The assessment report on

POLLINATORS, POLLINATION AND FOOD PRODUCTION

OF THE INTERGOVERNMENTAL SCIENCE-POLICY PLATFORM ON BIODIVERSITY AND ECOSYSTEM SERVICES

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CHAPTER **6**

RESPONSES TO RISKS AND OPPORTUNITIES ASSOCIATED WITH POLLINATORS AND POLLINATION

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CHAPTER 6

ECONOMIC VALUATION OF POLLINATOR GAINS AND LOSSES

EXECUTIVE SUMMARY

Loss of diversity of wild pollinators is a worldwide problem that generates risks for food production and society (*established but incomplete*). There is evidence from some parts of the world that it is associated with crop pollination deficits at local scale, loss of wild plant diversity, and loss of distinctive ways of life, cultural practices and traditions. There is global evidence of greater crop yield instability in insect-pollinated crops than in those that don't require pollination or are wind-pollinated (*well established*). These risks are largely driven by changes in land cover and agricultural management systems, including pesticide use (*established but incomplete*) (6.2.1).

Many responses are available that can reduce these risks of pollination deficit in the short term, including land management to conserve pollinator resources, decreasing pollinator exposure to pesticides, and improving managed pollinator techniques (*well established*). These include technical, knowledge, legal, economic, social and behavioural responses that are available in literature and in the traditions of people around the world (6.4).

Modifying farming practices can benefit pollinators on farms (*well established*). Retaining or creating patches of vegetation, including small areas (e.g. patches that are only meters across) helps to retain pollinator species in agricultural areas (*well established*). For example, planting flower strips near pollinator-dependent crops increases local numbers of foraging pollinating insects (*well established*) and improves yields through increased pollination (*established but incomplete*). However, potential negative impacts, through increased exposure to pesticides when pollinator numbers are concentrated in field margins, have not been explored (*inconclusive*). Due to a lack of long-term data, there is no direct evidence yet that these responses lead to long-term increases, or stabilise pollinator populations (*inconclusive*).

Protection of larger areas of semi-natural or natural habitat (e.g., tens of hectares or more) helps to maintain pollinator habitats at regional or national scales (*established but incomplete*), but will not directly support agricultural pollination in areas that are far (> a few kms) from large reserves because of the limited flight ranges of crop pollinators (*established but incomplete*). Enhancing connectivity at the landscape scale, for example by linking habitat patches (including with road verges), may enhance pollination of wild plants by enabling movement of pollinators (*established but incomplete*), but its role in maintaining pollinator populations remains unclear. Theory and observations for other taxa suggest that when the amount of natural habitat in the landscape declines below approximately 20%, pollinator populations are at risk of becoming isolated and connectivity may play an important role in their conservation (6.4.3.1.1, 6.4.3.1.2, 6.4.5.1.6).

Organic farms support more species of wild pollinators than non-organic farms, but evidence comes mostly from Western Europe and North America (*well established*). Pollination to crops are also enhanced on organic farms (*established but incomplete*). Increases in wild pollinators are less likely to occur in response to organic farming in landscapes that are already rich in non-farmed habitats (*well established*). There is some evidence that high-yielding organic farms do not support more pollinators, which suggests that the differences usually seen between organic and conventional farms are not related to the organic status per se but to specific strategies practiced on some organic farms (*established but incomplete*) (6.4.1.1.4).

Schemes that offer farmers short-term payments for prescribed environmental management – called agri-environment schemes – can include actions known to increase numbers of foraging pollinators, or pollinator species, on land under the scheme (*well established*). For example, organic farming, and planting or retaining flower-rich habitat, are supported under many European agri-environment schemes. Financial support for such activities is important, when these activities invoke labour and opportunity costs to landholders (*well established*) (6.4.1.1, 6.4.1.3).

Three complementary strategies are envisaged for producing more sustainable agriculture that address several important drivers of pollinator decline: ecological intensification, strengthening existing diverse farming systems and investing in ecological

infrastructure. These strategies concurrently address several important drivers of pollinator decline by mitigating against impacts of land use change, pesticide use and climate change. The policies and practices that form these strategies have direct economic benefits to people and livelihoods in many cases (*established but incomplete*). This is in contrast to some of the options for managing immediate risks, such as developing crop varieties not dependent on pollination, which may increase vulnerability to pests and pathogens due to reduced crop genetic diversity (*inconclusive*) (6.2.2, 6.9, 6.4.1.1.8, 6.4.1.1.12, 6.4.2.1.2, 6.4.4.1, 6.4.4.3, 6.9).

Strategies to adapt to climate change may be necessary to secure pollination for agriculture in the long term (*established but incomplete*), although the impacts of ongoing climate change on pollinators and pollination services and agriculture may not be fully apparent for several decades owing to delayed response times in ecological systems (*well established*). Adaptative responses to climate change include increasing crop diversity and regional farm diversity, and targeted habitat conservation, management and restoration. The effectiveness of these strategies at securing pollination under climate change is untested and likely to vary significantly between and within regions (*inconclusive*) (6.4.1.1.12, 6.4.3.1.2, 6.4.4.1.5, 6.5.1.10.2, 6.8.1).

Non-agricultural lands, both urban and rural, hold large potential for supporting pollinators, if managed appropriately. Increasing the abundance of nectar and pollen-providing flowering plants in urban or peri-urban green spaces such as parks, sport fields, gardens, and golf courses increases local pollinator diversity and abundance (*established but incomplete*). Many cities actively conserve and restore natural habitat for pollinators in such spaces. Other land uses including road verges, power line corridors, railway banks, and vacant land in cities hold large potential for supporting pollinators, if managed appropriately to provide flowering and nesting resources (*inconclusive*). This has been implemented in some areas, such as parts of the United States. A few studies demonstrate increased pollinator numbers on the managed areas, and one study found road verges help maintain genetic connectivity in a bird-pollinated plant (*established but incomplete*). There are possible negative impacts from pollinators feeding on road verges, such as metal contamination, which have not been fully explored (*established but incomplete*) (6.4.5.1).

Reducing risk by decreasing the use of pesticides is a central part of Integrated Pest Management (IPM) and National Risk Reduction programs promoted around the world. Many of the practices that comprise IPM, such as mixed cropping and field margin management, have co-benefits for pollinators (*well established*). Education and training for land managers, farm advisers, pesticide appliers and the public are necessary for the effective implementation of IPM, and to ensure correct and safe use of pesticides, in agricultural, municipal and domestic settings (*established but incomplete*). Exposure of pollinators to pesticides can also be reduced by a range of specific application practices, including technologies to reduce pesticide drift (*well established*) (6.4.1.1, 6.4.2.1.3, 6.4.2.4.2).

Risk assessment can be an effective tool for defining pollinator-safe uses of pesticides, and subsequent use regulations (including labelling) are important steps towards avoiding mis-use of specific pesticides that can harm pollinating insects (*well established*). Overall, the environmental hazard from pesticides used in agriculture is decreased at national level by risk assessment and use regulations (*established but incomplete*). Other policy strategies that can help to reduce pesticide use, or avoid mis-use, are supporting farmer field schools, which are known to increase adoption of IPM practices as well as agricultural production and farmer incomes (*well established*), and applying global codes of conduct (*inconclusive*). The International Code of Conduct on Pesticide Management of the Food and Agriculture Organization and the World Health Organization of the United Nations provides a set of voluntary actions for Government and industry to reduce risks for human health and environment; sixty-one per cent of countries surveyed (31 countries) are using the code, based on a survey from 2004 and 2005. Investment in independent ecological research on population-level effects of pesticides on pollinators in real agricultural landscapes would help resolve the uncertainties surrounding the risk of pesticides to pollinators and pollination. Risk assessments required for approval of genetically modified organism (GMO) crops in most countries do not adequately address the direct sublethal effects of insect-resistant (IR) crops or the indirect effects of herbicide-tolerant (HT) and insect-resistant (IR) crops, partly because of a lack of data. Extending monitoring and risk-indication of the environmental and biodiversity impacts of pesticides and GMOs specifically to include wild and managed pollinators (monitoring schemes exist in many countries) would improve understanding of the scale of the risks (*established but incomplete*) (6.4.1.5, 6.4.2.1, 6.4.2.4.1, 6.4.2.4.2, 6.4.2.2.6, 6.4.2.6.1, 6.4.2.6.2).

Preventing new invasions of species that harm pollinators (i.e., competitors, diseases, predators) and mitigating impact of established invaders can be more effective than attempting eradication (*established but incomplete*). There is case-study evidence of benefits to pollinator species or pollination of native plants from efforts to reduce numbers of invasive insect species in Japan and Hawaii (6.4.3.1.4).

Better regulation of the movement of all species of managed pollinators around the world, and within countries, can limit the spread of parasites and pathogens to managed and wild pollinators alike and reduce the likelihood that pollinators will be introduced outside their native ranges and cause negative impacts (*established but incomplete*). For example, Australia has strict biosecurity policy around honey bees and has avoided establishment of *Varroa* mites. Most countries have not regulated movement of managed pollinators other than honey bees (6.4.4.2). Movement regulation can also prevent or limit problems arising from pollinators being introduced outside their native range (*established but incomplete*).

While pollinator management by people has developed over thousands of years, there are opportunities for substantial further innovation and improvement of management practices (*well established*). These include better management of parasites and pathogens (*well established*); selection for desired traits (*established but incomplete*) and breeding for genetic diversity (*inconclusive*); pollinator symbionts, including both micro- (*established but incomplete*) and macro-organisms (*inconclusive*); and pollinator diet, including enhanced resource provision at the individual, colony, and landscape scales (*established but incomplete*). Development programs focusing on beekeeping skills, both for European honey bee and other species, can improve the value and benefits associated with these practices (*established but incomplete*) (6.4.4.1).

Disease and parasite pressures threaten managed pollinators (*well established*) and while a range of prevention and treatment options are available (*well established*) there are many opportunities to improve pollinator health outcomes through training, technology development and research. For example, there are no proven options for treating viruses in any managed pollinator species, but RNAi technology could provide one pathway toward such treatment (*established but incomplete*). *Varroa* mites, a key parasite of honey bees, have developed resistance to some chemical treatments (*well established*) so new treatment options are required (6.4.4.1, 6.4.4.5).

New managed pollinator species could contribute to agricultural pollination but incur a risk of disease transfer to wild populations and species invasions (*well established*). For example, the development of commercial bumble bee rearing and management has transformed the cultivation of several crops in glasshouse settings but there have been disease impacts on wild pollinators (*well established*) (6.4.4.1.8).

Long-term monitoring of wild and managed pollinators and pollination can provide crucial data for responding rapidly to threats such as pesticide poisonings and disease outbreaks, as well as long-term information about trends, chronic issues and the effectiveness of interventions (*well established*). Such monitoring would address major knowledge gaps on the status and trends of pollinators and pollination, particularly outside Western Europe. Wild pollinators can be monitored to some extent through citizen science projects focused on bees, birds or pollinators generally (6.4.1.1.10, 6.4.4.5, 6.4.6.3.4).

Strategic initiatives on pollinators and pollination can lead to important research outcomes and national policy changes (*established but incomplete*). Fundamental and applied research on pollinators can generate findings of real policy relevance, especially when the research is designed to answer questions posed by policy makers, land managers and other stakeholders (*well established*) (6.4.6.3.2, 6.4.6.2.2).

Education and outreach projects focused on pollinators and pollination that combine awareness-raising with practical training and opportunity for action have a good chance of generating real behaviour change, and there is direct evidence for this in a small number of cases (*established but incomplete*). There are very many pollinator-focused education and outreach projects around the world. Most are relatively new (within the last five years) and so effects on broader pollinator abundance and diversity might not be seen yet (6.4.5.1, 6.4.6.3.1).

Tools and methods are available to inform policy decisions about pollinators and pollination including risk assessment, cost-benefit analysis, decision support tools and evidence synthesis. All of those except evidence synthesis require further method development and standardisation (*well established*). Other available tools that are well developed but not yet used specifically for pollinators include environmental accounting and multi-criteria analysis. Maps of pollination seem useful for targeting interventions to areas according to service valuation or service supply, but available maps at national or larger scales may be unreliable, because they have not been tested to find out if they accurately reflect actual pollination of crops or wild flowers (*established but incomplete*) (6.5.14, 6.5.9).

There remain significant uncertainties regarding pollinator decline and impacts on agriculture and ecosystems (*well established*). Decisions about how to reduce risks can be improved if uncertainty is clearly recognised, characterised and communicated (*well established*). Some sources of uncertainty are unavoidable, because there is inherent unpredictability in natural ecosystems and human economies. Other sources of uncertainty, such as limited data availability, human preferences and lack of clarity about concepts, can be more easily reduced, once recognised, by increasing the accuracy of information at the appropriate scale (6.4.2.2.4, 6.6).

There are both synergies and trade-offs among pollinator-related responses and policy options (*well established*). An example of synergy is that creation and conservation of pollinator habitats can enhance wider biodiversity (*well established*), as well as several ecosystem services including natural pest control (*established but incomplete*), soil and water quality, aesthetics, and human cultural and psychological values (*inconclusive*). An example of a trade-off is that organic farming benefits pollinators, but in many (not all) farming systems, current organic practices usually produce lower yields (*well established*). This trade-off may be minimised by supporting research into ecological intensification to help enhance organic farm yields without losing the pollination benefits, or by encouraging organic farms in less-productive agricultural landscapes, where yield differences between organic and conventional agriculture are lower (*inconclusive*) (6.4.1.1.4, 6.4.1.1.11, 6.7).

6.1 INTRODUCTION AND OUTLINE

This chapter reviews possible responses to the risks and opportunities associated with pollinators and pollination. By responses, we mean actions, interventions, policies or strategies designed to support pollinators or mitigate against pollinator decline, carried out at any scale by individuals or organisations.

We first summarise what the risks and opportunities are, in section 6.2. Responses to these can be categorised in various ways. We have grouped them according to the type of response (technical, legal, economic, social/behavioural and knowledge), as explained in section 6.3.

The responses are organised by sector in section 6.4, and listed in a table for each sector, with a summary of relevant information. The sectors are agriculture, pesticides, nature conservation, pollinator management & beekeeping, and urban & transport infrastructure. Pesticides are separated from agriculture in our structure because these two areas are often separated in policy. Responses that cut across these sectors, such as broad policy initiatives, research, education and knowledge exchange, are presented in section 6.4.6. For each possible response, we identify whether it is proposed, tested or established, and summarise existing knowledge about whether the response is known to achieve its objectives, with a particular focus on its effects on pollinators or pollination.

Section 6.5 provides an overview of the tools and methods that have been used to understand and compare alternative responses. Section 6.6 examines the problem of uncertainty, and ways of accommodating it in decision making. Section 6.7 describes what is known about trade-offs between different possible responses. Section 6.8 identifies knowledge gaps. Appendix 6A describes the methods and approaches used to write this chapter, including how the list of considered responses was developed.

Public policy has a significant role in shaping and implementing responses. The development and implementation of policy over time is often described in terms of a ‘policy cycle’ **(Figure 6.1)**. The ways in which scientific, indigenous and local knowledge are used during the policy cycle, and incorporated into policy, are complex and much discussed (for example, Juntti *et al.*, 2009; Owens, 2012; Dicks *et al.*, 2014). Relevant knowledge must be provided at the correct point in the policy cycle, if it is to be useful to policy makers, but the likelihood of its actual use also depends on economics, politics, governance and decision-making processes unique to each specific context. As a general guide, the scientific, indigenous and local knowledge reviewed in Chapters 4, 5 and 6 are most useful for policy **formulation, implementation** and **evaluation**. Knowledge from Chapters 2, 3 and 5 is most useful for **agenda setting**, which involves identifying problems that require a policy response.

Pollinators and pollination are relevant concerns in a range of policy areas, demonstrated by review of relevant legislation (Tang *et al.*, 2007) and by discussion with policy makers (Ratamäki *et al.*, 2011; Rose *et al.*, 2014). The important policy areas, and the subsections of this chapter that discuss possible policy responses, are:

- Agriculture and public health (section 6.4.1)
- Pesticide regulation (section 6.4.2)
- Biodiversity and ecosystem services (section 6.4.3, services related to food crops in 6.4.1)
- Animal health and international trade (section 6.4.4)
- Transport and infrastructure (section 6.4.5)
- Climate change and energy (some responses reviewed in 6.4.1)

A number of theoretical frameworks have been proposed to help understand what drives policy change, but there is no clear overarching framework (Sabatier and Wiebel, 2013) and no specific research has examined the development of pollinator-related policies. Drawing on the examples collated in this report, scientific knowledge can be an important driver, as in the example of the Brazilian Pollinators Initiative (see section 6.4.6.2.2). On the other hand, pollinator-related policy could change or be developed in response to a combination of science, public opinion and political opportunity, as has perhaps been the case for pollinator strategies developed in the UK (section 6.4.6.2.2; Dicks *et al.*, 2015).

Rose *et al.* (2014) suggest opportunities to 'mainstream' pollinator conservation and management in policy. 'Mainstreaming' means ensuring that impacts of policies on pollinators and pollination are considered during policy formulation and implementation in all relevant sectors (Maes *et al.*, 2013). The Sustainable Development Goals (http://www.un.org/sustainabledevelopment/sustainable-development-goals/), the Convention on Biological Diversity (www.cbd.int) and the Committee on World Food Security (http://www.fao.org/cfs/cfs-home/en/) are highlighted as opportunities to mainstream consideration of pollinators and pollination. The Aichi targets of the Convention on Biological Diversity (www.cbd.int/sp/targets/) also demand incorporation of pollinators and pollination into policy. Target 2 on integrating biodiversity values in strategies and processes, Target 7 on sustainable agriculture and Target 14 on restoring and safeguarding ecosystem services are particularly relevant to pollinators and pollination.

