal + moderate soil compaction; and 5) above-ground vegetation removal + all surface organic matter removed + moderate soil compaction. The most intensive treatment (treatment 5) had higher abundances and species richness compared with the least intensive (treatment 1). Species abundance and richness were higher in the second year of the trial than in the first for all treatments, with an increase in the number of ground-nesting bees and a decline in cavity-nesting species. One explanation for this is that the removal of ground debris, which exposes bare soil, may increase the number of potential nesting sites for ground-nesting species. In contrast, the retention of above-ground dead vegetation, which comprised logging slash from mature Douglas fir, did not provide additional nesting sites for cavity-nesting species, given that the wood is hard and lacks pithy hollow stems. The plots lacked standing dead wood and other downed woody debris and there was an overall lack of nesting sites for tree-nesting bees. Over time, however, forest succession may increase the availability of nesting sites for cavity-nesting bees, leading to an increase in cavity-nesting bee abundance and richness. Long-term studies are needed to understand how bee communities change over time following disturbance and how best to manage forests to provide suitable habitat for diverse bee species. In this study, nesting sites seemed to be more limiting than forage resources. Nevertheless, the extensive removal of ground flora could be detrimental to bee diversity and abundance if foraging resources become a limiting factor. Forest management practices that increase habitat heterogeneity (e.g. bare ground for ground-nesting bees and the retention of dead pithy wood that benefit cavity-nesting bees) could help increase bee populations. Increasing nesting sites for ground-nesting bees would help increase the diversity and abundance of this species group. Long-term studies are needed to fully understand how pollinator community structures change as logged areas regenerate.

**Case study 17.**

## The importance of ecotones in logged forests in providing nesting and forage resources for bees in North Carolina, United States of America

Mullally (2018) compared bee diversity at differing intensities of disturbance (in logged and intact forests and at the edges of logged and intact forests) in mixed mesophytic forest in North Carolina. The forest stands were dominated by *Quercus* spp. and *Liriodendron tulipifera* in the overstorey and by *Rhododendron maximum* in the middle storey and understorey. The highest bee diversity was at the centre and edges of logged forest, with differences in the dominant species across the sites. The trees at logged sites were retained. The presence of fallen trees, and an increase in open ground, possibly provided additional nesting sites for bees; moreover, the openings had an abundance of forage resources. There was a clear difference in bee diversity between sites based on nesting preferences. Cavity-nesting bees that prefer rotting wood were predominant in intact forests, and ground-nesting species preferred the logged and edge sites. As in other studies, bee diversity was highest at edge sites, demonstrating the importance of ecotones. Forest management practices that maintain habitat heterogeneity and varying canopy coverage at a local scale are likely to be beneficial for pollinators.

**Case study 18.**

## Disturbance caused by clearcut logging benefits herbs and associated pollinators in Lithuania

Česonienė *et al.* (2018) studied the effects, after two years, of clearcut logging in boreal Scots pine (*Pinus sylvestris*) forests (the *Vacciniosa* and *Vaccinio-myrtillosa* forest types) in southeastern Lithuania on understorey plants and associated pollinators. The main understorey plants were *Vaccinium myrtillus*, *V. vitis-idaea* and *Calluna vulgaris*, all of which provide many pollinator communities with forage resources. There was an immediate negative effect of logging on shrub cover. After two years, however, the shrub and herb layer had increased substantially with the inclusion of certain light-demanding species. Logging positively affected the number of annual and perennial herbs and led to an increase of associated pollinators: *Vaccinium myrtillus* was negatively affected by the increased sunlight caused by tree removal, but the presence of *V. vitis-idaea* and *Calluna vulgaris* increased. Although the study showed that clearcut areas sustained larger pollinator assemblages than mature forests, the slower rate of recovery for certain important plant species is a matter of concern. The possibility of changes in the composition of pollinator species and the associated impacts on pollination services is less researched. Variables such as the size of clearcut areas, distance from the nearest forested habitat, and the quality and characteristics of the surrounding habitat matrix might be expected to influence the rate of recovery of pollinators.

**Case study 19.**

## Forest openings increase bee abundance and diversity in Massachusetts, United States of America, but the response is guild-specific

Roberts, King and Milam (2017) evaluated the impact of early-successional forests in small forest openings created by logging (4–8 years earlier) on bee communities in hardwood–white pine forests in Massachusetts. Bee abundance and diversity were significantly higher in openings, but the size of the opening had no effect. The percentage of early successional habitat within 200 m of forest openings had a positive effect on bee diversity. The abundance and diversity of bees were negatively influenced by vegetation height except for softwood-nesting bees. The abundance and diversity of all bees combined, regardless of sociality, nesting traits or size, were positively influenced by floral index. Overall bee abundance and diversity in the forest increased with an increase in the extent of early-successional habitats within the landscape. Social, softwood-nesting and small bees, however, showed no response to the extent of nearby early-successional habitat, indicating that bee habitat requirements should be identified based on traits such as nesting type (e.g. ground, tree or cavity). Although forest openings increased bee abundance and diversity in the forests, the response was not consistent across guilds. To enhance the diversity of pollinator communities in a range of guilds, forest management practices should aim to ensure adequate provisions for the nesting requirements of all guilds.


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Slash-and-burn practice in a forest in Quellomayo, Cusco, Peru.

**Case study 20.**

## Temporal and spatial heterogeneity benefits pollinators in Finland

Rodríguez and Kouki (2017) studied the effects of disturbance on pollinator communities in boreal vegetation dominated by Scots pine (*Pinus sylvestris*) in Finland, which was undisturbed for about 100 years before the experiment. The forest was subjected to eight treatments involving four levels of tree retention: 1) clearcut; 2) 10 m$^3$ of trees retained per ha; 3) 50 m$^3$ of trees retained per ha; and 4) a control of unlogged forests. There were two fire treatments: 1) burned in June 2001; and 2) unburned. The sites were harvested 13 years before the study (in winter 2000–2001) and allowed to regenerate naturally. No major difference in species richness (bees and hoverflies) was detected between burned and unburned harvested sites, but harvested sites had higher bee richness than unharvested sites. Harvested sites had abundant nesting sites for both wood- and ground-nesting bees, enabling them to thrive. There was temporal variation in species dominance in bees, with solitary bees more dominant in spring to early summer (benefiting from the flowering of bilberry and lingonberry), and bumblebees were present throughout the year. The availability of bare ground (which is associated with fire) was an important indicator for ground-nesting species. Over time, the creation of nesting sites such as dead wood and early successional habitats (such as grass) affected bee community composition. More research is needed on larval microhabitats and hosts for hoverflies to better understand their resource requirements.