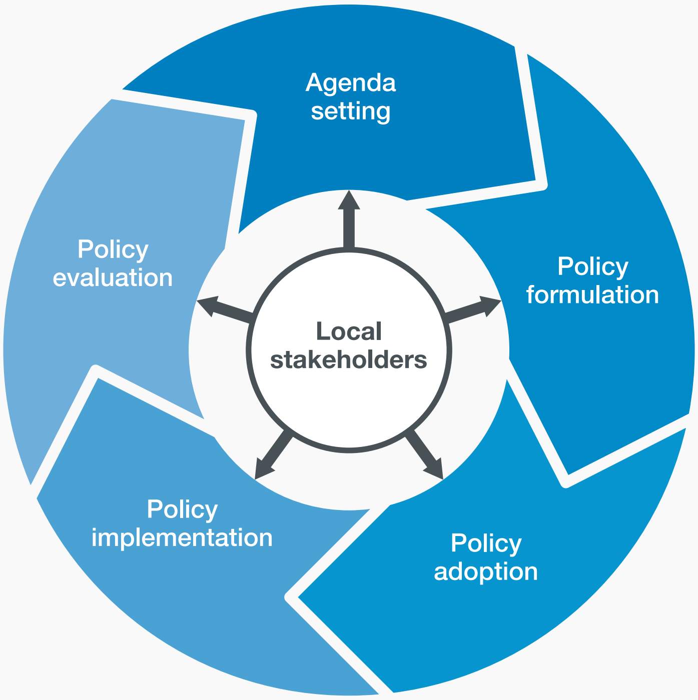
6.2 SUMMARY OF RISKS AND OPPORTUNITIES ASSOCIATED WITH POLLINATORS AND POLLINATION

We take a scientific-technical approach to risk, from a realist and individual-level perspective. This assumes that the risks are real, and they are perceived and responded to independently by individuals, with no consideration of cultural factors or social norms. From this perspective, a risk is usually understood as the probability of a specific hazard or impact taking place. A common way to evaluate a risk is to estimate both the probability and the size or scale of the impact. We have not considered sociological or psychological understandings of risk (Taylor-Gooby and Zinn, 2006). While the cultural framing of risk perceptions and responses is clearly important in the context of pollinators and pollination, we did not find any research or relevant knowledge that would allow us to evaluate its influence critically.

An opportunity is a time or set of circumstances that make it possible to do something. The clearest opportunities

FIGURE **6.1**

A simplified representation of the 'policy cycle', the iterative decision-making process by which public policy is developed and revised. Local stakeholders, particularly local people and businesses, are involved at every stage. See text for a discussion of how scientific and local and indigenous knowledge are incorporated.



associated with pollinators and management of pollination arise when there are direct economic benefits to taking action.

The potential impacts and opportunities listed in **Table 6.2.1** have been defined through deliberation and discussion among the report authors (including Chapters 1 to 5).

A risk assessment for the economic, social and environmental impacts of pollinator decline would require both the probability and the scale or magnitude of each of the impacts listed in **Table 6.2.1** to be assessed, and preferably quantified in some way. Given the substantial knowledge gaps regarding the status, trends and drivers of change in pollinators in most regions of the world (see Chapters 2 and 3), this has not been possible. Here we provide a brief overview of what is known about the risks posed by the direct impacts.

TABLE **6.2.1**

A summary of the main potential impacts of pollinator decline, and opportunities associated with pollinators and pollination

Potential impacts of pollinator decline	Opportunities created by sustainable management of pollinators and pollination
Production of food (and other products)	
Direct impacts on food production	
Crop pollination deficit leading to lower quantity or visual/nutritional quality of food (and other products, such as fibre, fuel or seeds). Crop yield instability due to loss of pollinators or change in pollinator communities. Fall in honey production (and other hive products) due to declining honey/stingless bee numbers. Decline in long term resilience of food production systems. Decline in yields of wild fruit, harvested from natural habitats by local communities. Reduced availability of managed pollinators.	Improved or more stable yield in the long term, at lower cost. Reduced dependence on managed pollinators due to more reliable pollination service delivery by natural ecosystems. Reduced financial risk due to diversified income streams through more crop types. Product premium from a more sustainable approach to farming or beekeeping. Increased production of good quality honey and other bee products. Enhancement of other ecosystem services, particularly natural pest regulation/biocontrol.
Indirect impacts on food production	
Decline in dairy and meat production due to decline in forage quality (includes cattle feeding on sown clover or soya forage, for example, or camels browsing on legumes). Decline in nutritional quality of human diets (vitamin content etc.) due to increasing prices or falling quality of animal-pollinated food products and honey. Price changes and changes in demand, in response to yield changes. More land conversion required as yields decline. Loss of income/livelihoods for growers of pollinator dependent crops.	More economically sustainable agriculture for the long term (for example, a more diverse pollinator community enables a broader range of responses to climate or other environmental change).
Biocultural diversity	
Direct biocultural diversity impacts	
Loss of wild pollinator diversity. Loss of wild plant diversity due to pollination deficit. Loss of aesthetic value, happiness or well-being associated with wild pollinators or wild plants dependent on pollinators. Loss of distinctive ways of life, cultural practices and traditions in which pollinators or their products play an integral part.	Maintenance of wild pollinator and plant diversity. Improved conditions and habitats for other species (entire ecological communities). Decreased risk of long range disease transfer and invasion by non-native species. Maintenance of aesthetic value, happiness or well-being associated with wild pollinators or wild plants dependent on pollinators. Maintenance of distinctive ways of life, cultural practices and traditions in which pollinators or their products play an integral part.
Indirect biocultural diversity impacts	
Increase disease incidence in wild and managed pollinator populations. Increased incidence and spread of invasive species due to transport of pollinators by humans. Ecosystem instability due to loss of plant-pollinator interactions (includes, for example, reduced availability of food for other animals due to lack of fruits and seeds). Decreased economic or dietary self-sufficiency of indigenous peoples leading to loss of sovereignty. Loss of biological resources for research (for example, medicines based on bee products, or aerial robots based on bee flight).	Maintenance of pollinators as biological resources for research (for example, to develop medicines based on bee products, or aerial robots based on bee flight).

6.2.1 An overview of direct risks associated with pollinator decline

Table 6.2.2 summarises the evidence included in this assessment for each of the direct impacts listed in **Table 6.2.1**, including whether and where the impact is known to be happening. Based on this information, we categorise the direct impacts into those that pose an immediate risk to people and livelihoods at least somewhere in the world (**immediate risk**), those that do not pose an immediate risk but could develop in the longer term (**future risk**), and those for which we do not have sufficient knowledge to assess the risk, even conceptually (**unknown**).

6.2.1.1 Linking risks to drivers

Table 6.2.3 shows the main drivers associated with the risks identified. The drivers listed are those most frequently selected as one of the 'two or three main drivers' by the Lead Authors and Co-ordinating Lead Authors, in an anonymous individual consultation exercise. Of the drivers discussed in Chapter 2, changes in land cover and spatial configuration (2.1.1), land management (2.1.2), and pesticides (2.2.1) are the most prominent drivers of risks associated with pollinator decline.

Kuldna *et al.* (2009) also found that land use practices and agrochemicals were regarded as the most significant pressures on pollinators, using a combination of literature review and expert judgement.

6.2.1.2 Other perspectives on risk

A report by the International Risk Governance Council (IRGC, 2009) identified a number of barriers, or 'governance deficits' that prevent effective governance of the risks related to pollination. These barriers can be summarised as: scientific uncertainty, lack of economic mechanisms, inadequate land use policies, inadequate stakeholder consultation, and lack of long-term planning. All these barriers persist to some extent, but this chapter demonstrates progress towards reducing them. Research funding has reduced scientific uncertainty (section 6.4.6), there are examples of stakeholder participation and communication around the world (6.4.1, 6.4.4, 6.4.6 and 6.5), and a range of economic methods and mechanisms have been developed, and tested or established in some regions (Chapter 4 and Section 6.5.1.5).

In 2014, the global asset management firm Schroders Investment Management Ltd. published a report on the economic and corporate significance of pollinator decline (Stathers, 2014). The report provides an insight into global business perceptions of the first two food production impacts in our list. According to the report, pollinator decline is likely to affect cash flow for some companies with exposure to agricultural produce, due to impacts on raw material prices, but it concludes that pollinator decline is more significant at national and farm levels than at the level of the global economy.

6.2.2 Opportunities to benefit pollinators and improve pollination

It is beyond the scope of this report to review evidence for the social or economic benefits that underlie many of the opportunities listed in **Table 6.2.1**. However, evidence for the likelihood of some of these opportunities comes from what we know about the effectiveness of the responses, and is described in the rest of this chapter.

Section 6.4.1, *Agriculture, horticulture and forestry practices*, compiles what is known about the likelihood of improved or more stable yields, reduced reliance on managed pollinators, diversified income and premium prices, and more economically sustainable agriculture in the long term, following action on pollinators. Section 6.4.2 *Pesticides and pollutants* provides information on reduced environmental hazards associated with agriculture, which could contribute to maintaining wild pollinator and plant diversity, and generate improved conditions and habitats for other species. Section 6.4.3 *Nature conservation* discusses the likelihood that better biodiversity conservation overall is associated with pollinator management. Section 6.4.4, *Pollinator management and beekeeping*, discusses what is known about the likelihood of increased production of honey and bee products from better management of pollinators. Finally, section 6.7 *Trade-offs and synergies in decisions about pollination*, discusses the evidence on whether mitigating pollinator decline and active management of pollination enhances other ecosystem services through synergy.

We can also use this assessment to identify responses that have been established and shown to be effective. These may represent opportunities to act in other places or contexts, if there are appropriate resources available, and suitable openings in the policy cycle. These responses are shown in bold, in **Table 6.9.1**.

TABLE **6.2.2**

Summary of available information on the nature, magnitude and scale of direct impacts from Table 6.2.1.
Sections of the report where more information can be found are given in brackets { }.

Direct impact	Evidence from this assessment	Immediate, future or unknown risk
Crop pollination deficit leading to lower quantity or quality of food (and other products)	• Decreased crop yield relates to local declines in pollinator diversity, but this trend does not scale up globally {3.8}. For example, pollen limitation has been shown to greatly reduce cacao yields on farms in Indonesia {2.2.2.2.4}, and hand pollination is required in apple orchards of Maoxian County, China. {2.2.2.1.1} • Globally, yield growth of pollinator-dependent crops has not slowed relative to pollinator-independent crops over the last five decades (1961-2007). {3.8}	Immediate
Crop yield instability	• Globally, pollinator-dependent crops show less stable yields than non-pollinator-dependent crops. {3.8}	Immediate
Fall in honey production (and other hive products)	• Globally, honey production has been increasing for the last five decades, although growth rates vary between countries. {3.2.2}	Future
Decline in long term resilience of food production systems	• Global agriculture is becoming increasingly pollinator-dependent and the proportion of agricultural production dependent on pollinators has increased by >300% during the last five decades. {3.7} • There is no specific evidence of changes in resilience of food production systems in response to pollinator decline.	Future
Decline in yields of wild fruit, harvested from natural habitats by local communities	• Our assessment contains no specific evidence for this.	Unknown
Reduced availability of managed pollinators	• The number of managed honeybee hives is increasing at the global scale, although undergoing declines in some European countries and N America. {3.3.2} • The stock of domesticated honey-bees hives is growing at a much lower rate than growth in demand for pollination services. Shortages of honey bee hives for crop pollination are apparent in some countries (UK, USA and China). {3.8.2} • Commercial management of a few species of bumblebee as pollinators, particularly for fruit crops, has increased dramatically since the 1980s, with an estimated 2 million colonies traded annually around the world. {3.3.3} • A few other solitary bee and other pollinator species are traded around the world. There are clear opportunities to develop further species for commercial management. {3.3.5, 6.4.4.1.3}	Immediate
Loss of wild pollinator diversity	• Wild pollinators are declining in abundance, species occurrence, and diversity at local and regional scales, although evidence comes mostly from NW Europe and North America. At larger spatial scales, declines in bee diversity and shrinkage of geographical ranges, e.g. of bumblebees, have been recorded in highly industrialized regions of the world, particularly Europe and North America, over the last century. {3.2.2}	Immediate
Loss of wild plant diversity due to pollination deficit	• Local declines in pollinator abundance and diversity have been linked to decreasing trends in wild plant pollination and seed production in habitat fragments, and to declines in the diversity of pollinator-dependent wild plant species at regional scales. {3.2.2}	Immediate
Loss of aesthetic value, happiness or well-being associated with wild pollinators or wild plants dependent on pollinators	• Pollinators are a source of multiple benefits to people, contributing to medicines, biofuels, fibres, construction materials, musical instruments, arts and crafts, and as sources of inspiration for art, music, literature, religion and technology. Loss of wild and managed pollinators will ultimately erode these benefits, but there is no specific evidence of this loss taking place yet. {5.2.3, 5.2.4}	Future
Loss of distinctive ways of life, cultural practices and traditions in which pollinators or their products play an integral part	• There is a loss of indigenous and local knowledge and sustainable bee management practices within local communities. Indigenous local knowledge from Mexico suggests that numbers of stingless bee colonies and traditional meliponiculture practices are declining. {3.3.4} • Shifts in social systems, cultural values, and accelerated loss of natural habitats have been associated with a decrease in the transfer of knowledge within and between generations. This has led to a decline in stingless bee husbandry in the Americas and Africa, and changes in habitat management for wild honeybee species in Asia by local and indigenous communities. {3.9}	Immediate

TABLE **6.2.3**

Linking direct risks to drivers and responses. This table shows the drivers most frequently selected by the Lead Authors and Co-ordinating Lead Authors as one of the 'two or three main drivers' for each direct impact from Table 6.2.1, in an anonymous individual consultation exercise (see Appendix A). It does not list all possible drivers for each impact, but indicates those for which there is strongest support.

Risk	Main drivers {relevant section}	Responses described in section:
Crop pollination deficit leading to lower quantity or quality of food (and other products)	• Changes in land cover and spatial configuration {2.1.1} • Land management {2.1.2} • Pesticides {2.2.1}	6.4.1 Agriculture 6.4.2 Pesticides 6.4.3 Nature Conservation 6.4.4 Pollinator management and beekeeping 6.4.6 Policy, research and knowledge exchange across sectors
Crop yield instability	• Changes in land cover and spatial configuration {2.1.1} • Land management {2.1.2} • Pesticides {2.2.1}	6.4.1 Agriculture 6.4.2 Pesticides 6.4.3 Nature Conservation 6.4.6 Policy, research and knowledge exchange across sectors
Fall in honey production (and other hive products)	• Pesticides {2.2.1} • Pollinator parasites and pathogens {2.3}	6.4.2 Pesticides 6.4.4 Pollinator management and beekeeping
Decline in long term resilience of food production systems	• Changes in land cover and spatial configuration {2.1.1} • Land management {2.1.2} • Pesticides {2.2.1} • Climate change	6.4.1 Agriculture 6.4.2 Pesticides 6.4.3 Nature Conservation 6.4.6 Policy, research and knowledge exchange across sectors
Decline in yields of wild fruit, harvested from natural habitats by local communities	• Changes in land cover and spatial configuration {2.1.1} • Land management {2.1.2} • Pesticides {2.2.1} • Pollinator parasites and pathogens {2.3} • Climate change {2.5}	6.4.1 Agriculture 6.4.2 Pesticides 6.4.3 Nature Conservation 6.4.4 Pollinator management and beekeeping 6.4.6 Policy, research and knowledge exchange across sectors
Loss of wild pollinator diversity	• Changes in land cover and spatial configuration {2.1.1} • Land management {2.1.2} • Pesticides {2.2.1}	6.4.1 Agriculture 6.4.2 Pesticides 6.4.3 Nature Conservation 6.4.5 Urban and transport infrastructure 6.4.6 Policy, research and knowledge exchange across sectors
Loss of wild plant diversity due to pollination deficit	• Changes in land cover and spatial configuration {2.1.1} • Land management {2.1.2} • Invasive alien species (plants and animals) {2.4}	6.4.1 Agriculture 6.4.3 Nature Conservation 6.4.5 Urban and transport infrastructure 6.4.6 Policy, research and knowledge exchange across sectors
Reduced availability of managed pollinators	• Pesticides {2.2.1} • Pollinator management (includes transport of managed pollinators) {2.3.1}	6.4.2 Pesticides 6.4.4Pollinator management and beekeeping
Loss of aesthetic value, happiness or well-being associated with wild pollinators or wild plants dependent on pollinators	• Changes in land cover and spatial configuration {2.1.1} • Land management {2.1.2}	6.4.1 Agriculture 6.4.3 Nature Conservation 6.4.5 Urban and transport infrastructure 6.4.6 Policy, research and knowledge exchange across sectors
Loss of distinctive ways of life, cultural practices and traditions in which pollinators or their products play an integral part	• Changes in land cover and spatial configuration {2.1.1} • Land management {2.1.2}	6.4.1 Agriculture 6.4.3 Nature Conservation 6.4.6 Policy, research and knowledge exchange across sectors

6.3 TYPOLOGY OF RESPONSES

Responses can be classified according to: the driver or threat generating a need for action (e.g., habitat loss, pesticides), the actors taking the action (from private individuals to intergovernmental institutions), the type of action (e.g., policy, financial, etc.) or the scale of impact (international, regional, etc.). Most sets of responses could be variously classified according to all these different classifications, and there is no right way, but there is usually a way that seems most logical and informative for a particular subject.

Previous attempts to classify responses relating to ecosystem services include the Millennium Ecosystem Assessment (Chopra *et al.*, 2005), the UK National Ecosystem Assessment (UK NEA; Brown *et al.*, 2014), and a recent policy analysis carried out by the Food and Agricultural Organization of the United Nations, which classified policy responses for pollinators into six themes (FAO; Rose *et al.*, 2014).

After reviewing these typologies, we decided classifying by type of action is the most straightforward way to group responses for pollinators and pollination. Classifications based on actors, scales or threats were less useful, as many responses involve several actors working together, operate at several scales or respond to many possible threats.

For our action-based typology, we adapted the Millennium Ecosystem Assessment model (MEA, 2011), including their technological, legal, economic and social/behavioural categories, and modifying their cognitive category to one that included not only research and indigenous and traditional knowledge, but also education and awareness-raising (see definitions in **Box**). Our definitions were informed also by the NEA and FAO reports.

The six thematic policy areas identified by the FAO exercise (Rose *et al.*, 2014) are listed in **Table 6.3.1**. These were identified by policymakers and scientists from eleven, predominantly developing countries, as a set of successful approaches for decision makers to support. We did not use them to structure our chapter, because they represent a mix of policy sectors (e.g., pesticides, nature conservation) and action types (e.g., economic, social/behavioural and knowledge). **Table 6.3.1** shows where in this chapter relevant information can be found.

BOX **6.1**
Types of response

TECHNICAL. These responses are tools and procedures that people use to manage pollinators or pollination, or land management approaches that could benefit pollinators. For example, they include farming or agroforestry practices such as organic farming and crop rotation (section 6.4.1), techniques to reduce the impact of pesticide use (6.4.2), creation or restoration of pollinator habitat (6.4.3) and methods of bee disease control (6.4.4).

LEGAL. These responses are mandatory rules at international, national and regional levels ('hard' law) and also non-legally binding treaties, guidelines, standards and codes of practice developed by law-making institutions ('soft' law). For pollinators and pollination, the responses include habitat or species protection through conservation designations, and controlling imports of non-native species, for example.

ECONOMIC. These responses are financial or economic actions either to either punish bad practices or provide economic incentives for good practices, related to pollinators. They include, for example, taxes on pesticides that increment their costs and reduce the benefits for the farmers (6.4.2), incentive payments to farmers for pollinator-friendly practices (6.4.1), and markets instruments such as payments for ecosystem services (6.4.3).

SOCIAL/BEHAVIOURAL: These responses focus on the informal institutions, governance and decision-making processes that shape people's choices. They include participatory processes to involve communities in decision-making (not the same as involving communities in research and knowledge gathering), adaptive management of native habitats, and voluntary codes of practice generated by community, consumer or industry groups rather than by law-making institutions.

KNOWLEDGE. Knowledge responses include actions that generate new knowledge and actions that transfer or share knowledge among groups of actors. They cover scientific research and monitoring, as well as documenting and sharing indigenous and local knowledge. They also include education, outreach, knowledge exchange and collaborative research activities. These are distinguished from social and behavioural actions because they focus on the communication or transfer of knowledge, rather than on decisions, actions and behaviour.

6.3.1 Combining and integrating responses

A central challenge when organising and categorising responses is that sets of individual actions are often combined together in management systems, strategies or policies, but scientific research tends to test individual management actions in isolation. In this report, we compile what is known about the effects of integrated responses that cut across sectors in section 6.4.6. In the preceding sections we include combined, system-level responses where several actions within a single sector are carried out together, if they are commonly proposed or established (for example, 'agri-environment schemes', 'diversified farming systems', or 'Integrated Pest Management').

6.4 OPTIONS TO RESTORE AND STRENGTHEN POLLINATION

This section reviews responses in each sector that have been **proposed** in response to evidence of drivers, status and trends in pollinators (see Chapters 2 and 3 for information about drivers, status and trends). Then we ask which, if any, have been **tested** or are already **established**, drawing on Indigenous and Local Knowledge in addition to scientific knowledge.

There is a subsection for each of five main sectors: a) agriculture, b) pesticides, c) nature conservation, d) pollinator management and beekeeping and e) urban and transport infrastructure; Subsection f) covers integrated responses that involve actions in more than one sector.

Responses are grouped according to the type of response (see section 6.3). Evidence relating to the opportunities described in section 6.2 is identified with summary statements where possible.

For each chosen response or category of response, we reviewed what is known about its **effects** on pollinators, pollination or any other measures or outcomes that relate to the risks and opportunities discussed in section 6.2.

6.4.1 Agricultural, agro-forestry and horticultural practices

This section focuses on agricultural practices, and adaptive techniques to enhance pollinator and pollination and to maintain yields in the wake of pollinator decline. These agricultural practices are commonly applied to mitigate negative impacts of agriculture, such as those identified in Chapter 2.

6.4.1.1 Technical responses

6.4.1.1.1 Conserve or sow field margins within or around crops

There is considerable evidence indicating the potential of non-crop areas within agricultural landscapes, including flower strips, permanent grassland, sown grassland, buffer strips, managed hedgerows (Kremen and M'Gonigle, 2015), set-aside fields (Greaves and Marshall, 1987), for enhancing pollinator diversity in agroecosystems (Morandin and Kremen, 2013; Garibaldi *et al.*, 2014). These practices can benefit pollinator richness by providing suitable food and nesting resources within and across arable farms without changing cropping patterns (Nicholls and Altieri, 2013). We know of no evidence for population-level effects on pollinators, although some studies indicate that numbers of bumble bee reproductives (males or males and queens) tend to increase as flowers are added to a landscape (Williams *et al.*, 2012, Carvell *et al.*, 2015). Far less is known about which plant species are beneficial for bees and other pollinators in terms of quality of nectar and pollen (see section 6.8.1).

A recent review (Dicks *et al.*, 2014) found 65 studies in Europe that focused of the effect of sown flower strips

TABLE **6.3.1**
Thematic areas for action identified by the FAO (Rose *et al.* 2014)

FAO thematic area	IPBES report section
Pollinator-friendly pesticide policies	6.4.2 Responses to reduce impacts of pesticides
Conservation and enhancement of pollinator habitats	6.4.3 Responses for nature conservation
Valuation, incentives, and payments for ecosystem services	6.4.2, 6.4.3, 6.4.4, 6.4.5 Economic responses (most well-developed in agriculture)
Participation, knowledge-sharing and empowerment of rural and indigenous peoples and local communities	6.4.1, 6.4.3, 6.4.4 Social and behavioural responses
Collaborative research and outreach	6.4.6 Knowledge responses
Public awareness raising and knowledge sharing	6.4.6 Knowledge responses

on invertebrates; 41 of the studies identified positive effects on number, diversity, or activity of invertebrates. Strips sowed with flowers, particularly those rich in nectar or pollen, support higher insect abundances and diversity than cropped habitats or other field margin types such as sown grass margins and natural regeneration (Carvell *et al.*, 2007; Scheper *et al.*, 2013). However the effectiveness of these small-scale practices varied with (1) the magnitude of increase in flowering plant cover resulting from the practices, (2) farmland type, and (3) landscape context (Scheper *et al.*, 2013). It is possible that flowering resources placed alongside crop fields increase exposure of pollinators to pesticides, however, this hypothesis has not been tested (see section 2.2.1 for a discussion of possible exposure routes).

Regional programs to increase the quality and availability of seeds from native flowering plants are important for the success of these practices (Isaacs *et al.*, 2009). Operation Pollinator, a programme to boost numbers of pollinating insects on farms and golf courses across Europe, run by the agri-chemical company Syngenta, has developed and tested seed mixtures to provide to land managers (http://www.operationpollinator.com/).

Although some of the above studies have shown direct benefits of wildflower strips in terms of increased pollinator richness, abundance and activity on crops, there is limited evidence about the direct impact of those practices on crop yield. One study showed that floral strips surrounding crops modify the level of outcrossing within the cultivar, consequently affecting the genetic structure of the cultivar (Suso *et al.*, 2008).

Some studies demonstrate that habitat enhancements can provide increased pollination to adjacent crops. One example of such a study was on mango production in South Africa showing that pollination was improved by planting small patches of perennial plants (Carvalheiro *et al.*, 2012). Similar results were found in USA for blueberry, where pollination was improved after three years by the establishment of wildflower patches (Blauw and Isaacs, 2014).

Many examples of small-scale farmers maintaining habitat elements such as hedgerows and fallow areas for pollinators can be found around the world (see section 5.3.3), and there are reports from other countries of the effectiveness of these practices for increasing yields for other crops (FAO, 2008).

6.4.1.1.2 Provide nesting resources

Artificial or natural substrates, such as reed internodes and muddy spots for cavity nesters, and bare ground for soil nesters, can be enhanced at crop edges without requiring much crop area. This practice can promote the recruitment of certain bee species (Steffan-Dewenter and Schiele, 2008) and pollinator density on crops (Junqueira *et al.*, 2013). Strategic placements of nesting cavities where abundant floral resources occur have been observed to increase population growth of pollinators (Oliveira-Filho and Feitas, 2003). Evidences that such practices lead to greater yields are few, but there are example that such management practices increase population growth of pollinators (MacIvor and Packer, 2015). The introduction of bamboo nests for bees of the genus *Xylocopa* in Brazilian passion fruit plantations increased the yield by 781% (Camillo, 1996). In apple orchards in Canada, habitat management and placement of cavity nests for Osmiine bees resulted in increased offspring of the Osmiine bees (Sheffield *et al.*, 2008).

6.4.1.1.3 Sow mass-flowering crops and manage the timing of blooming

Some mass-flowering crops when grown in diverse farming systems could be managed to bloom in different periods of time at a landscape scale. In Sweden, bumble bee reproduction was improved in landscapes with both late-season flowering red clover and early-season mass-flowering crops (Rundlöf *et al.*, 2014). But the short duration of floral availability, low diversity of resources, insecticide application, and tillage may limit the capacity of mass flowering monocultures to support wild pollinator populations on their own (Vanbergen and the Insect Pollinators Initiative, 2013). In addition studies have found strong evidence for food resource availability regulating bee populations (Roulston and Goodell, 2011) and also have revealed the critical role of resource availability on bee health (Alaux *et al.*, 2010). Thus in heterogeneous landscapes rich in flowering species, sowing mass flowering crops can be an alternative practice to enhance wild pollinators and pollination (Holzschuh *et al.*, 2013; Bailes *et al.*, 2015), but more work is needed to define how this should be done.

6.4.1.1.4 Organic farming

Pollination benefits of organic practices were found in some crops such as strawberries in Sweden (Andersson *et al.*, 2012) and canola in Canada (Morandin and Winston, 2005). Organically-farmed fields can enhance bee abundance, richness and diversity compared to conventionally-farmed fields, and also help to sustain pollination by generalist bees in agricultural landscapes (Tuck *et al.*, 2014), but the magnitude of the effect varies with the organism group and crop studied, and is greater in landscapes with high proportions of cultivated lands (Holzschuh *et al.*, 2007; Kennedy *et al.*, 2013). However, the studies have been carried out mainly in Europe and North America and their applicability to other areas of the world is uncertain.

A large-scale study in ten European and two African countries showed that organic farms have much smaller effects on the diversity of habitats or species richness at farm and regional scales than at the field scale. This implies that to ensure positive benefits of biodiversity at larger spatial scales, even organic farms have to support biodiversity actively by maintaining and expanding habitats and natural landscape features (Schneider *et al.*, 2014).

In England, a study suggested that organic farming should be mainly encouraged in mosaic (low productivity) landscapes, where yield differences between organic and conventional agriculture are lower. In less-productive agricultural landscapes, biodiversity benefit can be gained by concentrating organic farms into hotspots without a commensurate reduction in yield (Gabriel *et al.*, 2013). This study also revealed a decrease in the abundance and diversity of some pollinator groups with increasing yield in both organic and non-organic ("conventional") wheat farms. The factors that co-vary with yield ultimately influence this pattern, and could include management practices, and management of habitats and/or cropping systems, in both conventional and organic farms.

6.4.1.1.5 No-till farming

No-till farming is a practice for soil conservation that can reverse long-term soil degradation due to organic matter loss. No-till farming has increased in the Cerrado region of Brazil from 180,000 hectares in 1992 to 6,000,000 hectares in 2002. Producers have found that no-till techniques within certain planting sequences each year, as well as longer-term crop rotations, may increase production by 10%. The estimated annual benefits of adopting no-till agriculture techniques in Brazil amount to $1.4 billion on 35% and $3.1billion on 80% of a total cultivated area of 15.4 million hectares (Clay, 2004). In contrast a global meta-analysis across 48 crops and 63 countries showed that overall no-till reduces yields, but this depends on the system. Yield difference is minimised when no-till is combined with crop residue retention and crop rotation, and no-till significantly increases rainfed crop productivity in dry climates (Pittelkow *et al.*, 2015; see Chapter 2, section 2.2.2.1.3 for more details).

No-till coupled with the use of cover crops might be expected to enhance populations of ground-nesting bees, as many species place their brood cells < 30 cm below the surface (Roulston and Goodell, 2011; Williams *et al.*, 2010), but there is little evidence for this. One study found an increase in squash bees *Peponapis pruinosa*, but not other bee species, on no-till squash farms in the USA (Shuler *et al.*, 2005), while another study did not find this effect (Julier and Roulston, 2009).

6.4.1.1.6 Change irrigation frequency or type

Although there is little evidence, similarly to no-till, changing irrigation frequency or type can be a pollinator-supporting practice. In arid irrigated systems, changing from flood irrigation that may be detrimental for pollinators because of nest flooding, to drip irrigation can reduce the impact on pollinators, but in general irrigation can promote wild insect abundance through higher productivity of flowering plants or by making the soil easier to excavate (Julier and Roulston, 2009).

6.4.1.1.7 Change management of productive grasslands

Productive grasslands used for grazing or hay can be managed to be more flower-rich by reducing fertilizer inputs, or delaying mowing dates. In experimental studies in Europe, these changes usually lead to increased numbers of bees, hoverflies and/or butterflies (Humbert *et al.*, 2012; Dicks *et al.*, 2014a). Adding legumes and other flowering species to grassland seed mixtures is supported by some agri-environment schemes in Europe (see section 6.4.1.3) and probably benefits pollinators by supplying flowers in grassland-dominated landscapes, but this has not been clearly demonstrated (Dicks *et al.*, 2010; Dicks *et al.*, 2014). Two European studies have shown that avoiding use of rotary mowers and mechanical processors substantially reduces mortality of bees or butterfly larvae when cutting flowering meadows (Dicks *et al.*, 2014b). However, studies have not been designed to look for landscape-scale, population-level effects of any of these management changes on pollinators.

6.4.1.1.8 Diversify farming systems

Diversity is the foundation of any sustainable agriculture system, and mixed crop types, crop-livestock mixtures, intercropping and cover crops bring pollinator diversity to the farm by providing floral resources and habitat for many different species of pollinators, and promote wild pollinator stability on farms (Kennedy *et al.*, 2013). There is some evidence in Western Europe and North America suggesting that increased floral diversity achieved through diversified farming can improve pollination (Batáry *et al.*, 2009; Kremen and Miles, 2012; Kennedy *et al.*, 2013). Intercropping cacao with banana or plantain is correlated with an increase in the density of cacao-pollinating midges, as well as cacao fruit set, in Ghana (Frimpong *et al.*, 2011). A recent study in Canada (Fahrig *et al.*, 2015) suggested that reduced field size may be a more important feature of diversified farming systems than increased number of crop types, if the aim is to increase or maintain farmland biodiversity generally (including bees, hoverflies and butterflies). Recent meta-analysis suggests that two management practices that diversify crop fields – polyculture and crop rotations –

increase yields in both organic and conventional cropping systems (Ponisio *et al.*, 2015).

Diversified farming practices are an important element of the diverse cultures and practices of indigenous peoples and local communities across the globe. Scientific evidence of a benefit to pollinators or pollination in those systems is scarce but can be expected where there is increased diversity of flowering plants and habitats. For example, areas surrounding milpa systems in Central America house a wide variety of plant species that are highly attractive to insects (Lyver *et al.*, 2015; Chapter 5, section 5.2.5.3). Indigenous Tarahumara people (Mexico) have developed an expanded cropping system that involves consuming weed seedlings (e.g., *Amaranthus*, *Chenopodium*, *Brassica*) early in the season and harvesting cucurbits, beans and maize late in the season (Bye, 1981). Similarly, small-scale farmers in the semi-arid Tehuaca´n-Cuicatla´n Biosphere Reserve (Mexico) make use of more than 90% of the 161 weed species (Blanckaert *et al.*, 2007). Maintaining weed resources alongside local crops creates a diverse set of flowering resources for pollinators, although indigenous or rural people do not comment on the relationship between weeds or crop reproduction and pollinators (Bye, 1981; Altieri, 2003).

6.4.1.1.9 Make crops more attractive to pollinators, to enhance pollination

Spraying crops with pheromones to attract pollinators and/or enhance pollination is a well-known practice for some crops. Studies carried out in Australia (Keshlaf *et al.*, 2013) and India (Chandrashekhar and Sattigi 2009; Nithya *et al.*, 2012; Sivaram *et al.*, 2013) with crop flowers sprayed with attractants significantly increased bee visitation rate, seed yield, and percent germination. In Brazil, Bee-Here^{R}, eugenol, geraniol, citral, and lemon grass extract, mainly diluted in water, were effective in attracting honeybees to sweet orange orchards (Malerbo-Souza *et al.*, 2004).

More recently, there are ongoing studies to identify crop flower traits (e.g., brighter colours, increased scent, and increased nectar) to increase visitation by pollinators to improve the yield stability of the crop (Bailes *et al.*, 2015).

'Participatory Plant Breeding and Management' is being used to develop pollinator friendly-crops that require pollinator friendly-practices (Duc *et al.*, 2010; Suso *et al.*, 2013). The central idea is to develop varieties to maintain open pollination, selecting flowers that can attract more pollinators. This approach aims to enhance the genetic diversity of crops, maintain pollinators and reduce chemical inputs (low-input agriculture). It requires decentralized and farmer participatory breeding methods designed to incorporate the "know-how" of farmers. There are no conclusive examples in practice yet.

6.4.1.1.10 Monitor and evaluate pollinators and pollination on farms

Systematic long-term monitoring of pollinators on farms and crop pollination deficit evaluation are still rare in literature and there are no national programmes in place. Recently FAO/GEF/UNEP has been supporting national partners in eleven countries for assessing pollinator abundance and diversity within and around crops, and for evaluation of crop pollination deficits using a standard protocol (Vaissiere *et al.*, 2011). The projects were conducted over a five-yr-period, with studies in Brazil, Argentina, Colombia, Ghana, Kenya, Zimbabwe, India (two locations, one by an indigenous group), Nepal, Pakistan, Indonesia, and China. Results of this project, as well as of other studies can be accessed in a Special Issue on Pollination Deficits published in 2014 (volumes 12, 13 and 14) in the open Access Journal Pollination Ecology (http://www.pollinationecology.org).

More recently, a collaborative research project tested wild bees and bumble bees as part of a biodiversity indicator set at farm scale across Europe and in Ukraine, Tunisia and Uganda. The resulting toolkit is available at www.biobio-indicator.org.

6.4.1.1.11 Reduce dependence on pollinators

As global agriculture is becoming increasingly pollinator-dependent (see Chapter 3), an option to remove all the risk associated with biotic pollination is switching from dependent to non-dependent crops. This can reduce overall crop genetic diversity, thus increasing potential vulnerability to pests and pathogens (see section 6.7.1). In the USA a self-fertile variety of almond, the Independence® Almond, has been developed that needs few bees to produce numerous large nuts.

Manual or mechanical pollination can be used in high-value crops such as glasshouse tomatoes, passion fruit, kiwi or apple to compensate for deficits in pollination. In Iran, Mostaan *et al.* (2010) have developed a new electrical apparatus for pollinating date palms. In the absence of natural pollinators, some apple farmers in China initially adapted by using hand pollination techniques, but this has been followed by changing to fruit and vegetable crops that do not need to be cross-pollinated (Partap and Ya, 2012). However, hand pollination by human pollinators is still practiced with apples to a lesser degree, which indicates that all these farmers have yet to find satisfactory alternatives to this economically unsustainable practice (Partap and Ya, 2012).

As manual pollination represents an additional cost of production, its cost and benefits should be analysed locally. Estimates of labour costs for manual pollination of yellow passion fruit (*Passiflora edulis*), reported in studies conducted in the Brazilian states of Minas Gerais (Vieira *et al.*, 2007) and Bahia (Viana *et al.*, 2014), show that the cost to producers of paying workers to conduct manual pollination is equivalent to around 20% of their annual net profit.

6.4.1.1.12 Adapt farming methods to climate change

Possible adaptation strategies at the farm level include managing for a diverse pollinator community, changes in crop diversity, sowing rate, and crops/cultivars to ensure pollination in areas where pollinator populations and pollinators diversity are reduced (Reidsma and Ewert, 2008). There is evidence that biodiversity can stabilize pollination against environmental change (Rader *et al.*, 2013). High biodiversity levels can ensure plant–pollinator phenological synchrony and thus pollination function (Bartomeus *et al.*, 2013; Brittain *et al.*, 2013). Greater crop diversity also can decrease crop vulnerability to climate variability, as different crops respond differently to a changing climate. But the effectiveness of adaptation efforts is likely to vary significantly between and within regions, depending on geographic location, vulnerability to current climate extremes, level of economic diversification and wealth, and institutional capacity (Burton and Lim, 2005). See section 6.4.4.1.5 for a discussion of boosting pollination by translocating native pollinators.