Temporal and environmental heterogeneity were the most important variables determining pollinator communities in this experiment. Management practices should aim to maintain or create both spatial and temporal forest heterogeneity, especially in ground cover.

In the same experiment, Rodríguez and Kouki (2015) and Rodríguez (2018) further investigated the effects of fire and logging on pollinator communities associated with bilberry and lingonberry. Nesting resources such as bare ground and coarse woody debris (CWD) were the most important variables in determining the bilberry and lingonberry pollinator community composition. Burned sites that had considerably more open bare ground had higher abundance and species richness and lower pollinator evenness. Logged sites had an abundant supply of CWD, which provided nesting sites for trap-nesting bees. Bees and hoverfly species richness was higher in burned logged forest and unburned logged forest than in unlogged unburned forests. Metrics such as percent bare ground, number of CWD logs, percent grasses, percent herbs and amount of edge habitat best explained the beta diversity of bees and hoverflies. Forest management that promotes different levels of disturbance can promote habitat diversity and hence pollinator diversity at the landscape scale.

**Case study 21.**

## Benefits of post-fire salvage logging for floral and bee communities in Montana, United States of America

Heil and Burkle (2018) investigated the impacts of post-wildfire (i.e. recent – eight years since fire; and older – 24 years since fire) salvage logging (immediately after fire) on local floral and bee density, species richness and community composition and dispersion in coniferous forests in the Gallatin National Forest near Pray, Montana. Floral and bee density and species richness were higher in logged compared with unlogged sites after recent fire, but this effect was lower in older post-wildfire logged sites. Bee community heterogeneity was higher in unlogged sites after recent fire, but overall bee diversity was higher in logged sites after recent fire. Mean floral richness was different only at recent-fire sites, with higher richness in logged than unlogged sites. Vegetation differed between logged and unlogged sites, and a mosaic of both habitats maximized plant and bee diversity.

Another study (Heil and Burkle, 2019) at the same sites on the effect of post-wildfire logged and unlogged forests on the pollination and reproductive success of *Symphoricarpos albus* (snowberry, an ecologically important, fire-tolerant shrub) found no difference among treatments in bee visits to flowers. There were indications of pollen limitation in unlogged sites, however, which is related to high floral densities of potential competitors of *S. albus*. Although this study shows that there is pollen limitation in undisturbed compared with disturbed areas, such responses are often species- and case-specific, depending on variables such as the extent of disturbance and post-disturbance recovery time. The development of management practices to favour pollinators should take into account temporal changes in pollinator communities after fire and the role of salvage logging in promoting pollinator diversity.

**Case study 22.**

## Effect of repeated prescribed fire and thinning on pollinators in temperate forests of North Carolina, United States of America

Campbell, Vigueira *et al.* (2018) assessed the effects on bee and other flower-visitor abundance and diversity in temperate forests in North Carolina over a 15-year period of the following treatments: four repeated prescribed burns (B); two mechanical thinnings (M); a combination of one mechanical thinning followed by four repeated prescribed burns (MB); and a control (C). Bee abundance and diversity were higher in the MB treatment than in M and C, and abundance was higher in the B treatment than in C. The abundance of *Syrphid* flies was lower in C than in all other treatments. These results are consistent with other studies. Fire burns most of the leaf-litter layer and thus exposes the forest floor, which is preferred by ground-nesting bees. The opening up of the

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canopy due to tree deaths caused by fire is followed by an increase in the herbaceous layer, which provides forage for a wide variety of pollinators. Wasps were not affected by any of the treatments, probably because their nesting and forage resources were not limiting. Repeated prescribed fire maintains high abundance and diversity of bees and other flower-visiting insects.

### Case study 23.

## Mowing and fire benefit bees in New Hampshire, United States of America

Tucker and Rehan (2019) studied the impact of four types of management practices on bees in Ossipee Pine barrens in New Hampshire: 1) burning; 2) burning followed by mowing; 3) mowing; and 4) a control (i.e. no treatment). Bee abundance and richness were higher in the burning-followed-by-mowing treatment than in the other treatments. The authors infer that burning followed by mowing may control the growth of non-flowering forbs (herbaceous plants) and increase the area of open ground suitable for nesting. In some forest management contexts, combining periodic fire and infrequent mowing may be beneficial for pollinating bee communities by increasing the availability of ground-nesting sites.

### Case study 24.

## Synthesis of the effects of fire on pollinators

A meta-analysis by Carbone *et al.* (2019) found that the overall weighted-mean effect size of fire on pollinator abundance and richness was positive across all studies and was particularly so in the case of wildfires, possibly because pollinators are mostly mobile (flyers) and can easily colonize burned areas. Additionally, an increase in flowers following fire due to increased resource availability and a reduction in competition increases resources for pollinators and thus their populations. The meta-analysis could not ascertain, however, whether pollinators nest in burned areas or only forage there while residing outside burned areas. Although pollinator abundance and richness increase in early post-fire stages (≤3 years), which correspond with an increase in floral resources, such an effect was not observed in later post-fire stages. This finding was consistent across vegetation types. The meta-analysis also found that assessing fire effects at higher taxonomic levels could lead to unreliable results regarding abundance because species within a single order can respond in contrasting directions.

Carbone *et al.* (2019) found that recurrent fires, especially wildfires, have a negative effect on Lepidoptera abundance and a positive effect on Hymenoptera, with Lepidoptera larvae much more susceptible to direct fire effects (unlike Hymenoptera species, which have protected nests). Moreover, forage availability following fire might be limited for Lepidoptera larvae. No differences were observed in response to fire between

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Hymenoptera species groups that differed in nesting (i.e. above- or below-ground), feeding specialization (i.e. specialist or generalist) or sociality (i.e. solitary or social). Pollinators from different biomes and with differing physiognomies responded similarly. Wild pollinators are resilient to wildfire and many even benefit from it in terms of subsequent increases in abundance and richness; however, repeated fires may have negative impacts. Data are lacking on the role of spatial factors such as fire size and the spatial heterogeneity of fire regimes.