6.4.1.2 Legal responses

The degree to which pollination contributes to sustainable crop yields has not been addressed in agricultural policies in most countries, although China has officially recognized pollination as an agricultural input, along with other conventional inputs such as fertilizers and pesticides (FAO, 2008).

At large scale, agricultural policies in Europe, (European Common Agricultural Policy (http://www.ecpa.eu/information-page/agriculture-today/common-agricultural-policy-cap) and the USA (US Farm Bill: http://www.xerces.org/wp-content/uploads/2009/04/using-farmbill-programs-for-pollinator-conservation.pdf) provide important frameworks within which specific actions to benefit pollinators have been incentivised (see section 6.4.1.3).

Most policies to increase heterogeneity in agricultural landscapes reduce intensity of land use, adopt agroecological farming practices, and prevent abandonment of agricultural land are relevant to pollinators and pollination (Smith *et al.*, 2013). The initiative in Bhutan to eradicate chemical fertilizers and pesticides as part of its Gross National Happiness programme may have a positive impact on pollination (http://www.theguardian.com/sustainable-business/bhutan-organic-nation-gross-national-happiness-programme). Likewise, in Brazil the *National Plan for Agro-Ecology and Organic Production,* launched in 2013, with the aim to coordinate policies and actions for environmentally-friendly agriculture and organic food production may contribute to enhance pollinators and pollination (OECD, 2015). Even though the effectiveness of the regulations above is still untested, there is evidence of the positive impact of these agroecological practices on pollinators and pollination (see section 6.4.1.1). Legal responses that relate to the use of pesticides and other agrichemicals in agriculture are covered in section 6.4.2.2.

6.4.1.3 Economic responses

Financial support is often necessary to allow the farmer to switch farming practices and bear the loss in production that may result. In Europe, the USA and Australia agri-environment schemes (AES) offer farmers short-term payments for performing prescribed environmental management behaviour. Use of AES to support pollinators in Europe was reviewed by Rundlöf and Bommarco (2011), who identified three main measures that may specifically promote pollinators: creation and restoration of semi-natural habitats, establishment of flower strips, and reduction of pesticide inputs by conversion to organic farming or introduction of unsprayed field margins. Another, management of hedgerows to enhance flowering, is supported in some countries.

Effects of AES on pollinator numbers are well documented (Pywell *et al.*, 2006; Batáry *et al.*, 2011; http://www.conservationevidence.com/actions/700) but effects on pollinator populations are still unknown. Payment for ecosystem services (PES) is another action (e.g. Daily *et al.*, 2009) that could promote practices to conserve pollinators on farms (see section 6.4.3.3).

More recently in the USA farmers receive financial support to diversify crops (Rose *et al.*, 2015). The United States Department of Agriculture introduced the Whole-Farm Revenue Protection Program (http://www.rma.usda.gov/policies/wfrp.html), which offers farmers an opportunity to insure all crops on their farms simultaneously, as opposed to insuring them crop-by-crop. The lack of specific insurance programmes for fruit and vegetables in the past has been a disincentive for growers to diversify beyond commodity crops. The new way of insuring crops offers farmers enhanced flexibility and provides a greater incentive to diversify cropping systems within farming regions (USDA, 2014).

Certification schemes led by consumer or industry bodies with a price premium are a market-based instrument that can be used to encourage pollinator-friendly farm management practices. One scheme, 'Fair to Nature: Conservation Grade' in the UK, offers a price premium to farmers for planting flowers and managing habitat for pollinators (among other actions), as part of the licence agreement from businesses that sign up for the 'Fair to Nature' label (http://www.conservationgrade.org/conservation-farming/). One very small research project has shown that farms managed under this scheme have higher functional diversity (but not abundance) of hoverflies than conventionally managed farms (Cullum, 2014). Similar research on bees and butterflies is ongoing.

In Mexico, a proposal currently being developed is to market 'bat-friendly mezcal'. The Mexican beverages tequila and mezcal are extracted from plants of the genus *Agave*, which are pollinated mainly by bats when they flower. Production of these drinks does not rely directly on pollination – they are extracted from vegetative parts of the plant before flowering – but agave flowers are an important food source for bats. Bat pollination is needed for seed production, which could potentially help restore agave genetic diversity for tequila production (this currently relies on clonal propagation: Colunga-GarciaMarin and Zizumbo-Villarreal, 2007; Torres-Moran *et al.*, 2013). The Mexican endemic plant *Agave cupreata*, sometimes used for mezcal, can only be grown from seed (Martínez Palacios *et al.*, 2011). To get this label, growers would have to leave some agave plants to flower and breed sexually through bat pollination, rather than cutting them all for production before flowering.

Financial schemes and insurance programs such as those identified above may be costly to developing countries. One alternative is where indigenous community forestry enterprises are supported by the Non-Timber Forest Products Exchange Program (NTFP-EP; http://www.ntfp.org) in South and Southeast Asia. This program empowers forestry-based communities to manage forest resources in a sustainable manner. To this end, the NTFP-EP catalyses and supports activities that strengthen the capacity of their partner organisations in their work with forest-dependent communities, particularly indigenous peoples. However, despite the great potential of this program to enhance pollinators and pollination, its efficacy is untested yet.

There is no simple relationship between financial reward and behaviour change. Payments may increase motivation, but they can also weaken motivation (Deci *et al.*, 1999). Knowing this should make us sensitive to the way in which financial measures are applied to compensate for loss of income (Canton *et al.*, 2009; Burton and Paragahawewa, 2011).

A recent review examining more effective instruments for changing farming social behaviour suggests switching AES for "payment by results schemes" (De Snoo *et al.*, 2012). The latter differ from conventional agri-environmental schemes by paying farmers for outcomes rather than performing set management activities.

The intended result is that, unlike conventional schemes, farmers are encouraged to engage with conservation groups to identify common goals and to recognize the need to innovate and, in many cases, cooperate to achieve greater financial reward. There is some evidence that alternative designs for the delivery of financial rewards may also deliver environmental benefits and be associated with more enduring social and cultural changes (De Snoo *et al.*, 2012). In Switzerland, a farmer-led initiative has successfully lobbied the government for the introduction of "bee pastures" (sown flower strips) in the national agri-environmental scheme (http://www.lobag.ch/LOBAG/Bereiche/Pflanzenproduktion/%C3%96lsaatenzuteilung/tabid/92/language/de-CH/Default.aspx)

Result-oriented schemes thus create common goals between farmers and conservationists (Musters *et al.*, 2001), enable productivity comparisons with conventional farming products (Klimek *et al.*, 2008; Matzdorf and Lorenz, 2010), and lead to the creation of cultural (skills and knowledge) and social capital (i.e., access to shared peer group resources) as knowledge of conservation management becomes socially valuable (Burton and Paragahawewa, 2011).

6.4.1.4 Social and behavioural responses

Conservation of ecosystem services in agricultural areas can only be effective in the long term with the active support of farming communities. Responses are required that are able not only to affect short-term changes in farmer behaviour, but also establish or re-establish group norms that will make durable changes (De Snoo *et al.*, 2012). Effects on non-economic forms of social capital should be considered, such as how the behaviours generate status and prestige within farming communities (Burton and Paragahawewa, 2011).

For knowledge of ecosystem service conservation to have social legitimacy from the farmers' perspective, the knowledge must be generated within the farming community, rather than imposed by outsiders (De Snoo *et al.*, 2012). Community engagement and empowerment on managing pollinators in agriculture and forestry is one broad approach to achieve this, although untested yet.

Participatory dialogue inclusive of multiple stakeholders is valuable to understand and address different perspectives and needs, and confers many benefits to policy implementation (e.g., higher-quality decisions, greater legitimacy of decisions, increased compliance (Menzel and Teng, 2009). This kind of discussion can introduce stakeholders to potential policy ideas, based on information from other regions or countries. Accounting for farmers' insights and concerns, and engaging them in change processes, is important, because they are likely to be directly impacted by laws, policies and changes to incentive schemes.

Encouraging farmers to collaborate to manage landscapes is an approach that has been tested through agri-environment schemes (see section 6.4.1.3) in some European countries (Prager, 2015). This can generate environmental, social and economic benefits, although there is no specific experience relevant to pollinators or pollination. It is more likely to be successful where there is a shared awareness among land managers of a common problem, and where schemes are flexible and can be adapted to suit local issues.

Prohibitions on behaviour, or voluntary codes of conduct, are an important social mechanism that protect and enhance pollinator presence in local communities. Farmers in Roslagen (Sweden) recognize bumble bees as important pollinators for garden and field production and afford them social protection, including restricting the cutting of trees that flower in early spring when other pollen- and nectar-producing plants are rare (Tengo and Belfrage, 2004).

6.4.1.5 Knowledge responses

Higher education and training programs for agronomists, agroecologists, veterinarians, policy-makers and farmers are important responses to support pollinators and pollination.

The Indigenous Pollinators Network promoted by the Indigenous Partnership for Agrobiodiversity and Food Sovereignty (http://agrobiodiversityplatform.org/par/2013/12/24/the-indigenous-pollinators-network/) provides a platform for scientists and indigenous people to share their ideas and best practices around pollination (see section 5.4.4.1).

Translating research into agricultural practice requires implementation, demonstration and extension work, as well as knowledge exchange between scientists and farmers, and different methodologies have been developed for promoting farmer innovation and horizontal sharing and learning (see section 6.4.6.3). In USA, the Land Grant University System, created in the mid-1800s, also provides practical knowledge and information sharing (extension), based on unbiased scientific research, to citizens everywhere, both rural and urban (National Research Council, 1995).

There are few examples where training has been demonstrated to change farmer knowledge or behaviour. The Xerces Society for Invertebrate Conservation and the US Department of Agriculture in the USA run short courses on pollinator conservation aimed at farmers and agricultural professionals. In a survey of those who participated in these short courses, 91% indicated that they would adopt bee-safe practices discussed in the course (Xerces Society, 2014), although this not does guarantee they actually did change their practice. One research project in the UK demonstrated that training farmers increases their confidence and develops a more professional attitude to agri-environmental management (Lobley *et al.*, 2013), resulting in ecological benefits. For example, areas managed by trained farmers had more flower or seed resources and higher numbers of bees or birds than areas managed by untrained farmers (Dicks *et al.*, 2014b).

A common approach used to transfer specialist knowledge, promote skills and empower farmers around the world is Farmer Field Schools (FFS), at which 10 million farmers in 90 countries have benefited (Waddington *et al.*, 2014). A systematic review of FFS provides evidence that these schools are improving intermediate outcomes relating to knowledge learned and adoption of beneficial practices, as well as final outcomes relating to agricultural production and farmers' incomes (Waddington *et al.*, 2014).

6.4.2 Pesticides, pollutants and genetically modified organisms

This section collates experience and scientific information about responses relating to pesticides, pollutants and genetically modified organisms. The impacts of these on pollinators and pollination are described in Chapter 2, sections 2.3.1 and 2.3.2. Responses are designed to reduce, eliminate or mitigate against known impacts.

Reducing the exposure of pollinators to pesticides and the toxicity of pesticides to pollinators will reduce direct risks to pollinators. Herbicides constitute the most used pesticides globally. They provide mainly an indirect risk by decreasing forb and flower availability to pollinators in the crop field, as well as in the landscape through drift and spraying of field and ditch edges, rights-of-way habitat etc. (Egan *et al.*, 2014; see Chapter 2, section 2.2.2.1.4). The potential direct risk for pollinators from herbicides is poorly known.

6.4.2.1 Technical responses

6.4.2.1.1 Risk assessment techniques

Risk assessment of pesticides (compounds meant for controlling weeds, fungi, bacteria or animal pests) and other agrochemicals (e.g., blossom-thinners, or crop growth regulators), is an important tool to estimate the risk to insect pollinators. (Throughout this section "pollinators"

TABLE **6.4.1**
Summary of evidence for responses relating to farming and agro-forestry

Response/action (relevant chapter 6 section)	Main driver(s) (chapter 2)	Type	Status	Scientific evidence
Conserve or sow field margins within or around crops (6.4.1.1.1)	Land management (2.1.2)	Technical	Rarely	Increases numbers of foraging pollinating insects **WELL ESTABLISHED** Enhances pollination services **ESTABLISHED BUT INCOMPLETE**
Provide nesting resources (6.4.1.1.2)	Land management (2.1.2)	Technical	Tested	Benefits to pollinator abundance and species **ESTABLISHED BUT INCOMPLETE** Little evidence for pollination service **INCONCLUSIVE**
Sow mass-flowering crops and manage of blooming (6.4.1.1.3)	Land management (2.1.2)	Technical	Tested	Benefits to pollinator abundance and species **ESTABLISHED BUT INCOMPLETE** Enhance pollination service **INCONCLUSIVE**
Organic farming (6.4.1.1.4)	Land management (2.1.2) pesticides (2.2.1)	Technical	Established	Supports more species of wild pollinators than non-organic **WELL-ESTABLISHED** Enhances for pollination service **ESTABLISHED BUT INCOMPLETE**
No-till farming (6.4.1.1.5)	Land management (2.1.2)	Technical knowledge	Tested	Contrasting results for effects on ground-nesting bees and overall yields **UNRESOLVED**
Change irrigation frequency or type (6.4.1.1.6)	Land management (2.1.2)	Technical	Tested	Promotes wild insects abundance **INCONCLUSIVE**
Change management of productive grasslands (6.4.1.1.7)	Land management (2.1.2)	Technical	Tested	Reduced chemical inputs and delayed mowing usually increase pollinator numbers **WELL ESTABLISHED** Little evidence for pollination service **INCONCLUSIVE**
Diversify farming system (mixed crop types; crop-livestock mixtures, intercropping, cover crops) (6.4.1.1.8)	Land management (2.1.2)	Technical	Established	Enhances pollinator abundance and species **WELL-ESTABLISHED** Enhances for pollination service **ESTABLISHED BUT INCOMPLETE**
Make crops more attractive to pollinators, to enhance pollination services (additives or breeding strategies) (6.4.1.1.9)	Land management (2.1.2)	Technical	Tested	Increases pollinators visitation rate **ESTABLISHED BUT INCOMPLETE** Little evidence for pollination service **INCONCLUSIVE**
Monitor and evaluate pollinators and pollination on farms (6.4.1.1.10)	Land management (2.1.2)	Technical knowledge	Tested	Promotes pollinator and pollination service conservation **ESTABLISHED BUT INCOMPLETE**
Reduce dependence on pollinators (mechanical replacement or breeding strategies). (6.4.1.1.11)	Land management (2.1.2)	Technical	Tested	Compensates pollination deficit. **INCONCLUSIVE**
Adapt farming methods to climate change (6.4.1.1.12)	Climate changes (2.5)	Technical knowledge	Tested	Effectiveness at securing pollination under climate change is untested and likely to vary significantly between and within regions **INCONCLUSIVE**
Establish regulatory norms and certification criteria for forest and agricultural products (6.4.1.2, 6.4.1.3)	Land management (2.1.2)	Legal economic	Proposed	Enhances pollination services and promotes pollinator conservation on farms **ESTABLISHED BUT INCOMPLETE** for pollinators **INCONCLUSIVE** for pollination service
Pay financial incentives to farmers for practices that support pollinators (6.4.1.3)	Land management (2.1.2)	Economic	Established	Enhances pollinator abundance and species. **WELL-ESTABLISHED**
Engage and empower farming communities to work together to manage pollinators (6.4.1.4)	Land management (2.1.2)	Social/ behavioural	Tested	Potential to enhance pollination services and promote pollinator conservation, but no evidence of this yet **INCONCLUSIVE**
Translate existing research into agricultural practice through implementation, demonstration and extension (includes providing information to farmers about pollination requirements of crops) (6.4.1.5)	All	Knowledge	Tested	Enhances pollination service and promotes pollinator conservation **ESTABLISHED BUT INCOMPLETE**

refers to insect pollinators (mainly bees), as the link between pesticides and non-insect pollinators are comparatively little studied.) Risk depends on a combination of the hazard (toxicity) of a compound and the exposure of pollinators to this compound (e.g., Alister and Kogan, 2006). Risk assessment is performed at registration of a pesticide for use in a country. The honey bee was the first species in the focus of regulators, who started attending to the bee safety of pesticides a century ago. In Germany, for instance, the first ecotoxicological tests on bee safety of pesticides were conducted in the 1920s, and the first decrees to protect bees from insecticides came in the early 1930s (Brasse, 2007). Registration is since then based on ecotoxicological studies using a well-established set of methods that are being constantly developed and refined. The methods assess direct (but not indirect) lethal and sublethal threats to pollinators.

Two general techniques are used. The first basic approach (termed low tier) adopted by many countries is to test the hazard, i.e., the acute toxicity of the active compound, by estimating lethal doses in the laboratory. For pollinators, this straightforward technique is usually performed using the adult honey bee as the indicator species (also called surrogate species) for pollinators (Alix and Lewis, 2010; Anonymous, 2010). Risks to other pollinator taxa are routinely represented by, for example, rats and other mammals (for bats) and upland game birds, waterfowl or other bird species (for pollinating birds such as hummingbirds). However, because other bee species, and also the larval life stage of the honey bee, may differ substantially in their responses to a compound, guidelines have been developed to include toxicity assessments also for honey bee larvae (Oomen *et al.*, 1992; OECD, 2013), and guidelines for toxicity tests on other bee species are under development (Fischer and Moriarty, 2014).

The second (higher tier) more resource-intensive approach is triggered by the outcome of the first tier, i.e., an intrinsic toxicity that is higher than a pre-defined threshold value that is empirically based on field incident data, and assesses the combination of toxicity and exposure under more realistic conditions in determining the likelihood on survival and sublethal effects in bees or their colonies. Techniques are becoming available for tests under semi-field or field conditions; some are standardized (e.g. EPPO 170 (http://pp1.eppo.int/getnorme.php?id=257) OECD, 2007) but the uncertainties linked to making assessments in the field are limiting their implementation in the regulatory process. These approaches are included in the regulatory registration process in some countries (see Legal responses below). For instance, guidelines for testing of pesticide impacts are internationally available for semi-field and field testing for pollinators (OECD, 2007; Anonymous, 2010; EPA, 2012; EPA *et al.*, 2014).

There is on-going research to support the development of tools for assessing risks to pollinators, including studies for assessing sublethal effects on honey bees as well as other surrogate test species (Desneaux *et al.*, 2007; EFSA, 2012; Hendriksma *et al.*, 2011; EFSA, 2013b; Arena and Sgolastra, 2014; Fischer and Moriarty, 2014). Current method developments, especially in Europe and North America, focus on validating tests of chronic exposure in the laboratory, and on methods assessing impacts on bumble bees and wild bees. It has been suggested that tests need to be developed of exposure and hazards of combinations of pesticides, also combined with other stressors (Vanbergen *et al.*, 2014). A novel approach is to consider potential impacts on ecosystem services, including pollination, in the risk assessment (Nienstedt *et al.*, 2012).

It is not feasible to implement a full global quantitative risk assessment for all chemicals. It was estimated that there were more than 900 active substances intended for agriculture on the global market in 2009 (Tomlin, 2009). Comparative risk assessments are used with pesticide risk ranking tools as an initial screening to identify chemicals to take forward for further assessments, identify information gaps, or inform a risk management approach. Labite *et al.* (2011) reviewed the main 19 pesticide risk ranking tools in use in Europe and North America, categorising them according to their data needs and the specific environmental risks covered. Ten of the 19 used bee toxicity data to assess toxicity of specific chemicals as part of the risk assessment, but only one risk-ranking tool specifically evaluated the risk to pollinators (bees) – the Environmental Risk Index (ERI) developed in Chile (Alister and Kogan, 2006). This tool does not appear to have been used in practice to screen pesticides for risk assessment.

FAO and other partners have developed a risk profiling tool that assesses risk from pesticide exposures to pollinators in the field (van der Valk *et al.*, 2013). The risk profiling is based on local information on which species provide pollination to the crop in question in the region, and a list of main factors influencing pesticide risk (e.g., pesticide type and use, phenology of crop flowering and pollinator activity). A risk profiling approach may be a cost efficient tool, particularly useful when a comprehensive risk assessment is not available. It provides a qualitative estimate of exposure, helps identify risks and knowledge gaps, and can provide a basis for education and to identify land management practices that may reduce pesticide exposure. The tool has been tested for three countries (Brazil, Kenya and the Netherlands) (van der Valk *et al.*, 2013).

6.4.2.1.2 Risk mitigation technology

There are three general approaches to reduce exposure and thereby risk of pesticides for bees with technology: i) reduction of pesticide drift, ii) development of pollinator-friendly pesticides, and iii) application of cultivation practices that reduce exposure from or entirely avoid use of pesticides.

Reducing pesticide drift has been identified as an important action to reduce risks from pesticides use (FOCUS, 2007). Low-drift spraying equipment has been developed and tested (Felsot *et al.*, 2010). Specific developments include sprayers with nozzles that generate larger droplet sizes, that apply the pesticide closer to the ground, or that have air wind shields mounted when spraying near the field borders. Also, changing formulation of the pesticide can reduce drift (Hilz and Vermeer, 2013). Planting buffer zones or wind breaks at field borders has been tested and recommended in several countries to reduce drift of pesticides into adjacent habitats (Ucar and Hall, 2001). However, because the buffer zone itself often contains flowers that attract pollinators, an additional in-field buffer zone can be used to protect pollinators from drifting pesticides.

Planting of pesticide-treated seeds can result in pesticide-contaminated dusts particularly in large pneumatic planters (Krupke *et al.*, 2012; Taparro *et al.*, 2012). Dust capture through filters and air recycling deflectors for seed-dressed neonicotinoid pesticides has been shown to reduce, but not eliminate, exposure and thereby risk from pesticides that have high acute toxicity to bees (APENET, 2011; EFSA, 2013; Girolami *et al.*, 2013). Based on a monitoring programme of acute bee poisoning incidents in Austria 2009-2011, it was concluded that improved seed dressing quality and regulated seed-drilling equipment, reduced, but did not completely avoid incidents (Austria, 2012). Recommendations to reduce exposure during sowing of treated seed with pneumatic planters have been developed for some crops, e.g., avoid planting in windy conditions or modify the sowing equipment. However, there is a knowledge gap on dust exposure to pollinators at sowing of dressed seeds for many crops (EFSA, 2013).

These actions can substantially reduce drift and thereby exposure and risk to pollinators in the agricultural landscape. The efficiency of these techniques is normally estimated as percent reduction of drifting pesticide based on measurements and models (Felsot *et al.*, 2010). The efficiency in terms of actual reduced impacts on pollinator individuals in the field remains scarce (e.g., Girolami *et al.*, 2013) and even less is known for communities of pollinator (but see Brittain *et al.*, 2010). There are no data on the extent to which drift reduction technologies have been implemented globally. A database has been set up for countries in Europe to list implemented pesticide drift reduction measures (http://sdrt.info).

Another technical response is to develop new pesticides with low toxicity to non-target organisms. These can potentially also be combined with biocontrol methods (Gentz *et al.*, 2010). However, the number of new active ingredients being developed and introduced is limited, due to economic and environmental challenges.

6.4.2.1.3 Best management practices

Potential risks from exposure of pollinators to pesticides can be reduced by developing and encouraging use practices sometimes referred to as 'best management practices' (Hooven *et al.*, 2013, Wojcik *et al.*, 2014). Suggestions and training for best management and stewardship with specific reference to pollinators appear in advice to pesticide users and education material to pesticide applicators in several countries. This is mainly provided by governmental institutions and universities (e.g., http://insect.pnwhandbooks.org/bee-protection), but also by pesticide distributors and producers (https://croplife.org), universities and commodity groups. They also appear as recommendations for use on the pesticide labels.

There is no comprehensive summary of available advice internationally, but general recommendations include the following. First, to avoid applying the pesticide when the pollinators are actively foraging in the treatment area, e.g., not to apply insecticides when crops and weeds are in flower and in some cases several days before flowering, or at the time of the day when bees are foraging (Thompson, 2001). In public health efforts to reduce mosquito populations, impacts on pollinators have been minimized through timing and mode of application (Khallaayoune *et al.*, 2013). Other recommendations include, whenever possible, to select pesticides with the lowest toxicity rating to pollinators, that rapidly detoxify via degradation and that have a as low as possible residual toxicity; to avoid tank mixing of pesticides as risks from most combined compounds are largely unknown (see Chapter 2); to remove weeds before flowering, e.g., by mowing before application; and to follow the label which may also include information on best management practices (see also Chapter 6.5). It can also be recommended not to apply pesticides when unusually low temperatures or dew are forecast as residues can remain toxic to bees much longer under these conditions. However, the toxicity can increase or decrease with temperature depending on the compound (Medrzycki *et al.*, 2013). There are several techniques to minimize spray drift into adjacent pollinator habitats and non-target crops: spraying at calm wind conditions, adopting low-drift machinery (see above), and using in-crop buffer zones by turning off the sprayer near pollinator habitats at field margins. Other actions include to communicate to nearby beekeepers about when and which pesticide is being applied, such that honey bee hives can be removed or closed during application and a period after the pesticide treatment (Hooven *et al.*, 2013). Obviously this measure will possibly protect honey bees but not other pollinators.

6.4.2.1.4 Reduce pesticide use (includes Integrated Pest Management)

Developing and implementing cropping systems that entail no or low use of pesticides, such as organic farming (see section 6.4.1.1.4) may reduce use and thereby exposure to pesticides. A major effort in conventional farming has been to decrease pesticide use through the adoption of integrated pest management (IPM). This entails a number of complementing pest control strategies with larger reliance on biological pest control and changed cultivation practices that decrease the need to use pesticides and to apply pesticides only when they are needed, i.e., when other measures are insufficient and pest abundances have reached the damage threshold (Desneux *et al.*, 2007; Ekström and Ekbom, 2011; USDA, 2014; http://www.ipmcenters.org/). The cultivation practices involved include crop rotation or mixed cropping, and field margin management, with co-benefits for pollinators discussed in section 6.4.1.1. Measures have to be balanced against the risk of attracting pollinators to or near areas treated with pesticides.

6.4.2.2 Legal responses

6.4.2.2.1 Registration

The requirement to register a pesticide before use is a primary level and regulatory policy tool that in many countries has as one aim: to limit use of bee-toxic pesticides and implement pollinator-safe use of the pesticide. Pesticide products are normally registered one by one, separately for specific uses (e.g., seed dressing, by crop) and separately in each country; but national registration can also be based on internationally agreed procedures. A comprehensive global overview of registration procedures and requirements is not available. It is, however, safe to say that the principle and strictness in the rules and procedures for a pesticide registration vary enormously among countries. An indication of this variation is given by the Environmental Performance Index (EPI) that is updated annually since 2000 (http://epi.yale.edu). It gives a country-based overall assessment of environmental stress on human health and ecosystems based on agricultural land use and policies, and includes pesticide use and regulation.

Information about pesticide use is largely lacking and many countries even lack sales statistics. The EPI therefore instead scores the regulatory strength at the registration of pesticides, and tracks plans by national governments to phase out and ban a number of Persistent Organic Pollutants (POP), including nine pesticides now obsolete in agriculture. Ekström and Ekbom (2011) list the scored capacity to regulate pesticides of 11 coffee-producing countries in 2008. The scores range from 0 or 1 (e.g., Guatemala, Uganda, and Honduras) to around 20 (e.g., Brazil, Indonesia, Peru, and Vietnam), which is level with the scores of countries with internationally recognized strict registration rules (New Zealand 22, Sweden 22, US 19).

Other indications of the global variation in the regulation of pesticide use through registration is given by a regional risk assessment report for West Africa. It shows that pesticide regulation in West African countries is weak and that 50% of pesticide applications in Mali, and 8% of marketed pesticide products in Niger are reported as unregistered and therefore entirely lack risk assessments for pollinators (Jepson *et al.*, 2014). Panuwet *et al.* (2012) report illegal use of pesticides, and weaknesses in the regulation and monitoring of pesticides use in Thailand. More strict registration rules not only include advanced risk assessments (with ecotoxicological studies) and rules of use (through labelling), but can also include responsibilities for the pesticide producer to mitigate risks and monitor use after registration, and allows for further restrictions of use should negative impacts on the environment and non-target organisms be observed (e.g., EC 2009, see especially Articles 6, 36 and 44). New, even more conservative, risk assessment systems are being developed for the EU and US that include measures of lethal and sub-lethal effects for several bee species in addition to the honey bee (EFSA, 2013; Fischer and Moriarty, 2014).

6.4.2.2.2 Labelling

The label provides instruction for use of the pesticide and is considered an important tool to limit risk to non-target organisms and humans. Labelling is a regulatory action that is generally part of the pesticide registration. No comprehensive summary of labelling internationally is available. A label may or may not include instructions directly related to protecting pollinators, but many pesticide labels include clear warnings about the potential risks to pollinators. In a survey on registration procedures including 20 OECD countries worldwide, all countries were found to use label mitigation to reduce risk to pollinators including approval restrictions (e.g., excluded crops, rate restrictions), use restrictions (e.g., not to be used during flowering), and advice for risk-reducing practices (e.g., avoid drift). Most countries (~80%) have a mechanism for enforcing mandatory label mitigation measures and restrictions, e.g., such that “do not” statements are legally binding. Few countries have a formal mechanism for determining the effectiveness of risk mitigation with labelling (Alix, 2013; http://www.oecd.org/chemicalsafety/risk-mitigation-pollinators/), which is typically based on incident monitoring systems.

6.4.2.2.3 Compulsory training and education

Many countries require a licence (certification) for a person to apply certain pesticides; this licence or certification is issued after a formal training course. From a survey of 20 OECD countries, training and education for pesticide applicators was mandatory in half of the countries (Alix, 2013). It is likely that such mandatory training is an efficient way to disseminate information on the responsible use of pesticides for humans and the environment, but no evaluation of the effectiveness or compliance with such measures was found. Although a country may have mandatory training for some pesticides (e.g. for 'Restricted-use' pesticides in the US http://www.epa.gov/pesticides/safety/applicators/restrict.htm), many pesticide appliers (including professionals) are not required to receive formal training for other pesticides (e.g., 'General-use' pesticides in the US).

6.4.2.2.4 Bans and moratoriums

On the global level, 72 countries have joined the Rotterdam Convention on Prior Informed Consent (http://www.pic.int), which controls trade restrictions and regulation of toxic chemicals, and many countries adhere to the Stockholm Convention of Persistent Organic Pollutants (http://chm.pops.int). The conventions aim to phase out the use of the use of chemicals meeting certain criteria in terms of persistence, bioaccumulation, and toxicity; this list currently includes 9 pesticides used in agriculture (the insecticides aldrin, dieldrin, chlordane, DDT, endrin, mirex, heptachlor, and toxaphene, and the fungicide hexachlorobenzene).

A moratorium is a regulatory action in which a temporary suspension of certain uses is imposed at a regional or national level. Such suspensions have been imposed when monitoring and/or research demonstrate negative impacts on pollinators after an accepted registration. A recent, much debated, example is the temporary moratorium in the EU of certain uses of neonicotinoids (Dicks, 2013; Gross, 2013; Godfray *et al.*, 2014). The decision was based on identified effects and knowledge gaps in the estimated risks to wild pollinators and honey bee colonies in the field from neonicotinoid use (EFSA, 2013b; EFSA, 2013c; EFSA, 2013d; EFSA, 2013e; Godfray *et al.*, 2014; EU Regulation 485/2013). The 2013 European regulation (No 485/2013) required manufacturers to submit information on risks to pollinators other than honey bees, and a number of other aspects of risk. The debate is ongoing whether the scientific evidence is sufficient to warrant a continuation of the moratorium. Use of four neonicotinoids has also been restricted on *Tilia* spp. trees in Oregon, US (http://www.oregon.gov/oda/programs/Pesticides/RegulatoryIssues/Pages/PollinatorIssues.asp), following a major kill of bumble bees foraging on those trees when they were sprayed. A restriction on use of neonicotinoid seed treatments for corn and soy in Ontario, Canada, is now in force and will require an 80% reduction in use by 2017.

6.4.2.2.5 Options to strengthen pesticide regulation globally

Risks of pesticides to pollinators are likely to decline if nations match risk assessment stringency and regulation of pesticides with those countries that have the most advanced registration procedures. This would raise registration standards globally. However, there are important limits to realise this policy as it will require resources that are not always available. Advanced risk assessments at registration are costly. The pesticide producers need to perform more tests, and may be reluctant to go through a costly registration for small markets. Such standards are expensive and require considerable data to support them. Also the governments setting the standards need to fund staff to handle registrations and assess risks. Sufficient experience, technical skills and specializations may be lacking within government agencies to assess studies properly.

There are several possible solutions. One option is to make registration studies more readily available worldwide such that they can be used by more than one country. A more active communication of knowledge worldwide would allow for improved risk assessments in countries with weak regulatory institutions (http://www.oecd.org/chemicalsafety/testing/oecdguidelinesforthetestingofchemicals.htm).

Several countries can also merge resources and skills for a harmonized or common registration process on a joint market. For example, in 1994, thirteen countries in West Africa developed a joint registration process for pesticides to support enhanced control of the pesticide trade (http://www.insah.org/). Seven of the countries have fully integrated this registration into their legislation. Similarly, the Southern and East African Regulatory Committee on Harmonization of Pesticide Registration (SEARCH), the East African Community (EAC), and the Economic and Monetary Community of Central African States (CEMAC) have started to harmonize their pesticide regulations, but do not yet have a common registration process. In other parts of the world, such discussions have been initiated focusing primarily on information exchange (e.g., CARICOM in the Caribbean, Comunidad Andina CAN in South America, and Secretariat of the Pacific Community SPC in the Pacific). The Organization for Economic Cooperation and Development (OECD) has compiled a guideline for joint reviews of pesticides among nations (http://www.oecd.org/chemicalsafety/pesticides-biocides/46754279.pdf).

6.4.2.2.6 Global Code of Conduct

An International Code of Conduct on Pesticide Management was adopted by member countries of the FAO in 1985, revised in 2002 and again in 2014 (http://www.fao.org/docrep/005/y4544e/y4544e00.htm; http://www.fao.org/agriculture/crops/thematic-sitemap/theme/pests/code/en/), primarily targeting voluntary actions by government and industry to reduce risks for human health and environment from pesticide use. However, only a few countries (61% of those surveyed, or 31 countries) appear to be using the code, based on a survey in 2004 and 2005 (Ekström and Ekbom, 2010), possibly because it had not been well promoted internationally. Ekström and Ekbom (2010) suggest that the Code could be used as a vehicle to promote non-chemical pest management options and the use of pesticides with low toxicity and exposure, and to phase out the use of highly hazardous pesticides as ranked by researchers, NGOs and governmental organisations (Kovach *et al.*, 1992; WHO, 2009; PAN, 2013).

6.4.2.2.7 National risk reduction programmes

Several national pesticide risk-reduction programs have been implemented since the 1980s; examples include those in Brazil, Canada, Ethiopia, France, Sweden (e.g., Barzman and Dachbrodt-Saaydeh, 2011; Rusch *et al.*, 2013). The efficiency of these programmes is generally evaluated based on risk indicators to health and environment, but not considering pollinators specifically (see section 6.4.2.4.1). Development of specific risk indicators from exposure of pesticides to pollinators would be useful for evaluating possible impacts of such programmes on pollinators.

6.4.2.2.8 Promoting pollinator-friendly farming and forestry practices

Promoting reduced pesticide or non-chemical pest management practices depends not only on a technical or knowledge response, but a willingness to provide resources that give continuous support to pollinator-friendly pest management research, extension and practices. It entails enacting agricultural policies that promote agricultural methods that reduce pesticide use, adopt IPM strategies, and low- or no-pesticide crop production systems (e.g., organic farming). As an example, the EU has decided that member states develop an Integrated Pest Management (IPM) action plan by 2014 (91/414 EEC).

6.4.2.3 Economic responses

There are many subsidy programs aimed to support biodiversity in agricultural landscapes that include the non-use of agrochemicals. Available evidence on the efficacy of these actions provides a mixed and complex picture of the effects of reducing agrichemical impacts on wildlife (Dicks *et al.*, 2014b; http://www.conservationevidence.com/actions/139), but was unanimously characterised as beneficial in an expert assessment (Dicks *et al.*, 2014c).

Another economic response is to introduce pesticide taxes and fees. These are market-based instruments that have been proposed to discourage pesticide use, and have been implemented in some European countries (Skevas *et al.*, 2013). Important knowledge gaps remain with respect to introducing such policies broadly, e.g., related to actual efficiency in reducing risks depending on pesticide use, toxicity and productivity in a region (Skevas *et al.*, 2013). Pedersen *et al.* (2012) further show that the uptake efficiency when implementing these instruments will vary depending on the farmers' motivation to maximise profits or increase the yield, implying that it is necessary to adopt an array of policy instruments to match the rationales of many farmers.

The cost and crop damage risk of an IPM approach can be minimized by a yield insurance scheme. A promising example of this is in Italy, where the program is managed as a mutual fund by participating farmer associations (Furlan and Kreuzweiser, 2015).