**Case study 25.**

## Effect of fire on plant–bee networks in Argentina

Peralta *et al.* (2017) studied the impacts of fire on wood-nesting bees in Argentina. Both wood-nesting bee communities and their plant–bee networks were affected by fire. The abundance of generalist bees was higher in freshly burned (1–2 years post-fire) sites than at sites with longer recovery times (2–50 years). Although the diversity of available floral resources was higher in recently burned sites, bees did not change their feeding behaviour across the post-fire age gradient. Plant–pollinator interaction networks appeared to recover within a few years of fire events. This may depend, however, on the availability of plant–pollinator habitats that can provide source populations and also fire frequency, with sufficient gaps needed between fires to enable the recovery of pollinator populations.

**Case study 26.**

## The importance of larval habitats in maintaining longicorn beetle populations in Romania

For pollinator species with complex reproductive life-cycles, it is crucial that requirements are met for the differing habitats of the larval, pupa and adult life stages. In a study of longicorn beetles (many of which are pollinators) in southwest Romania, Brodie *et al.* (2019) found that beetle diversity, occurrence and abundance were associated with higher tree density and volume of dead wood and number of stumps, and with lower canopy cover. Tree species richness had a negative effect on community occupancy. Canopy gaps lead to warmer temperatures on the forest floor, which may benefit larval development in tree trunks; they also offer additional food sources for adults, which can forage on the herbs and shrubs that colonize newly formed gaps. Forest management practices that create heterogeneity are likely to benefit pollinators with diverse habitat requirements across multiple life stages, from larvae to adults.

**Case study 27.**

### Diet overlap in bees and ungulates in Oregon, United States of America

Grazing (by both domestic and wild animals) can lead to changes in floral abundance, plant architecture and community composition and in soil characteristics such as compaction, with potential implications for pollinators. In some cases, such changes may benefit pollinators by increasing the availability of floral resources, nesting materials and habitat but in other cases the opposite effect may occur. There may also be competition for food resources when there is a diet overlap between pollinators and herbivores (Wojcik *et al.*, 2018). DeBano *et al.* (2016), for example, reported a 55 percent overlap in the diets of ungulates (domestic cattle as well as elk and mule deer) and bees in riparian vegetation in Oregon. Stressors such as drought that – combined with grazing – supress wildflower blooms may exacerbate impacts on pollinators by further reducing resource access (Wojcik *et al.*, 2018).

**Case study 28.**

### A lack of diversity in plantation forests in Java, Indonesia, may be detrimental to pollinators

Widhiono, Sudiana and Sucianto (2016) surveyed seven habitat types on Mount Slamet, central Java, encompassing a range of wild plant species richness and abundance. The total size of the study area was 17 ha, and the habitat types were classified as natural forest (NF); teak forest (TF); pine forest (PF); *Agathis* forest (AF); community forest (CF); gardens (Gd); and agricultural areas (Ag). Among the forested habitats, AF and PF had the lowest richness of herbaceous wild plant species. Wild bee and wasp abundances were highest in NF, followed by CF, Gd, TF, Ag, AF and PF. The authors suggest that the low abundance of wild plants in AF may be due to land management practices, including the application of fertilizer, mowing, and weed control, which increase the availability of nutrients to the benefit of only a few plant species. The use of mowing and weed-control practices to exclude outcompeted plant species changed plant species assemblages by reducing plant diversity and plant species richness. The authors conclude that, in their study, wild bee diversity in habitats with few wild plant species was strongly correlated with wild plant diversity, whereas in habitats with high wild plant species richness, flowering plant abundance was more important. The number of wild bee taxa recorded in the studied habitats showed that the diversity of wild plant species in those areas was fairly high and that the quality of the habitats in terms of plant species richness was important in maintaining pollinator diversity, both for solitary wild bee species and for eusocial wild bees. Tropical plantation management practices could encourage diverse understoreys. Mowing, weed control and fertilizer application should be minimized to reduce their impacts on plant species in the understorey and thereby encourage a greater diversity of pollinator species.

**Case study 29.**

## Effect of logging on the reproductive ecology of a tropical timber species at differing disturbance intensities in Thailand

Ghazoul and McLeish (2001) studied the effect of differing disturbance intensities caused by logging on the reproductive ecology of *Shorea siamensis*, a self-incompatible timber species in the dry deciduous forests of western Thailand. The density of individuals of this species was 22–205 per hectare, depending on timber harvest intensity. Logging was banned in 1990, and the study was carried out 6–7 years after the logging ban. Although the number of flower visits by *Trigona* bees (the main pollinator) was unaffected by logging disturbance, the pollinators spent more time foraging in the canopies of isolated trees (because of the long distances between trees), which were much more prevalent in heavily logged forests, and therefore were able to visit fewer individuals. This resulted in fewer cross-pollinations and lower fruit set because *S. siamensis* requires cross-pollination. This finding could have major implications for the conservation of *S. siamensis*.

**Case study 30.**

## Role of acrocerid fly in maintaining wild iris population

*Iris bracteate* is a wild iris sought for its beautiful flowers with the potential to hybridize; it is largely restricted to shaded coniferous forests in California and Oregon. An acrocerid fly, *Eulonchus tristis* (jewelled spider fly), is the main pollinator of *I. bracteata*. Its larvae parasitize on mygalomorph spider hosts that nest in shallow burrows in soft soil. The fly is anthophilous, and it has a long proboscis that allows it to feed on deep tubular flowers. Although the species is known to visit a diverse guild of flowering plants in various regions of the United States of America, it tends to assume a local foraging specialization on a single plant in each region. Ponte (2018) found that *E. tristis* exclusively visited *I. bracteata* flowers and is an excellent pollinator of them. It is a large (7–12 mm in length), fast fly; it can traverse long distances, thereby potentially reducing inbreeding depression in the plant species for which it specializes as a pollinator. More research is needed on the impacts of fire, logging and other disturbances that could affect the pollinator life-cycle (e.g. by altering soil conditions or affecting the larval hosts of the flies). The role of flies in pollination – especially specialized interactions – has received insufficient attention.