6.4.2.4 Knowledge responses

6.4.2.4.1 Monitoring and evaluations

Monitoring of environmental risks from pesticides is performed in many countries. It can be based on health and environmental risk indicators based on pesticide sales and use estimates, toxicity, and of measurements of residues in the environment (e.g., Labite *et al.*, 2011, http://www.oecd.org/env/ehs/pesticides-biocides/pesticidesriskindicators.htm).

Little monitoring assesses risks on pollinators specifically. However, there is some evidence that restrictions have reduced the risk to pollinators in the UK. Based on risk indicators, Cross and colleagues found a decrease in the average environmental risk of pesticides per hectare for fruit and arable crops between the first introduction of risk-based regulations in 2002, and 2009 (Cross and Edwards-Jones, 2011; Cross, 2013). They combined pesticide usage data with a measure of hazard (toxicity) for each specific chemical, including simple scores for bee and beneficial insect toxicity. Reduced risks were largely due to removal of specific chemicals from the market, but were not consistent across crops as the risk score increased for, e.g., cider apples and pears (Cross, 2013).

There has been continuous, or time-limited, monitoring of poisoning incidents of mainly honey bees in some countries. In some EU countries and the US (http://www.npic.orst.edu/incidents.html) authorities maintain intoxication incident surveillance. No environmental monitoring of pesticide impacts on wild bees is documented except for bumble bees in the UK and in the US.

Evaluations of such monitoring programmes published in the scientific literature include incidents of honey bee and bumble bee poisoning in the UK 1994-2003. Bee death incidents attributed to pesticide poisoning declined from 23 to 5 per year in this period (Barnett *et al.*, 2007). Similarly, the number of incidents had a decreasing tendency, but with some intermittent peaks, in the UK, the Netherlands and Germany 1981- 2006 (Thompson and Thorbahn, 2009). Very few incidents occurred in Canada 2007-2011, but with a sharp increase in 2012 in the Ontario province, where exposure to neonicotinoid dust during planting of corn was suspected to have caused the incident in up to 70% of cases (Cutler *et al.*, 2014a). Monitoring of bee poisoning from use of neonicotinoid insecticides has taken place in Austria, Slovenia, Italy, and France. Several incidents were reported, but the direct causality between pesticide exposure and observed bee deaths is uncertain for several of these studies (EFSA, 2013).

6.4.2.4.2 Education

An important and efficient action is to educate pesticide applicators on the correct use of pesticides by following the label instructions and to adopt risk reduction practices. Many such programs exist around the world (see section 6.4.2.1). Farmer education has also been shown to result in effective implementation of IPM measures that reduce exposure and risks to beneficial organisms (van den Berg *et al.*, 2007, Waddington *et al.* 2014). Studies of pesticide applicator attitudes suggest that there is potential for voluntary approaches to raise awareness among applicators of habitats sensitive to pesticide drift in rural landscapes (Reimer and Prokopy, 2012). Other important target groups are students in plant protection, agronomy and agriculture in general, and extension personnel who give pest management advice to farmers in particular. Education of extension personnel can serve as effective means of promoting pollinator-friendly practices and avoid unnecessary pollinator exposure to pesticides, as exemplified by a study from Ghana (Hordzi, 2010).

See section 6.5.12 for an example of a decision support tool designed to help farmers and advisers choose crop protection products with lower toxicity to pollinators.

6.4.2.4.3 Research

Ecotoxicology is an area of very active research (see section 2.2.1), which can have a substantial impact on policies and registration if it demonstrates unanticipated impacts of a particular pesticide on non-target species (see section 6.4.2.2.4, for example). In response to new research, regulatory authorities want to understand why non-target effects are happening and seek to impose mitigation measures.

Increased funding into research for the development of biological and agroecological methods of pest control would create opportunities for viable alternatives to pesticide uses. More information on the economic benefits (or lack thereof) of pesticide usage would improve the decision base for pesticide users.

6.4.2.5 Heavy metals and other pollutants

There is a lot of concern and monitoring of heavy metals and other pollutants in the environment. However, there are few studies addressing impacts specifically on pollinators and pollination (section 2.2.4). There are no policies to mitigate impacts of heavy metals and other pollutants specifically on pollinators. Actions employed to reduce risks for wider biodiversity (e.g., soil removal, or phytoremediation) might be useful to pollinators by removing hazards, or they might constitute risks, e.g., by providing contaminated pollen for pollinators, but this remains to be evaluated and tested.

6.4.2.6 Genetically modified organisms

6.4.2.6.1 Legal responses

In most countries, commercial release of genetically modified (GM) crops is subject to specific legislation and for those countries that are signatories to the Cartagena Protocol on Biosafety to the Convention on Biological Diversity (CBD), environmental risk assessment (ERA) is required for the regulatory approval of GM organisms (CBD 2000, Annex II; 6; 1, Annex III). The Cartagena Protocol states that ERA of GM plants should be conducted on a case by case basis, taking into account the environment where the plants will be released and the characteristics expressed by the transgene. Despite that, in general, the environmental risk assessments of GM plants have followed the toxicological model used for synthetic pesticides. Usually this model evaluates the direct toxic effects of a specific product (such as an insecticide) on surrogate species and extrapolates the results to all other species in the environment (Suter II, 2007). Therefore, the species *Apis mellifera* has been used in ERA as a representative organism of all pollinator species (Duan *et al.*, 2008; Carstens *et al.*, 2014). The toxicological model has been criticized when used for GM organisms for not considering the characteristics of the transformed plant for the selection of non-target species, the inserted transgene and the environment where the plant will be released (Andow and Hilbeck, 2004; Hilbeck *et al.*, 2011; Andow *et al.*, 2013). Furthermore, this toxicological model applied to pre-release evaluation of GM plants has focused almost exclusively on the isolated proteins produced by the GM plants (Duan *et al.*, 2008; Wolfenbarger *et al.*, 2008; Lövei *et al.*, 2009) with little consideration of the whole plant. It does not adequately address the possible indirect effects of importance to pollination, such as possible changes in the bee foraging behaviour (Arpaia *et al.*, 2011). Indirect effects through

TABLE **6.4.2.1**
Summary of evidence for responses relating to pesticides, pollutants and genetically modified organisms

Response (relevant chapter 6 section)	Main driver(s) (chapter 2)	Type of response	Status	Scientific evidence
Globally raise standards of risk assessment and regulation of pesticide use (includes labelling) (6.4.2.1.1; 6.4.2.2.2; 6.4.2.2.5, 6.4.2.2.6)	Pesticides (2.2.1)	Technical legal	Established	Reduces risks to pollinators **WELL ESTABLISHED**
Risk assessment using risk indicators based on pesticide use (6.4.2.1.1)	Pesticides (2.2.1)	Technical	Proposed	Few indicators specifically addressing pollinators available **ESTABLISHED BUT INCOMPLETE**
Risk profiling to assesses risk from pesticide exposures to pollinators for particular crops and regions (6.4.2.1.1)	Pesticides (2.2.1)	Technical knowledge	Tested	Tested in three countries **ESTABLISHED BUT INCOMPLETE**
Risk reduction and mitigation through agricultural practices that reduce exposure to pesticides (6.4.2.1.2; 6.4.2.1.3; 6.4.2.4.3)	Pesticides (2.2.1)	Technical Legal Knowledge	Established	Reduces risks to pollinators inside and outside fields **WELL ESTABLISHED**
Risk reduction and mitigation through technology that reduces pesticide drift (6.4.2.1.2)	Pesticides (2.2.1)	Technical	Established	There is evidence of substantially lower drift and dust emissions with improved technology **WELL ESTABLISHED**
Risk reduction through the development of less pollinator-toxic pesticides (6.4.2.1.2)	Pesticides (2.2.1)	Technical	Proposed	Few new pesticides are being developed in general **INCONCLUSIVE**
Educate and train extension, farmers, land managers and the public on the risks and responsible use of pesticides and pollutants (6.4.2.4.2)	Pesticides (2.2.1)	Knowledge	Established in many countries	Reduces risks to pollinators **WELL ESTABLISHED**
Monitor and evaluate the risks and impacts of pesticides and pollutants (6.4.2.4.1)	Pesticides (2.2.1)	Knowledge	Poorly developed for pollinators	**ESTABLISHED BUT INCOMPLETE**
Retract registration if research shows negative impacts on pollinators from actual use (6.4.2.4.3)	Pesticides (2.2.1)	Legal knowledge	Tested	Reduces risks to pollinators **UNRESOLVED**
Globally phase out obsolete chemistries that may be more persistent bioaccumulative and/or toxic (6.4.2.4.3)	Pesticides (2.2.1)	Legal	Established	**WELL ESTABLISHED**
Research, implement, and promote practices for pest management with non-pesticide options, or less toxic pesticides (e.g. Integrated Pest Management) 6.4.2.1.3; 6.4.2.1.4; 6.4.2.2.8; 6.4.2.4.2)	Pesticides (2.2.1) Changes in land management (2.1.2)	Technical legal Knowledge legal	Established	Reduces risks to pollinators **WELL ESTABLISHED**
Continually evaluate the efficiency of measures and programmes aimed at reducing risk from pesticide use and pollution (6.4.2.4.1)	Pesticides (2.2.1)	Technical knowledge	Proposed	**INCONCLUSIVE**
Introduce national risk reduction programmes (6.4.2.2.7)	Pesticides (2.2.1)	Legal policy	Established	Reduces risks to pollinators **ESTABLISHED BUT INCOMPLETE**
Subsidize non-use of pesticides (6.4.2.3)	Pesticides (2.2.1)	Economic	Tested	**ESTABLISHED BUT INCOMPLETE**
Market based instruments to discourage pesticide use (taxes and fees) (6.4.2.3)	Pesticides (2.2.1)	Economic	Tested	Tested but not evaluated in some countries **INCONCLUSIVE**
Provide insurance against loss and damage risk linked to IPM (6.4.2.3)	Pesticides (2.2.1)	Economic	Tested	Tested in Italy **INCONCLUSIVE**
Consider wild bees in the risk assessment and monitoring of impacts of gene modified plants (6.4.2.6)	Genetically modified organisms (??)	Technical legal	Proposed	Indirect and sublethal effects of GMO crops on wild pollinators are not adequately addressed in GMO risk assessments **INCONCLUSIVE**

the food chain and those generated by loss of flowers in response to herbicide use, are not considered in the risk assessments for insect resistant or herbicide tolerant GM crops (see section 2.2.2.2.1 for assessment of these effects).

Possible changes in the toxicological model have been discussed and new approaches for ERA of GM plants have been proposed to match the Cartagena Protocol guidelines (Hilbeck *et al.*, 2011; Sensi *et al.*, 2011; Dana *et al.*, 2012; Sanvido *et al.*, 2012; Andow *et al.*, 2013; Carstens *et al.*, 2014), but there is no consensus about the exact scope of the assessment of GM plants on non-target species. Globally, there is a clear need for comprehensive, transparent, scientific guidelines for selecting the non-target species to be evaluated, and among those, different species of pollinators need to be considered, not only *Apis mellifera*. The lack of these guidelines has led to different interpretations of the risk assessment process of GM plants among stakeholders (developer companies of GM crops, governmental regulators, and scientists) (Hilbeck *et al.*, 2011; Andow *et al.*, 2013; see **Table 1** in Carstens *et al.*, 2014).

In conclusion, there are no international specific policies for risk assessment of GM plants on pollinators and no specific mitigation action to deal with the possible risks. The Cartagena Protocol does not make a clear reference to pollinators, but they are in the legislation of many countries within the scope of non-target organisms, along with other beneficial species such as those used as biological control agents (Flint *et al.*, 2012). Various species, among them *Apis mellifera*, quail and mouse have been used in the ERA of GM crops. Whether these are appropriate surrogate species for wild pollinators has been questioned for toxicological tests of synthetic pesticides (see section 6.4.2.1).

6.4.2.6.2 Knowledge responses

In Brazil, a monitoring program may be required by CTNBio (National Biosafety Technical Commission, http://www.ctnbio.gov.br), based on the results of risk analysis and it is designed on a case by case basis. Until now, this committee has not required monitoring specifically for pollinators. In Europe, post-market environmental monitoring is required for all GM crops released in the environment (EFSA, 2011), but there are few specific guidelines for pollinators (Shindler *et al.*, 2013; Dolek and Theissen, 2013).

6.4.3 Nature conservation

Many pollinator species are known to be vulnerable or in decline (Chapter 3). This section examines nature conservation responses that are intended to or likely to support pollinators and pollination. The nature conservation focus means that the targets are wild pollinators rather than domesticated pollinators (e.g., the European honey bee *Apis mellifera*) but may nevertheless be important to agricultural pollination. Nature conservation responses are commonly applied to mitigate negative impacts of land use change, such as those identified in Chapter 2.

6.4.3.1 Technical responses

6.4.3.1.1 Habitat management

This area has the strongest knowledge base because it has been a focus for land management practitioners and ecological scientists. The evidence that loss of habitat has been a driver of pollinator decline is very strong (see section 2.1.1). Many studies have examined the response of pollinators to on-ground actions, which inform possibilities for the future. Possible actions range from the protection or maintenance of existing natural habitat to the creation of new habitat patches by ecological restoration. At a larger spatial scale there are also actions that relate to the planning of natural habitat networks and how they spatially relate to one another to ensure that pollinators can disperse and adapt to global change, and that there is the best benefit flow into agricultural landscapes (crop pollination).

There is evidence that forage resources commonly limit wild bee populations (Roulston and Goodell, 2011), which suggests that provision of additional appropriate forage resources could have significant population effects, but most studies do not assess these, instead focusing only on activity and frequency of pollinators. Planted forage resources might be focused on native plant species, and therefore be considered part of a nature conservation strategy, but because these plantings are generally integrated into agricultural practice, we have reviewed them in section 6.4.1.1 as agricultural responses. Forest management practices also influence bee communities, and planted forests have been shown to host significant bee communities in the early stages, but declining as a more closed forest environment develops (Taki *et al.*, 2013). In New Jersey, USA, bees were more diverse and abundant when there was less closed forest in the surrounding landscape (Winfree *et al.*, 2007). In tropical forest successional communities in Kenya, pollinator abundance and diversity actually increased across a gradient from natural forests to cultivated areas (Gikungu, 2006). Greater generalization was found among the bee communities in more mature forests, and more specialized and rare bee species were found in the earlier successional and more open habitats. In general, bees benefit from native plants and non-farmed habitats, but increasing cover of forests with closed canopies is less likely to favour rich bee communities.

In addition to the potential to improve crop pollination (Garibaldi *et al.*, 2014), restored patches might re-establish pollination networks of wild plant species and their pollinators (Menz *et al.*, 2011). Some studies have shown that restored patches compare well with remnant patches in terms of diversity and identity of dominant pollinators (Forup *et al.*, 2008; Williams, 2011; Hopwood, 2008) but the flower visitation rate for native plant species (Williams, 2011) and interactions with insect parasites (Henson *et al.*, 2009) may take longer to recover.

Bees often require specific nesting resources that can be enriched in a nature conservation strategy. For *Osmia bicornis* (formerly *rufa*), a stem-nesting bee in Europe, the provision of nesting material (reeds) in habitat patches in an agricultural landscape led to a local population increase (Steffan-Dewenter and Schiele, 2008) and many other trials establish that appropriate artificial nesting materials are used by a range of solitary bee species (Dicks *et al.*, 2010). In contrast, the provision of boxes intended to host bumble bees has had highly variable outcomes (Dicks *et al.*, 2010; Williams and Osborne, 2009) with average occupation of boxes low (Lye *et al.*, 2011). Honey bees and stingless bees prefer to nest in large old trees, so protection of such trees is important. For example, the stingless bee species *Melipona quadrifasciata* was shown to nest selectively in the legally protected cerrado tree *Caryocar brasilense* (Atonini and Martins, 2003) (further discussion of nest sites for social bees is in 6.4.4.1.9 and 6.4.4.4.).

6.4.3.1.2 Landscape planning and connectivity

Landscape planning for better pollinator outcomes has been the subject of theory and discussion (e.g., Menz *et al.*, 2011; Viana *et al.*, 2012) and a component of large-scale research projects, such as LEGATO (http://www.legato-project.net/). Although landscape planning has aided conservation of some species, little information is available to demonstrate the effectiveness of landscape planning strategies for pollinators and pollination specifically. Studies of existing fragmented landscapes have shown that in some biomes, the edge environments that predominate in small or linear patches tend to favour only certain pollinators (Girão *et al.*, 2007; Lopes *et al.*, 2009). An important theme in landscape planning is the maintenance of landscape connectivity for animal movement and gene flow. Several recent studies imply that the configuration of landscape features (the way they are arranged in the landscape) have only weak effects on bee populations or population persistence (Franzen and Nilsson, 2010; Kennedy *et al.*, 2013, for example). However, in a review of studies examining landscape effects on the pollination, Hadley and Betts (2012) indicated that it had been very difficult to distinguish effects of landscape configuration (i.e., the shapes and position of habitat fragments) from the more general impact of habitat loss (i.e., direct effects of land clearing).

Strategically-placed replanted vegetation might increase connectivity for ecological processes, which could benefit species in fragmented landscapes and support the ability for species to move in response to climate change. There is experimental and modelling evidence that pollen flow occurs between remnant and replanted vegetation (Cruz Neto *et al.*, 2014) and that linear features linking patches of floral resource promote movement of bees and other pollinators through landscapes (Cranmer *et al.*, 2012; Hodgson *et al.* 2012), thereby enhancing pollen transfer between plants in those patches (Townsend and Levey, 2005; Van Geert *et al.*, 2010). These patterns provide some documentation of the benefits that habitat connectivity can provide. The role habitat connectivity has in maintaining pollinator populations remains unclear, but theory and observations for other taxa suggest that when the amount of natural habitat in the landscape declines below approximately 20% populations risk becoming isolated and connectivity may play an important role in their conservation (Hanski, 2015). Increased connectivity can be achieved by making the matrix (i.e., land between the habitat patches) more hospitable to dispersing organisms (Mendenhall *et al.* 2014), as well as by preserving or creating “stepping stones” and corridors of habitat connection.

Climate change can impact populations in many ways, and in some cases species are expected to shift in distribution (i.e., populations move) generally poleward or to higher elevations, so that they remain within a climatically suitable environment (Chen *et al.*, 2011). This kind of movement is only possible if suitable habitat for the species occurs at the new locations. Further, for migration to occur naturally, connectivity of habitat for the species in question may be important, keeping in mind that species vary greatly in their capacity to move long distance or cross inhospitable environments. With this in mind, adaption to climate change could include habitat improvements and increasing connectivity across landscapes, but currently there is limited evidence regarding effectiveness of this strategy.