**Case study 31.**

### The importance of biotic pollination to food and financial security in India

Rehel *et al.* (2009) used a systematic assessment to identify the benefits of biotic pollination for NWFPs and crops in the Nilgiri Biosphere Reserve, India. They found 139 NWFP species considered important for local livelihoods; these were mainly leaves and fruits for medicinal and nutritional purposes, with about half the species commonly traded. Of the 139 species, 40.3 percent benefited directly from biotic pollination. Bees and other insects were the most frequently observed pollinators, and birds and bats were observed rarely. The authors concluded that biotic pollination plays an important role in the nutritional, food and financial security of local people by enhancing the production of NWFPs and crops. An understanding of the modes of pollination and the contribution of insects to NWFPs is essential for enabling appropriate management measures.

**Case study 32.**

### Indigenous knowledge of honeybees in the Lao People's Democratic Republic

Baird and Bounphasy (2011) describe the harvesting of honey in Pathoumphone, from both managed and wild bee colonies. Wild honey and wax are important NWFPs harvested from the three main locally identified honeybee types: 1) *pheung phoum* (nests on all types of trees); 2) *pheung ton* (nests only on deua han (*Ficus* spp.) trees; and 3) *pheung kon* (nests in the hollowed insides of trees). The harvesting method and ownership differ for each type. Fire is used in both *pheung phoum* and pheung ton to drive the bees away but, for the latter, harvesting is performed by an expert involving a ceremony connected to cosmological perceptions of this bee type. *Pheung phoum* bees are considered available on the basis of "first come, first served" – whoever finds the nest has ownership of it and authority to harvest its honey and wax. The situation differs for *pheung ton*, because this type usually nests in the same place over the long term and ownership is heritable. In many cases, the harvested honey and wax is shared among members of the owner's family. One nest of *pheung ton* or *pheung phoum* generally yields 1–2 kg of bees' wax, which sells for LAK 60 000–80 000 (USD 6–9) per kg. The benefits of conserving these pollinators are not limited to pollination services – they include direct economic and cultural benefits.

**Case study 33.**

## Importance for livelihoods of Brazil nut, an obligate outcrossing species, in the western Amazon

The pollination of one of the most important NWFPs in the western Amazon, the Brazil nut (*Bertholletia excelsa*), could be affected by forest degradation. This species is regarded as an obligate outcrosser and is therefore dependent on pollinators, specifically bees, for reproduction and fruit set (Mori and Prance, 1990; Zuidema, 2003; Cavalcante *et al.*, 2012). Brazil nuts have high economic value, both locally and nationally; they have been an essential source of income for local people since the early 1900s (Mori and Prance, 1990; Zuidema, 2003; Ribeiro *et al.*, 2014; Rockwell *et al.*, 2015) and a significant contributor to the gross domestic product of Bolivia (Plurinational State of), Brazil and Peru. The nut is harvested almost entirely from the wild and can also play an important role in the economic viability of sustainable natural forest management (Mori and Prance, 1990). Brazil nut trees are legally protected from felling in Bolivia (Plurinational State of) and Peru (Mori and Prance, 1990; Cronkleton, Guariguata and Albornoz, 2012; Rockwell *et al.*, 2015); nevertheless, there is pressure on Brazil nut tree populations. Forest degradation through (for example) logging, agricultural expansion and mining may affect the visitation frequency of Brazil nut tree pollinators, which depend on old-growth forests. This would reduce fruit production (Zuidema, 2003), with implications for local livelihoods and regional economies (Kainer, Wadt and Staudhammer, 2007; Ribeiro *et al.*, 2014). Little is known, however, about the impacts of forest degradation on the visitation frequency of Brazil nut pollinators (Zuidema, 2003; Kainer, Wadt and Staudhammer, 2007; Ribeiro *et al.*, 2014).

**Case study 34.**

## Forest practices could be crucial for ensuring pollination services for the economically important açaí palm in the Amazon River delta

The açaí fruit is an important source of income for about 25 000 forest-dependent people in the Amazon River delta. It has considerable market value, generating revenues of USD 149 million per year. Because of this high value, açaí farms have been established in upland (*terra firme*) areas and floodplains, leading to landscape-scale changes that could affect pollination. Campbell, Carvalheiro *et al.* (2018) compared flower-visitor communities and fruit production in floodplain forests and upland plantations in the state of Pará, Brazil, taking into consideration factors such as management intensity (i.e. açaí density per ha) and amount of forest cover. The relative contribution of biotic pollination and degree of pollen limitation were assessed using insect exclusion and hand-pollination experiments.

The study found that açaí-flower visitors are highly diverse (c. 200 distinct taxa), with

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continued

variable responses to disturbance. Bee visitation was higher on the floodplains and positively related to surrounding forest cover, but other flower visitors, including specialized curculionid beetles, were unresponsive to changes in surrounding forest cover. High açaí palm densities on floodplains and in uplands had contrasting effects on flower-visitor communities, with flower-visitor richness lower on intensively managed floodplain farms and ant densities higher on intensive upland farms. Pollination experiments showed that açaí palm is highly dependent on biotic pollination. Fruit set in open-pollinated inflorescences was positively related to flower-visitor richness and specialized curculionid beetle visitation, whereas the presence of ants on inflorescences had a negative effect. The study by Campbell, Carvalheiro *et al.* (2018) showed that pollinators are essential for açaí fruit production but that intensive farming practices have eroded the relationship between surrounding forest cover and ecosystem function in floodplains (i.e. the conversion of native forest into simplified agroforests) and increased the frequency of antagonistic interactions in uplands (e.g. high ant densities). According to the authors, their findings underline the value of extensive management practices, such as the maintenance of other tree species within farms and adjacent unmanaged forest patches, to ensure the long-term sustainability of açaí fruit production in the Amazon River delta. Land managers should encourage the establishment and maintenance of diverse tree species on farms and the conservation of natural forests at the landscape scale.