6.4.3.1.3 Non-timber forest products

Pollinators might also be important to the productivity and maintenance of non-timber forest products (NTFPs) (Rehel *et al.*, 2009). For example, Brazil nut is primarily harvested from wild sources (Clay, 1997) and the production of nuts depends on pollination by large-bodied wild bees (Motta Maués 2002). Another interesting example showed that Yucatec Mayan people in Central America relocate honey bees into maturing stands of secondary forest, aged 10–25 years, to aid pollination and take advantage of the many flowering plant species for honey production (Diemont *et al.*, 2011). While there are, no doubt, many other examples of NTFP’s that are animal pollinated (e.g. guarana, Krug *et al.*, 2014; *Euterpe* palm, Venturieri, 2006), little is known of the extent to which sustainable yield depends on pollination rates or pollinator conservation and there is little scientific knowledge available regarding the effectiveness of nature conservation strategies in protecting the pollinators of NTFPs.

6.4.3.1.4 Invasive species

Where non-native insect pollinators pose a threat to the native fauna (see Chapter 2, section 2.5), management of invasive species is likely to be an important component of a pollinator conservation strategy. However, eradication of invasive species has proven difficult in most circumstances, with successful eradication most often occurring on islands where the area to manage is limited, and re-invasion is less likely. Because of this challenge, studies of the effectiveness of invader management in terms of pollinator response are rare. Nagamitsu *et al.* (2010) showed that active removal of *Bombus terrestris* from sites in Japan allowed an increase in abundance of queens for two native *Bombus* species, but attempts to reduce *Bombus terrestris* numbers in the next year failed. Hanna *et al.* (2013) show that a reduction in invasive wasps (using poison baits) led to an increase in pollination and subsequent fruit set of a native plant in Hawaii, although interestingly in this case the primary pollinator was also an invasive species (*Apis mellifera*).

Because it is so difficult to eradicate invasive species, a focus on mitigating their impact can be the necessary alternative. There have been many examples where management has successfully contained or reduced populations of invasive species, reducing their impact (Mack *et al.*, 2000).

6.4.3.1.5 Species-focused conservation actions

Butterflies have often been a target group for species-focused conservation actions (New *et al.*, 1995) with a number of successful projects (e.g., Thomas *et al.*, 2009) including *ex situ* conservation (Schultz *et al.*, 2008). Although they have had a high profile in species conservation, relative to other insects, butterflies are considered minor pollinators relative to other insect groups, especially bees (Chapter 1). One group of wild bees has been a focus for nature conservation: the bumble bees (*Bombus* spp.). This reflects that bumble bees are large and distinctive, and some species have experienced significant declines in parts of Europe, Japan, and the Americas (Williams and Osborne, 2009). Generalising from *Bombus* to other species should be done with caution, but these studies provide a starting point for understanding the potential for species-focused conservation actions.

Most on-ground strategies for species conservation are essentially forms of habitat management (and are therefore discussed above), albeit that some habitat interventions can be more precisely targeted if single species are the focus. For example, nest preferences are quite specific, and so provision of nest resources should match the preferences of the species of concern. Beyond habitat management, conservation strategies for single species might also include *ex situ* conservation and species re-locations. For example, *Bombus subterraneus* has been extirpated from its original range in the UK, but still occurs on the European mainland and in its introduced range in New Zealand. A project has been established to restore the required habitat and then reintroduce bees (http://hymettus.org.uk/downloads/B_subterraneus_Project_report_2011.pdf accessed September 5 2014). Bees were released in 2012 and are still being sighted in 2014 (http://www.bumblebeereintroduction.org/news/news/ accessed September 5 2014).

Wild *Apis* species in Asia, such as *Apis dorsata*, have also been subject of special attention. There is a long history of traditional exploitation of these species for their honey, and as a consequence they have particular cultural significance and are the subject of traditional knowledge. Use of traditional techniques to create good nesting locations might help support their populations (Hadisoesilo, 2001).

We could find no reports of other active *ex situ* conservation actions that were specifically pollinator targeted, although some vertebrate pollinator species (especially birds and bats) that are endangered in their native range are held in captive populations in zoos and other institutions (e.g., the Rodrigues Fruit Bat, *Pteropus rodricensis*, O'Brien *et al.*, 2007). Fruit bats are the primary pollinators of some plants on Pacific Islands but are hunted for meat and threatened by hunting and invasive species (Cox and Elmqvist, 2000). Captive populations may contribute to species re-introductions if the drivers of threat can be managed in the natural range.

Translocation of species into new locations, where they may have a better chance of survival, has been suggested as a strategy that might be increasingly called for under climate change (Seddon *et al.*, 2014) and has recently been suggested for bumble bees in particular (Kerr *et al.*, 2015). This strategy might also have the effect of restoring ecological function to locations that have lost species. The number of case studies for the practice of translocation is a rapidly increasing and therefore helping to reveal the logistic challenges of the strategy (Seddon *et al.*, 2014). The knowledge base for translocation of pollinators in particular is poor because insects, the most important group of pollinators, are rarely the subject of translocations (most cases focus on birds and mammals: Seddon *et al.*, 2014). Nevertheless there have been successful translocations of some butterfly species (Kuussaari *et al.*, 2015) and among the important lessons is that there must be high-quality suitable habitat available in the new location. Translocation comes with considerable risk of failure to establish and could also lead to unintended harm if translocated species become invasive pests or vectors for disease in the new range (Seddon *et al.*, 2014 and see section 6.4.3.1.4.

Invasive species). Given the complexity of the task, the shortage of practical experience, and the known risks associated with translocations, evidence that translocation could play an important role in pollinator conservation remains very limited.

For plants that rely on specialised pollinators for seed production, loss of pollinators might threaten their population viability even if conditions for vegetative growth are suitable (Pauw, 2007; Vovides *et al.*, 1997; Machado and Lopes, 2000). For these plants recovery plans may require direct action to save their pollinators also. We are not aware of any studies that have assessed the effectiveness of this strategy. One European project is testing integrated plant and pollinator conservation for the dittany (*Dictamnus albus*). This plant species is rare and protected in several European countries, pollinated by generalist medium to large bees and threatened in some populations by pollination deficit (http://www.pp-icon.eu/). Management techniques being tested include flower planting and adding artificial solitary bee nest sites.

6.4.3.2 Legal responses

Legal responses can drive on-ground change, but are not in themselves a change to the natural environment in which pollination occurs. Literature on the effectiveness of legal responses in terms of pollination outcomes is lacking. Here we review some of the policy responses that are relevant to nature conservation for pollinators and pollination, but can provide only limited insight to their effectiveness.

6.4.3.2.1 Species listing and trade regulation

A traditional mechanism for managing species facing high extinction risk is to assess them as critically endangered, endangered or vulnerable (e.g., the IUCN Red Lists, national red lists, the Convention on Biological Diversity, European Community Birds directive), which might then invoke a protected status in national or international law, or heightened community awareness. The Endangered Species Act has been credited with improving the prospect of survival of listed butterflies in in the USA (Black, 2012), where the legislation has led to specific actions and investments by the federal government that might not have happened without the Act.

The formal listing of species has traditionally been biased towards certain taxonomic groups (e.g., plants, vertebrates) whereas insects (which are overwhelmingly the most important pollinators) are grossly under-represented (Stuart *et al.*, 2010; Winfree, 2010; Byrne and Fitzpatrick, 2009). However, the first continent-wide list Red List for bees was recently published for Europe (Nieto *et al.*, 2014); it reports that an estimated 9% of all bees (but 26% of bumble bees) are threatened. Importantly, for 56% of species there were not enough data to assign a status, underlining the size of the knowledge gap.

Another form of species-specific protection is to limit the permitted trade in species that have commercial value, and in some cases this could influence outcomes for pollinators. Lee *et al.* (2005) record that the establishment of a wildlife crimes unit in Sulawesi, Indonesia reduced the trade in some protected species, but in this case fruit bats, which are threatened by exploitation and known to be significant pollinators, were not on the list for protection.

Regulations restrict the import and/or release alien pollinator species in some countries. For example, there are regulations in a number of countries to restrict the import and use of non-native bumble bees as greenhouse pollinators (see Velthuis, 2002; Velthuis and van Doorn, 2006). The Invasive Alien Species Act in Japan restricts the transport of *Bombus terrestris* (https://www.env.go.jp/en/nature/as.html). In the UK, it is illegal to release non-native species according to the Wildlife and Countryside Act 1981 (http://www.legislation.gov.uk/ukpga/1981/69). Guidance on the regulations related to importing non-native bumble bees in this context can be found in the Guidance on Importing Bees into England (Animal and Plant Health Agency's (APHA) http://www.nationalbeeunit.com/index.cfm?pageId=126). The regulation has been recently amended to take account of non-native subspecies (Natural England, 2014), such as non-native subspecies of *Bombus terrestris*. In the USA, import of certain bee species (*Bombus impatiens*, *B. occidentails*, *Megachile rotundata*, *Osmia lignaria*, and *O. cornifrons*) from Canada is possible, while import of other species is restricted (USDA APHIS, 2013). Australia has rejected the import of *Bombus terrestris* as greenhouse pollinator and one state has classified the import of this species as key threatening process for native fauna (Australian Government Media release, 2008; NSW Scientific Committee, 2004). For North American countries, there are guidelines for the petition for import and release of non-*Apis* pollinators (NAPPO, 2008). National-level regulations are not effective if neighbouring countries on a land mass do not have similar regulations. An example of this is the invasion of *B. terrestris* in Argentina after its introduction into Chile (see Chapter 3).

The European honey bee is considered an introduced species in the Americas, most parts of Asia, Australia, and Oceania. Though there are concerns that managed honey bees may be a competitor of native bees (see Chapter 2), there are relatively few regulations in place that restrict the spread of honey bees as an alien species. Regulations in most Australian states prohibit the placement of apiaries in certain natural areas (Salvin, 2015). The Africanized honey bee is considered undesirable in many countries and there are regulations in some countries to restrict its potential spread. In Mexico, for example, there are measures to control the Africanized bee (Modificación a la Norma Oficial Mexicana NOM-002-ZOO-1994, Actividades técnicas y operativas aplicables al Programa Nacional para el Control de la Abeja Africana). In some Argentinian provinces Africanized honey bee colonies are prohibited or have to be destroyed (e.g., Neuquén: La Legislatura de la Provincia del Neuquén Sanciona con Fuerza de Ley 1796; San Luis: Legislación Apícola de la provincia de San Luis Ley Nº 4.899 / 90). In the Australian State of Victoria, and the neighbouring country of New Zealand, the Africanized honey bee is classified as an exotic notifiable disease (New Zealand Ministry for Primary Industries – Bees and Honey, 2014) (Victoria Department of Environment and Primary Industries – Notifiable Diseases in Victoria).

6.4.3.2.2 Protected areas and other area-based conservation measures

Another widely-applied policy mechanism for nature conservation is the use of protected area status to conserve habitat. This approach has been applied in many counties around the world, leading to protected status, at least in name, for significant areas of land (Gaston *et al.*, 2008). Of course, protected area status is not usually used solely to achieve a goal as specific as pollinator conservation, but higher-level goals such as biodiversity conservation usually apply. In Indonesia, decrees to conserve Karst landscapes, their natural caves and the bats living in them (acknowledging their importance as pollinators) is contained with the Guidelines for Management of Karst areas (2000) and Regulation on the Delineation of Karst areas (2012).

In some countries protected status is conferred on certain locations on the basis of religious or spiritual belief. There is increasing recognition of the importance of protected areas of this kind, sometimes recognised as "Indigenous and Community Conserved Areas" (https://iucn.org/about/union/commissions/ceesp/topics/governance/icca/). This form of protected status might support conservation of pollinators, even if this outcome is not an explicit part of the rationale. In parts of Madagascar local people protect small forest patches and modelling suggests these patches might support a significant level of pollination for surrounding agriculture (Bodin *et al.*, 2006).

There is some evidence that protected area status has reduced the rate of habitat loss in many locations (Joppa and Pfaff, 2011), although there are also examples where this has failed (Gaston *et al.*, 2008). It is fair to assume that protection of habitat has benefitted pollinators or pollination interactions, but we are not aware of any studies that have specifically addressed this question. In addition to supporting populations of wild pollinators, protected areas can, in some circumstances, provide floral resources that support beekeeping (Hausser *et al.*, 2009).

Although the value of small habitat fragments has been recognised (Tscharntke *et al.*, 2002, Turner and Corlett, 1996), reserve design for nature conservation has typically emphasised the benefits of protecting large parcels of land where possible. Large areas of habitat (tens of hectares or more) can be effective for preserving large populations of species, but because many pollinators move over relatively short distances (Greenleaf *et al.*, 2007) such large reserves will not generally support crop pollination on agricultural land that is more than approximately 1km from reserved land. The benefits of non-agricultural habitats in supporting pollination generally extend a few hundred meters into fields (Ricketts *et al.*, 2008). What remnant patches exist in farmed landscapes will often be too small to support populations of the larger species of conservation concern, such as vertebrates, but can play a very important role in keeping a diversity of insect pollinators (invertebrates) to support food production (Marlin and LaBerge, 2001). In this context it is important to think of small patches (meters across) of natural and semi-natural habitat (including field margins, pasture trees, etc.) as a target for "protected status". Even individual trees in an agricultural landscape help support farmland pollinator diversity (Lentini *et al.*, 2012). The emerging paradigm of "countryside biogeography" seeks to address the special challenges of achieving conservation outcomes in these kinds of landscapes (Mendenhall *et al.*, 2014).

6.4.3.3 Economic responses

Payment for ecosystem services is a market-based instrument (e.g., Daily *et al.*, 2009; Engel *et al.*, 2008) that could promote practices that conserve pollinators. Crop pollination is well understood to be an ecosystem service that can flow across property boundaries, creating the possibility for a payment incentive for neighbours to conserve or create pollinator habitat (Dunn, 2011; Satake *et al.*, 2008). Some governments reward land holders for carbon sequestration benefits of certain land uses (e.g., planting woody vegetation), and there is the possibility that co-benefits could also be rewarded (e.g., crop pollination that is promoted by the new habitat; Lin *et al.*, 2013), but the effectiveness of these incentives in terms of pollinator conservation has not been assessed.

Turning the science-based concept into market mechanism is challenging (Madoff, 2011). There can be complex economic and social tradeoffs around the values of pollinators, such as seen in conflicts among the interests of almond growers, citrus farmers, and apiarists in the San Joaquin Valley (Madoff, 2011). Small payments may not be sufficient to motivate producers, but large payments risk distorting trade in a way that affects trade agreements. Because pollinators are mobile and there is a shortage of knowledge regarding key pollinators for many crops, it can be it difficult to identify which land owners could receive a payment for supporting them.

In France, an agri-environment scheme under the European Common Agricultural Policy (i.e., dispositif apiculture API: http://www.eure.gouv.fr/layout/set/print/Politiques-publiques/Agriculture/Mesures-Agro-Environnementales) pays beekeepers to place hives in areas of high biodiversity. Its stated aim is to enhance the pollination provided by honey bees, although the effect of this on pollination has not been measured.

6.4.3.4 Social and behavioural responses

Responses based on influencing social attitudes have occurred in many places around the world. A number of initiatives related to pollinator conservation have garnered significant public support, including citizen science data collection and on-ground actions (see section 6.4.6.3.4). However, there have not been systematic studies of their effectiveness, so that while we have identified some of the strategies for how nature conservation strategies for pollination could benefit from social and behavioural responses **(Table 6.4.3)**, there is little to report regarding assessment of the effectiveness of these strategies.

Social action also requires an appreciation of the threats to pollinators, which might be lacking in many communities. For example, people in the Cook Islands proved to be open to the idea that hunting restrictions might be necessary to protect fruit bats, but only after they were made aware that hunting was a significant threat to these pollinators (Cousins and Compton, 2005). In Europe surveys revealed a positive attitude towards the planting of wildflower strips for pollinator conservation among both farmers and the general public (Jacot *et al.*, 2007), indicating that some communities are inclined to support active ecological restoration options.

TABLE **6.4.3**
Summary of evidence for responses relating to nature conservation

Response	Main drivers	Type of response	Status	Scientific evidence
Manage or restore native habitat patches to support pollinators	Land use and its changes (2.1)	Technical 6.4.3.1.1.	Established	Increases diversity and abundance of pollinating insects **WELL ESTABLISHED**
Increase connectivity of habitat patches	Changes in land cover and spatial configuration (2.1.2)	Technical 6.4.3.1.2.	Tested	Some evidence that habitat connections help pollinator movement and gene flow **ESTABLISHED BUT INCOMPLETE**
Manage invasive species (plants, pests, predators or pollinators) that diminish pollinators or pollinator habitat	Invasive species	Technical 6.4.3.1.4.	Tested	Case study evidence of some benefits to pollinator species, but eradication is difficult to achieve **ESTABLISHED BUT INCOMPLETE**
Targeted conservation of specific pollinator species or groups of species (includes ex situ conservation of threatened species, includes species of special cultural value)	Multiple, interacting threats	Technical 6.4.3.1.5.	Tested	Examples exist for a limited range of taxa **ESTABLISHED BUT INCOMPLETE**
Targeted conservation of pollinators associated with specific plant species threatened by pollination deficit	Multiple, interacting threats	Technical 6.4.3.1.5.	Tested	One European example known, for dittany (*Dictamnus albus*) **INCONCLUSIVE**
Establish protected areas or improve the quality of existing ones (including protected areas of cultural value)	Land use and its changes (2.1)	Legal 6.4.3.2.2	Established	Protected areas host species diversity, but it is difficult to determine the impact of legislation in achieving protection **WELL ESTABLISHED**
Payment for ecosystem services	Land use and its changes (2.1)	Economic 6.4.3.3.	Tested	Ecosystems services payments have been established for other services (watershed protection, carbon sequestration) but no examples for pollination **ESTABLISHED BUT INCOMPLETE**
Maintain sacred and other culturally protected areas that support pollinators	Land use and its changes (2.1)	Social/behavioural 6.4.3.2.2	Established	Protected areas host species diversity, but few case studies **ESTABLISHED BUT INCOMPLETE** (see also 5.4.2.4)
Increase taxonomic expertise on pollinator groups (formal education/training) and technology to support discovery and identification	All	Knowledge 6.4.3.5.	Tested	Significant training has been achieved in a number of countries **WELL ESTABLISHED**

In a similar vein, other studies have shown that people's aesthetic preferences lean toward floral diverse areas (e.g., Junge *et al.*, 2011).