©Juan Carlos Huarillapuma

**The plant–pollinator relationship between Brazil nut trees and *Xylocopa frontalis* in Madre de Dios, Peru.**

**Case study 35.**

### Impacts of the loss of keystone species and the unsustainable use of tree species related to non-wood forest products

Shackleton, Ticktin and Cunningham (2018) found that most studies of NWFPs focus on sustainable harvest levels, aim to understand only the utilitarian value, and overlook the ecosystem services that NWFPs may provide to other species in an ecosystem. Likewise, many studies assessing the impacts of people harvesting NWFPs rarely consider the effects of other processes or species (e.g. competitors and invasives) on the life-cycles of NWFP species at the individual or population scales.

Shackleton, Ticktin and Cunningham (2018) provide examples of how the decline of a keystone species in an ecological community can affect other species – to the extent that co-extinction can occur. The examples are: the extinction of a host plant species in Singapore that led to the extinction of its pollinating butterfly species; the loss of two pollinating bird species, which led to the reduced density and reproduction of the shrub *Rhabdothamnus solandri* in New Zealand; and 3) the harvest of latex and other plant exudates, which may affect colonial bees (e.g. stingless bees) that depend on the same exudates to build their hives. In the latter, there may also be a loss of access to the antibacterial – and antimicrobial – compounds in such exudates, including xanthones, terpenoids and benzophenones, all of which show beneficial effects against specific honeybee pathogens. Although the selective logging and latex harvesting of latex-producing species may affect the health of beehives, little research has been done on this. Nevertheless, there is evidence that disturbance and the harvesting of NWFPs can result in changes to insect-pollinator communities and plant–pollinator networks and affect the viability of keystone species.


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Solitary bees collect tree resin.

**Case study 36.**

### The harvest of bark and latex could affect pollination services in Brazil

Da Silva *et al.* (2018) explored the effects of the unsustainable harvesting of NWFPs on the reproductive capacity of tree species, focusing on latex and bark removal from *Himatanthus drasticus* and *Stryphnodendron rotundifolium* in the Araripe National Forest, Brazil. Both species are harvested for medicinal and commercial purposes: for *H. drasticus*, the bark is removed to obtain the latex produced by the tree, which is used to treat cancer, while, for *S. rotundifolium*, the bark itself is harvested for its anti-inflammatory, antimicrobial and gastroprotective properties. Although the two species have differing harvesting frequencies, harvest intensity is high for both because of their high commercial value. The study examined 30 individuals of each species, of which half were treated and the other half were used as a control. Height and diameter at breast height were recorded for each individual to determine the amount of bark that would be harvested (based on local practices). The harvest was performed on treated individuals two months before the flowering period.

Bark removal had negative effects on both species but the impact was higher for *H. drasticus*, with reductions in several reproductive parameters. Pollination mechanisms were affected because pollinators are less attracted to individuals with fewer inflorescences and flowers; treated *H. drasticu*s exhibited reduced pollen and seed production and consequently lower-quality seeds (as measured by weight and size). The differences in the response to harvesting between the two species may be explained by the way each allocates resources for the repair and production of removed tree material. The bark of *H. drasticus* is slow to regenerate because latex synthesis requires considerable energy; ultimately, less energy is available, therefore, for reproductive elements (e.g. the production of inflorescences and flowers). *S. rotundifolium* does not produce exudates and therefore needs only regenerate its bark, with consequent less effect on reproductive parameters. Nevertheless, it is also important to take into account differences between the two species in soil conditions and harvesting area. Bark and latex extraction can have considerable impacts on forest tree species and plant–pollinator interactions. The authors suggest that harvesting should be performed three months before the blooming period with the aim of reducing the negative impacts of harvesting on seed production and quality

## 3.6 SUMMARY OF CASE-STUDY FINDINGS

The findings of these case studies on pollinators and forest management can be summarized as follows:

*Indigenous and local knowledge systems*

- Much can be learned from traditional management practices and how indigenous and local people have adapted their management systems over time.

**Bark removal by a Shipibo woman for medicinal and natural pigment use in Ucayali, Peru.**

*Forest structure*

- Canopy openness (such as that caused by logging of various intensities) increases light penetration and thus enhanced regeneration of herbs and shrubs. This may change the plant community structure and enhance forage and nesting resources for pollinators and change associated pollinator communities.
- Canopy gaps lead to warmer temperatures at ground level, which may assist beetle larval development.
- Canopy gaps offer additional food sources for adult beetles, which forage on herbs and shrubs.
- Cavity-nesting bees that prefer rotting wood are likely to predominate in mature forests, while ground-nesting species are more likely to prefer logged and edge sites. Ground-nesting pollinators may benefit from an increase in the availability of nesting sites in forest clearings.
- A combination of habitats with varying canopy coverage may be beneficial for pollinators.
- Fire (see also below) burns most of the leaf-litter layer and thus exposes the forest floor, which is preferred by ground-nesting bees. The opening up of the canopy due to tree deaths caused by fire is commonly followed by an increase in the herbaceous layer, increasing floral resources and thereby benefiting pollinators.

*Disturbance and fragmentation*

- Disturbances promote habitat diversity and hence pollinator diversity at the landscape scale.
- Habitat fragmentation and degradation may lead to pollen limitation by reducing tree density and altering habitat conditions for pollinators, increasing the risk of inbreeding depression, with negative consequences for population viability.
- Nesting resources (e.g. dead wood, bare ground and early successional plants such as grass) are important determinants of bee community composition.
- Up to a point, increasing tree mortality (from Douglas fir beetle) in a Douglas fir forest had a positive effect on bee abundance, species richness and diversity. Tree mortality was associated with more open canopies and increased herbaceous cover, which favoured bee abundance and diversity.

*Understorey management*

- The removal of ground debris that exposes bare soil may provide additional nesting sites for ground-nesting bees.
- Mowing, weed control and fertilizer application may reduce understorey plant diversity, with potential impacts on the diversity of pollinator species.
- Understorey mowing alters plant species composition, with potential impacts on pollinator diversity and abundance. Mowing can also affect the egg and larval stages of pollinators.
- Managers may reduce the impacts of mowing on pollinators by retaining unmown refuges and timing mowing to reduce impacts during heavy flowering events.
- In one study, bee species richness declined with increasing shrub cover and organic matter on the forest floor, which reduced the extent of herbs present and nesting sites for ground-nesting bees.
- Overlap in the diets of ungulates and bees in forests may supress pollinator populations, especially in the event of additional stressors such as drought that further reduce floral resources.

*Fire*

- Pollen limitation in a fire-tolerant shrub in post-wildfire unlogged sites was shown to be related to the high floral densities of potential competitors that emerged after fire.
- Floral and bee density and species richness have been found to be higher in post-wildfire logged areas than in post-wildfire unlogged sites due to increased resource availability.
- The opening up of tree canopies by fire-caused tree deaths can lead to an increase in the herbaceous layer, providing forage for various pollinators. Repeated prescribed fire has been associated with high abundance and diversity of bees and other flower-visiting insects.
- Early successional habitats following fire may support a larger number of bee communities as a result of increased floral resources immediately after fire. The

benefits of fire in terms of increased pollinator abundance and richness may decline over time, however.

- The responses of pollinators to fire may differ, depending on certain traits, and should be evaluated at lower taxonomic levels or according to traits. Fire could have detrimental effects if it occurs when pollinators are in a larval stage because of reduced mobility.
- Burning and mowing may reduce the presence of non-flowering forbs and thus increase the availability of ground-nesting sites, leading to higher bee abundance and richness.

*Dead wood*

- An increase in the volume of standing and lying dead wood can have a positive impact on pollinator diversity and abundance (e.g. on wood-nesting bees and beetles).
- Longicorn beetle diversity, occurrence and abundance have been observed to increase with increasing tree density, volume of dead wood and number of tree stumps and to decline with increasing canopy cover and tree species richness.

*Non-wood forest products*

- The harvesting of NWFPs can have negative impacts on insect pollinator communities and affect the viability of keystone species and plant–pollinator networks.
- Most plants that produce NWFPs are obligate outcrossers, and reduced gene flow due to a decline in animal-assisted pollination could therefore reduce fruit set and production.

# 4. Knowledge gaps

This chapter explores knowledge gaps and priority areas for follow-up research; provides a set of initial steps that forest and landscape managers should consider to safeguard pollinators in forests and landscapes; and outlines some of the initiatives underway to help in moving forward.

Because pollinators operate across landscapes, understanding the gaps in existing knowledge is more difficult than may be assumed.[2] It is necessary to take into consideration the management of both forests and surrounding landscapes (which play important roles in managing pollination services). Forest management is not just about silviculture and timber harvesting, and it is not only done by foresters. Many actors are involved, and this needs to be considered when targeting stakeholders. Efforts should be made to draw on indigenous and local knowledge, and attention should also be paid to the role of local forest users at the landscape scale. Moreover, there is a need to shift to context-related approaches and to compile strong baseline data. It is not possible to be prescriptive in recommendations at a broad scale because the responses of pollinators are species- and context-specific. For example, fragmentation is a natural feature of certain African landscapes where scrubland is the matrix; in other tropical forests, fragmentation is the result of anthropogenic activities. The spatial and temporal scales at which studies are undertaken is crucial.

## 4.1 FOREST MANAGEMENT AND POLLINATION

The way in which forests are managed can have significant effects on pollinators. In general, however, there remain large knowledge gaps on the impacts of forest management practices and regimes on plant–pollinator interactions, the behavioural plasticity of (especially wild and native) pollinators, metapopulation dynamics, functional diversity, and pollination networks in landscapes. There is a lack of research at appropriate time scales (i.e. decadal), and the integration of multiple knowledge systems – especially indigenous and local knowledge – in forest management is only nascent and needs much more work. The development of effective management strategies is difficult in the absence of a greater understanding of these aspects. The complexity of plant–pollinator interactions and pollination mechanisms generally requires much more research.

An important knowledge gap exists on relationships between pollen limitation and plant recruitment as a result of reduced seed set. Pollen limitation might not be the main factor affecting seed set and therefore plant recruitment; rather, it could be a combination of factors that are characteristic of different forest types (e.g. related to nutrients and microsite availability). Clarity is needed on the effects of such factors

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[2] The section draws on the findings of a survey among 25 experts and institutions and a workshop involving about 40 experts.

on natural regeneration and genetic diversity in forests and how they might relate to pollen limitation. Long-term data (at the decadal scale) at key locations is imperative for understanding these aspects.

There is a lack of understanding of the recovery capacity of pollinator populations – most crucially for those species considered to be effective pollinators of economically and ecologically important plant species. Information is lacking on the indirect effects of pollen limitation on other organisms (e.g. animals feeding on fruits and seeds).

## 4.2 LANDSCAPE MANAGEMENT AND POLLINATION

It is imperative to understand the interactions of pollinators in forests and adjoining land uses at a landscape scale. There exists a large gap in understanding on metapopulation dynamics, functional diversity and pollination networks at the landscape scale across diverse management regimes (e.g. forest and landscape restoration, primary and secondary forests, and agroforestry systems) and connectivity within landscapes (related to foraging distance and nesting habitat). Knowledge on native pollinator species and their interactions with introduced species (e.g. honeybees) is patchy, especially on the spillover effects in adjacent landscapes.

Social aspects of land management can play important roles in pollination and are understudied. For example, land-use conflicts and land governance are important in determining the success of conservation efforts and in maintaining connectivity within landscapes. There is a lack of knowledge on mechanisms and approaches that could achieve synergies among different land uses, especially between conservation and agricultural production.

## 4.3 CLIMATE CHANGE

Changes in climatic conditions may alter the time, quality and duration of phenological events. It is likely that phenological mismatches between plants and pollinators will increase under climate change. The asynchrony of plant–pollinator interactions could be disastrous, especially for pollinator specialists. Few long-term studies exist on the status of pollinators that could provide data for projecting the impacts of climate change on pollinators.

## 4.4 THE EFFECT OF DECLINES IN POLLINATORS ON CROPS AND FOREST-BASED FOOD PRODUCTS

Inventories and quantitative data are lacking on pollinator-dependent wood and non-wood forest product species and on the economic value of pollination services related to these. It is difficult, therefore, to determine the extent to which a decline in forest pollinators could affect livelihoods and value chains that depend on wood and non-wood forest products. Some species have been identified as pollinator-dependent, but the pollination mechanisms, and how changes in these mechanisms might affect seed consistency, quality and density, are often unknown.

A clearer assessment on the contribution of NWFPs and forest-based products to local diets and nutritional security is needed.

Research on the impacts of pollinator declines in agricultural areas is well developed, but knowledge gaps exist related to pests, diseases, genetic diversity, the reliance of crops on specific pollinators, and the roles of native pollinator species and nearby forests (and forest quality) in crop pollination and yields. More work is required to tease out the importance of pollinators versus biotic and abiotic factors affecting crop production.

## 4.5 INDIGENOUS AND LOCAL KNOWLEDGE

Indigenous and local knowledge is still undervalued and underused in scientific research and management. Systematic reviews of grey and academic literature on indigenous and local knowledge, including in languages other than English, are needed to map existing and available knowledge. Increasing efforts to integrate indigenous and local knowledge into scientific research could help bridge knowledge gaps by incorporating long-term observations (e.g. on changes in fruit and seed production of tree and shrub species and changes in forests and associated pollinators over time). In general, there is a need to improve communication among fields of expertise and to integrate information systems accessible to the public, including participative research (e.g. citizen-science programmes).

# 5. Recommendations for landscape and forest managers

Despite existing knowledge gaps, entry points exist for more pollinator-friendly management. The following proactive measures for forest and landscape managers, which draw on the findings of this review, especially the case studies, could help in safeguarding pollinators in forests and landscapes. Note, however, that the most effective means for conserving pollinators are likely to be highly specific to local conditions, and ongoing research, monitoring and adaptive management will be essential.

## 5.1 POTENTIAL MEASURES AT THE LANDSCAPE SCALE FOR SAFEGUARDING POLLINATION SERVICES

- In landscape-scale planning (comprising natural, agricultural, urban and other land uses), aim to maintain key landscape components, such as specific species and habitat types, on which pollinators depend.
- Before major landscape change, survey existing pollinator species and obtain knowledge on the habitat requirements of individual pollinator species.
- Make efforts to draw on and learn from indigenous and local knowledge about pollinators and phenologies, and their management.
- In land management and at the landscape scale, take into account species-specific responses to land uses.
- Ensure habitat connectivity, including through agroforestry, the creation of biological corridors or stepping stones, and the retention of native vegetation, as a means to maintain pollinator diversity in landscapes.
- Ensure sufficient numbers and diversity of bird-pollinated tree species (i.e. feeder trees) in rural landscapes.
- Maintain sufficient solitary trees, groups of trees and agroforestry plantings to act as biological stepping stones and help increase connectivity between habitat fragments as a means to maintain diverse pollinator species in landscapes.
- Aim to enhance the density of floral resources, such as through practices designed to retain specific species groups, enrichment plantings to encourage pollinators, and landscape planning to include floral resources.
- Encourage the establishment and maintenance of diverse tree species on farms and the conservation of natural forests at the landscape scale.
- Maintain and, where necessary, increase landscape heterogeneity and patchiness to increase the diversity and connectivity of floral and pollinator-nesting resources.
- Maintain large riverine buffers and restrict access to these and activities such as

sand extraction from riverbanks and side bars and clearcuts of riparian vegetation. Riparian forests harbour unique flora and fauna and are important in providing various ecosystem functions.
- Develop approaches to promote pollinator habitat heterogeneity in landscapes.
- Undertake or encourage long-term studies to understand the impacts of natural disturbances on pollinator communities over time.

## 5.2 POTENTIAL MEASURES AT THE FOREST SCALE FOR SAFEGUARDING POLLINATION SERVICES

- Establish a baseline of pollinator diversity and abundance and monitor these over time, including the impacts of management practices.
- Where fire is used as a management tool, maintain a mosaic of burned and unburned pollinator habitat to ensure the rapid repopulation of burned areas by pollinator insects.
- Ensure that the frequency of burning forest understoreys does not exceed the rate of recolonization of burned areas by pollinators.
- Develop field guides for pollinator management based on knowledge of the biological attributes of pollinator species in an area and flowering phenology and synchrony.
- Make efforts to draw on and learn from indigenous and local knowledge about pollinators and phenologies, and their management.
- Employ forest management practices such as selective logging, thinning, prescribed burning, mowing and coppicing in ways that increase the heterogeneity of tree communities, based on knowledge of how this is likely to benefit pollinators as well as other forest biodiversity.
- In planning forest management, consider the need for temporal (as well as spatial) habitat heterogeneity, especially in understoreys, taking into account the requirements of multiple life stages of pollinator species, from larvae to adults.
- Retain dead standing and lying wood in forests and ensure sufficient bare ground for cavity-nesting and ground-nesting bees, respectively, based on the best available knowledge of pollinator requirements in the area.
- Study the impacts of forest management practices on pollinator diversity and abundance.
- Regulate the grazing of domestic and wild ungulates in forests to minimize competition for floral resources between those ungulates and wild pollinators.
- Where mowing is employed, reduce its negative impacts on pollinators by retaining unmown refuges and timing mowing to minimize disturbance during heavy flowering events.
- Ensure adequate understanding of the modes of pollination and the contributions of insects to the pollination of NWFPs to enable appropriate management measures.
- Consider the potential impacts on local pollinator species of the introduction or expansion of non-native species.

- Harvest bark, latex and resins well in advance of tree blooming periods to reduce negative impacts on pollinators and pollination services.
- Consider the potential negative consequences of alternatives to mowing, such as herbicide application, as management options for weed control.
- In restoring degraded forests, aim to establish tree species at densities sufficient to enable their effective pollination.
- Conserve cavity-bearing trees in managed forests and maintain areas of unmanaged forest (which generally host far more tree cavities than their managed counterparts) as a means to safeguard and sustain wild native honeybee populations.
- Conserve bat roosting sites, which may not be confined to forests.

## 5.3 MOVING FORWARD

Developing pollinator-friendly policies in the forest and agriculture sectors should be a high priority. There is a need to integrate scientific knowledge and to increase understanding of desirable pollination-related outcomes, such as resilient pollination services; diverse pollination services; and the amelioration of climate-change impacts on pollination services. Existing policies for addressing pollination services tend to have minimal impact, and increasing the impact requires creating dialogue across sectors and among stakeholders – especially because goals are constantly shifting and more knowledge flow is needed to adapt policies and management practices. Interactions between forest and landscape management and pollinator services are highly contextual, and prescriptive guidelines will not be useful. There is a need to fill important knowledge gaps and to develop baselines to better inform practitioners and policymakers and enable adaptive management. Therefore, generating relevant knowledge and data should continue to be a priority, especially at the landscape scale and on trade-offs between approaches. Better baseline data on pollinator abundance and distribution will be important for increasing knowledge flow between sectors and evaluating the impacts of management on pollination services.

Raising awareness and building capacity will be important. The aim should be to build stronger baselines on pollinator species status and trends (i.e. a diversity focus) and to address the knowledge gaps identified in this report. This would enable the development of evidence-based best practices and toolkits, which should be context- and location-dependent. Developing certainties and uncertainties around specific management actions and their impacts on pollination could be a useful way forward. To better integrate scientific information into policies, an understanding is needed of existing policies and what they address. A survey could be conducted to gather data on existing policies that address – either directly or indirectly – pollination services.

In addressing the needs and challenges of stakeholders and actors, the focus should be on those with the greatest impact at the landscape level – such as forest managers, farmers, pastoralists and urban planners. Attention should also be paid to the large-scale private sector, the crop yields and seed systems of which are highly dependent on the maintenance of pollination services. There is a need to explore the role of payments for pollination services and other economic models to support pollinator-friendly landscape management. Moreover, the increasing need for the restoration of degraded forest landscapes will require attention to native-plant seed systems. Other relevant actors often overlooked in the context of forest management are beekeepers.

Connecting the various initiatives on forest pollination services is essential for optimizing the flow of scientific information and the development of follow-up activities. These include various FAO-involved initiatives, such as the Biodiversity Mainstreaming Platform or the Global Action on Pollination Services for Sustainable Agriculture[3] and the International Pollinators Initiative 2.0,[4] as well as regional and national-level initiatives, or other efforts to raise awareness of the role of forest biodiversity for other agricultural sectors. An important step will be to develop general guidelines and protocols based on existing knowledge for ensuring pollinator-friendly forest and landscape management practices. The aim should be to establish a dynamic guide for forest and land managers and practitioners that can be updated periodically in light of new knowledge and experiences.

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[3] www.fao.org/biodiversity/mainstreaming-platform

[4] www.fao.org/pollination/major-initiatives/international-initiatives

# 6. Glossary

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| **Alpha diversity** | The average or mean species diversity in a site or habitat at a local scale |
| **Beta diversity** | The diversity of species between two habitats or regions, based on the ratio between alpha (local) and regional diversity |
| **Community structure** | The composition of a community in terms of the number of species and their relative numbers |
| **Cross-pollination** | The transfer of pollen between flowers of different plants of the same species. The pollen transfer may be via animals (e.g. insects, birds and bats), wind and water |
| **Biodiversity** | The variety of life forms, the ecological roles they perform and the genetic diversity they contain |
| **Biological stepping stones** | Discrete and typically small habitat patches within a matrix that enhance the connectivity of a species in a fragmented landscape |
| **Ecological redundancy** | The phenomenon in which multiple species representing a variety of taxonomic groups share similar, if not identical, roles in ecosystem functionality |
| **Ecotone** | A transitional area between two adjacent ecological communities or biomes |
| **Eusocial** | Organisms living in colonies in which the care of broods is done cooperatively and individuals are divided into reproductive and non-reproductive (or at least less-reproductive) castes |
| **Feral bees** | Managed bees that have escaped into wild habitats |

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| **Foraging habitat** | The area used by organisms in searching for wild food resources |
| **Forest management** | Practices that are planned and implemented for using forests and other wooded lands to meet certain economic, social, environmental and cultural objectives or standards |
| **Fragmentation** | The process of transforming large continuous forest patches into one or more smaller patches, creating areas of geographical discontinuity |
| **Fruit set** | The proportion of flowers that develop into fruits |
| **Gene flow** | The exchange of genes between populations |
| **Generalists** | Organisms that have a varied diet and can live in many types of environment |
| **Genetic diversity** | The sum total of genetic differences between and within species |
| **Guild** | A group of species with similar habitat requirements and which play similar roles in an ecological community |
| **Landscape attributes** | The basic elements or units that make up a landscape and which may change over time |
| **Landscape connectivity** | The degree to which a landscape facilitates or impedes movement among resource patches |
| **Landscape mosaic** | A heterogeneous area composed of different communities or a cluster of different ecosystems |
| **Larval host** | An organism (plant/animal) that provides food or shelter to larvae, inside or near its body, in a symbiotic or parasitic relationship |
| **Matrix** | The habitat with the dominant role in the functioning of a fragmented landscape |
| **Meta-analysis** | A statistical procedure for combining and analysing data from multiple studies |

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|---|---|
| **Metapopulation** | A group of populations of the same species coexisting in time but not space |
| **Mixed-mating plants** | Hermaphrodite plant species (i.e. plants, the flowers of which have both male and female parts) that can reproduce by both self- and cross-fertilization |
| **Nesting habitat** | The area used by organisms as nesting sites |
| **Outcrosser/outcrossing plant species** | A plant species that is self-incompatible and therefore depends on fertilization with pollen from a separate plant to set fruit |
| **Plant–pollinator network** | The mutualistic interaction of different pollinators and native plant species |
| **Pollination** | The transfer of pollen from the anther of a flower to the stigma of that or another flower |
| **Pollinator** | A living organism (e.g. insect, bird or mammal) that provides pollination services by transferring pollen |
| **Progeny vigour** | The measured growth, performance or survival of offspring |
| **Resilience** | The capacity of an ecosystem to respond to a perturbation or disturbance by resisting damage and recovering quickly |
| **Seed set** | The proportion of ovules that develop into seeds |
| **Self-fertilization** | The pollination of a flower by pollen from the same flower or from another flower from the same plant |
| **Species composition** | The identity of all the organisms that form part of a community |

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