6.4.3.5 Knowledge responses

Reviews of regional conservation needs for pollinators have identified that a shortage of taxonomic expertise is a constraint, with many regions likely to have many species not yet described and a shortage of experts to identify species even when descriptions exist (Batley and Hogendoorn, 2009; Eardley *et al.*, 2009; Freitas *et al.*, 2009; FAO, 2008). To address the shortage of taxonomic expertise some institutions have developed training courses. The American Museum of Natural History has conducted a training course annually since 1999, training >250 people, and while many participants are researchers some come from non-research backgrounds (http://www.amnh.org/our-research/invertebrate-zoology/bee-course-2014). Similarly the Kenyan "Centre for Bee Biology and Pollination Ecology" parataxonomy course (http://www.museums.or.ke/content/view/153/116/), was designed to give people without formal taxonomic training some of the skills required to identify specimens. These programs have effectively delivered training, but the impact on pollinator conservation of this increased capability is, of course, difficult to assess. Provision of these courses in developing countries especially is limited by availability of funding.

Use of new DNA sequencing methods provides tools that complement and extend traditional methods of species identification (Puillandre *et al.*, 2012). These approaches are rapidly becoming cheaper and are expected to become applied much more widely in support of monitoring and understanding pollinators.

There is an immense reserve of knowledge regarding management for nature conservation outcomes from indigenous and local knowledge. Many indigenous peoples are known to value diversity for its own sake (see Chapter 5, sections 5.3.2 and 5.3.3).

6.4.4 Pollinator management and beekeeping

This section focus on responses associated with managed pollinators, including beekeeping for the European honey bee *Apis mellifera* as well as any other managed pollinator

BOX **6.2**

Māori and the management of introduced honey bees in New Zealand

Following the introduction of the honey bee (*Apis mellifera mellifera*) into New Zealand in 1839 (Barrett, 1996), feral honey bees rapidly established and spread throughout the country (Donovan, 2007). Māori quickly recognized the value of bees and honey in the mid-19th Century and became New Zealand's first commercial honey beekeepers (Barrett, 1996; Donovan, 2007; Gillingham 2012). The first New Zealand book on beekeeping '*Ko Ngā Pi*' (Treatise on bees) was published in Māori in 1849 (Cotton, 1849). Māori also adopted the practice of harvesting honey from feral honey bee nests (Lyver *et al.*, 2015). Honey harvest would often occur twice a year (Tahi and Morunga, 2012) and feral hives were never depleted of honey to ensure the survival of the bees and the future potential to take honey. The relocation of swarms of feral honeybees during the *heke* or 'migration' period was also a common practice used to maintain access to honey (Doherty and Tumarae-Teka, 2015). Swarms were collected in a flax woven bag at night and moved to another site in an accessible tree cavity where the hive could develop.

Since the mid-1950s however the practice of harvesting honey from feral honey bee nests in the Te Urewera region by the Tuawhenua people has been in decline and today is no longer practiced (Doherty and Tumarae-Teka, 2015). Prior to 1950, honey would be collected from 20 to 25 feral hives in an area within 1 to 5 kilometre radius around homes. By the mid-1980s the gatherers were collecting honey from 1 to 5 nests in that same 1 to 5 km radius area, and by the late 1990s the feral honeybee nests had largely disappeared from the areas searched by Tuawhenua. The reason for the decline of feral honey bees is not well understood but the simultaneous rapid expansion of the European wasp (*Vespula germanica* Fabricius) (Fordham, 1961) is thought to be a factor; these wasps were known to consume honey bee brood and rob nests of honey (Thomas, 1960; Mayer *et al.*, 1987).

In recent years, Māori have returned to management practices which facilitated within-forest pollination and production of apicultural products from indigenous flora such as rewarewa (*Knightia excelsa*) (Indigenous New Zealand, 2012), tawari (*Ixerba brexioides*) and mānuka (*Leptospermum scoparium*). Today beekeeping is widespread and Māori have once again developed strong commercial links to the apiculture industry, especially bee products which are derived from mānuka which are recognised for its pharmaceutical purposes. Mānuka provides a highly valued source of honey and essential oil production (Stephens *et al.*, 2005). The highest quality mānuka honey can provide returns of up to NZD$80/kilogram (Lyver *et al.*, 2015).

species, including but not limited to other honey bees (such as *Apis cerana*), social stingless bees (Apidae: tribe Meliponini), bumble bees (primarily *Bombus impatiens* and *B. terrestris*), *Osmia* species (including *lignaria*, *cornifrons*, *cornuta,* and *bicornis*), the alfalfa leafcutter bee *Megachile rotundata,* and the alkali bee *Nomia melanderi*. An exhaustive list of managed pollinators is given in Chapter 2.5.

6.4.4.1 Technical responses

6.4.4.1.1 Improve husbandry of managed pollinators

The focus of this section is on the development and testing of new technologies and management techniques, and scientific evaluation / testing of existing technologies and management techniques. This section is also focused only on currently managed pollinator species, as there is a separate section (6.4.4.1.3) on development of newly managed species.

The technical responses in this section are written to be taxonomically general wherever possible, i.e., aimed at any managed insect pollinator species, though there are clearly some responses that are taxonomically specific. Generally, there is a very long and well-documented history of beekeeping with honey bees (in particular *Apis mellifera*, and to a lesser extent *A. cerana*) and thus most of the evidence in terms of improving husbandry comes from *A. mellifera*. An exhaustive review of all *A. mellifera* beekeeping management practices is beyond the scope of this section, and many management practices are relevant only to particular geographic areas. Instead, we highlight general categories of management practices that offer the possibility of addressing threats to managed pollinators, with many of them focused on *A. mellifera*.

There is a growing literature on managed bumble bees (both *Bombus terrestris* in Europe and *B. impatiens* in the USA), and on pollinators such as *Osmia*, which are increasingly being used in orchard crops in the USA (*O. lignaria*), Europe (*O. bicornis* and *O. cornuta*), and Japan (*O. cornifrons*). While there is a long history of management of social stingless bees or meliponines (Apidae: Meliponini), particularly in Mexico and Central America (see Chapter 2.5), there has been less documentation and scientific study of this group relative to other groups. Recent advances have been made in several areas including stingless bee queen rearing (Menezes *et al.*, 2013), non-destructive honey collection and nest box construction (Cortopassi-Laurino *et al.*, 2006).

Indigenous and local knowledge adds new information and innovation on husbandry techniques for a range of managed bee species (see Chapter 5, section 5.4.10). There is a robust body of indigenous and local knowledge on stingless bee management (see Chapter 5, Case Examples 3, 9 and 14). For example, Quilombola communities in northern Brazil have a long tradition of stingless beekeeping. They have elaborate ecological knowledge of the 12 native stingless bee species, the melliferous flora and the management techniques (de Carvalho *et al.*, 2014). Local people recognize that patches of habitat with trees, dense vegetation and an abundance of water, are preferred. In Indonesia and southern Vietnam, people have developed a method of 'rafter' beekeeping for the giant honey bee *Apis dorsata*. Wild, migratory bee colonies nest on the artificial rafters cut from young trees, allowing people to collect up to 80% of the honey without destroying the colony. There has been some research on how to improve this practice in Vietnam by placing rafters with open space in front (Dicks *et al.*, 2010; Tan *et al.*, 1997).

We address improvements in bee husbandry in six broad categories: i) general management, ii) management of disease threats, iii) genetic management, iv) management of pesticide threats (at the level of the beekeeper or pollinator manager, distinct from general management of pesticide threats), v) management of pollinator symbionts and vi) combinations of different management strategies.

6.4.4.1.1.1 General management

General management is focused on multiple goals, including reducing losses of bees; maintaining bee health generally; increasing honey production; and improving beekeeper livelihoods among others. This category includes a very wide range of different actions, and it is beyond the scope of this section to review these exhaustively, especially in terms of management of *A. mellifera*. Still, management innovation in these actions can lead to significant improvements in the survival and productivity of managed bees. It is worth noting that many of these management interventions likely have trade-offs, such that increases in some desired outcomes might, in some cases, lead to reductions in other desired outcomes.

General Management techniques include:

- hive / nest design and management (especially for bees other than honey bees; but for honey bees this could include reduction of costs of nest boxes, e.g. top-bar hives)

- diet / feeding (including management of forage *in situ*, management of moving bees to specific forage, and supplemental feeding)

- management of swarming / splitting colonies / requeening / queen rearing in eusocial managed bees (honey bees, bumble bees, and social stingless bees)

- reducing robbing and absconding in honey bees and social stingless bees (e.g., through use of unique colony markings, entry orientation, height above ground, etc.)
- migration / movement: at least one managed species (*Apis cerana*) has natural seasonal migrations in parts of its range (Koetz 2013), and other managed species, especially but not exclusively *A. mellifera,* are moved extensive distances especially in the USA (Daberkow *et al.* 2009). At a smaller scale, populations of *Megachile rotundata* are moved between alfalfa fields. Once a field has been pollinated, populations can be moved in large trailers to a newly blooming field (Osgood 1974). We continue to know very little about ways to manage migration and movement that minimize stress to bees
- Africanized honey bees: a specific topic related to these practices is the development of strategies for managing Africanized honey bees, especially in the tropical and subtropical Americas, in order to increase human safety concerns related to management as well as colony productivity (Winston 1992)
- stocking density of managed bees in crop fields and forage areas. Maintaining appropriate stocking densities can potentially increase crop yields and reduce costs to farmers and/or pollinator managers (e.g., Eaton and Nams 2012), and preventing overstocking could potentially reduce competitive interactions with wild pollinators (e.g., Thomson 2004), the risk of pathogen spillover from managed to wild pollinators (Otterstater and Thomson 2008), and speculatively the risk of pathogen transmission in managed pollinators

6.4.4.1.1.2 Manage pathogen and parasite threats

This is a very large category, with intensive work for both honey bees and bumble bees, along with a growing body of work on other managed pollinators (see Chapter 2 for an overview of disease threats). We focus on five major categories of responses related to disease: detection/diagnosis (6.4.4.1.1.2.1); prevention (6.4.4.1.1.2.2); treatment (6.4.4.1.1.2.3); supporting social immunity mechanisms in eusocial taxa (6.4.4.1.1.2.4); and management of pathogen and parasite evolution (6.4.4.1.1.2.5).

6.4.4.1.1.2.1 Detect / diagnose disease problems

Rapid, precise detection and diagnosis of parasite and pathogen threats are critical for understanding, treating, and controlling these threats in managed bees. For many parasites and pathogens with macroscopic visual cues, detection is well established based on apiary inspection, including macroscopic mites (Sammataro *et al.*, 2000) and some fungal pathogens such as chalkbrood (Aronstein and Murray, 2010). For other pathogens, either microscopic analysis is needed, such as in tracheal mites (Sammataro *et al.*, 2000; Otterstater and Whitten, 2004), or molecular methods are needed, such as in the microsporidian fungal parasite *Nosema* (Fries, 2010) and many viruses (de Miranda *et al.*, 2010). There is considerable opportunity and a research gap for improving detection and diagnosis of managed bee pathogen and parasite threats. In particular, improvements could be made in terms of speed, reliability, and accessibility of diagnostic tests, as well as reduction of costs. Rapid developments in molecular genetic technology offer considerable promise on this front.

Another opportunity is to integrate detection of disease in a legal framework with registration and inspection of managed bees, as exists in some countries, including the UK (The Bee Diseases and Pests Control [England] Order 2006, SI 2006/342). Such a framework has the potential to contribute to prevention of widespread pathogen and parasite outbreaks.

6.4.4.1.1.2.2 Prevent infections

This is a broad category, which includes: 1) management of pollinator movement; 2) general management practices; and 3) rearing facility practices. As mentioned in the previous section, detection of parasite / pathogen threats in a legal inspection framework has considerable prevention potential. We discuss country- and continental-scale preventative measures (i.e., preventing introductions of parasites and pathogens) in the "legal responses" section 6.4.4.2.

Managing pollinator movement is a key method of disease prevention. Spatial scale is a critically important consideration. At very large, within-continent scales, many pollinators are moved considerable distances for crop pollination, especially (but not limited to) honey bees in the US (Pettis *et al.*, 2014), and alfalfa leafcutter bees from Canada to the US (Bosch and Kemp, 2005; Pitts-Singer and Cane, 2011). These operations have potential to spread diseases long distances, but limiting their movement could reduce the provision of pollination to agriculture, and also reduce beekeeper profitability.

At a smaller spatial scale, we can consider movement of *Apis mellifera* colonies among multiple apiaries managed by the same beekeeper at a landscape or regional scale, as well as movement of brood or honey frames between colonies. Movement of bees or frames again has the potential to transmit disease, but stopping such practices altogether is unlikely to be practical for most beekeepers.

General management of pollinators can also contribute strongly to disease prevention. For example, chalkbrood is a fungal disease that is highly prevalent in managed populations of the alfalfa leafcutting bee, *Megachile* *rotundata* in the USA, where it can reach levels as high as 20-40%. Sorting loose *Megachile* cocoons and removing those with fungal infections can be an effective way to reduce infestation (Bosch and Kemp, 2005; James and Pitts-Singer, 2005; Pitts-Singer and Cane, 2011). Several products (including bleach, methyl bromide, paraformaldehyde, various fungicides) have been used to disinfect nesting materials with irregular success (Parker 1985, 1987, 1988; James 2005, 2008, 2011). In honey bee colonies, soil management can potentially help prevent infestations of small hive beetle (*Aethina tumida*), which pupate in the soil. For example, additions of diatomaceous earth and/or slaked lime management of soil near honey bee colonies can reduce pupation success and also kill adult beetles (Buchholz *et al.*, 2009). Maintaining appropriate stocking density of pollinators could potentially reduce parasite and pathogen transmission among managed pollinators and/or disease spillover between managed and wild pollinators, though research is needed on this topic.

Disease prevention practices in rearing facilities are a key concern for commercial bumble bee operations, which produce very high volumes of bumble bees and colonies in close proximity. Such facilities may increasingly be used in the future to rear solitary pollinators such as *Osmia lignaria*, which are currently largely provided to commercial markets by trap-nesting in the wild (Bosch and Kemp, 2002). There is a high level of secrecy and protection of intellectual property in commercial bumble bee rearing operations, and thus any particular rearing facility practices focused on disease prevention remain speculative. Because of disease problems in managed bumble bees (Velthius and Van Doorn, 2006), improved disease prevention in rearing facilities could potentially improve colony production and even profits.

6.4.4.1.1.2.3 Treat diseases

Disease treatment in managed bees is a critical component of pollinator management given the central role of parasites and pathogens in bee health. Treatments are organized here by the taxonomic group of the parasite / pathogen, rather than the pollinator host, because treatments are largely similar within taxonomically similar parasites and pathogens. This section covers treatment of viruses (6.4.4.1.1.2.3.1), bacteria (6.4.4.1.1.2.3.2), fungi (6.4.4.1.1.2.3.3), protozoa (6.4.4.1.1.2.3.4), mites (6.4.4.1.1.2.3.5) and other colony pests (6.4.4.1.1.2.3.5). One general issue with treatment is that the impacts of parasites and pathogens on managed pollinators are context-dependent. For example, *Varroa* mites, one of the most important parasite pressures on honey bees, have different effects on colony fitness in tropical and temperate environments (reviewed in Rosenkranz *et al.*, 2010).

6.4.4.1.1.2.3.1 Viruses

As reported in Chapter 2, more than 20 bee-associated viruses have been identified, some of which contribute to substantial bee morbidity and mortality, in honey bees, bumble bees and managed solitary bees. Treatment options for viral diseases are limited in managed pollinators, and currently preventative measures are the best protection against viral infection. One potentially promising treatment method is interference RNA, or RNAi, in which double-stranded RNA is introduced into the host in order to silence the expression of one or more viral proteins, which replicate in host cells (Fire *et al.*, 1998). RNAi has been demonstrated to reduce viral titer, and in some cases increase bee survival, in laboratory settings in *Apis mellifera* infected with Israeli Acute Paralysis Virus (IAPV; Maori *et al.*, 2009) and Deformed Wing Virus (Desai *et al.*, 2012), and, in *Apis cerana*, of Chinese Sacbrood Virus (Liu *et al.*, 2010). While RNAi technology seems to have considerable promise, it has not been widely used in field beekeeping settings, even though a relatively large-scale trial showed increases in total number of adult honey bees, forager activity, and honey production in RNAi-treated vs. untreated colonies when experimentally infected with IAPV (Hunter *et al.*, 2010). This trial was sponsored and largely conducted by a commercial RNAi producer. Given that this trial was published five years ago, it remains unclear why RNAi technology has not had broader uptake; costs and incomplete viral clearance may contribute. There has been no assessment of the risks of RNAi technology or the costs of this technology relative to its benefits.

6.4.4.1.1.2.3.2 Bacteria

The primary known bacterial pathogens of managed bees are American and European Foulbrood ("AFB", *Paenibacillus larvae*; and "EFB", *Melissocccus plutonius*, respectively). These bacteria impact larval-stage bees, which if infected have very high mortality rates. Both are highly transmissible and capable of re-infecting larvae in the same colony in subsequent years after an initial infection (reviewed in Forsgren, 2010; Genersch, 2010). AFB in particular is spore-forming, and the spores are highly resistant to desiccation and remain infectious >35 years after an initial infection (Genersch, 2010). A single infected larva can produce millions of spores, and the infectious dose consists of as few as 10 spores (Genersch, 2010). Foulbrood of both types is mandatorily notifiable in many countries (Forsgren, 2010; Genersch 2010), including the UK (Wilkins *et al.*, 2007; the Bees Act [UK] 1980; The Bee Diseases and Pests Control [England] Order 2006, SI 2006/342).

Three primary treatment mechanisms exist for foulbrood diseases (reviewed in Forsgren, 2010; Genersch, 2010): 1) colony eradication and subsequent destruction or sterilization of hive body equipment; 2) the "shook swarm" method, in which adult bees are shaken out of a colony and only the infected comb is destroyed; and 3) treatment with antibiotics. The first method, colony eradication, is considered the best method for reducing potential future infections, given the high level of transmissibility, but comes at the expense of colony and equipment losses (Wilkins *et al.*, 2007; Forsgren, 2010; Genersch, 2010). Eradication is mandatory in some countries and localities for AFB infestation, and often recommended in colonies or apiaries with high infestation levels for EFB (Wilkins *et al.*, 2007; Forsgren, 2010; Genersch, 2010).

The shook swarm method allows for maintaining adult bees from a colony while destroying infected brood and comb. The remaining components of hive body equipment are often sterilized with bleach or localized flame application (or ethylene gas, Robinson *et al.*, 1972). The shook swarm method is often recommended for colonies infected with EFB (or in some cases AFB) but not yet clinically diseased (Genersch, 2010). A similar method, where brood are removed but adult bees maintained, is employed and reported to be effective in controlling foulbrood in China (Duan, 1992; Du *et al.*, 2007).

Antibiotic administration is used by beekeepers for prevention and treatment of both EFB and AFB. Antibiotics reduce the reproduction of foulbrood bacteria but do not completely "cure" a colony of infection (Forsgren, 2010; Genersch, 2010). In particular, antibiotics do not operate on AFB spores (Genersch, 2010), leaving infested colonies open to subsequent re-infection from spores. Antibiotic treatment of honey bees for foulbrood is illegal in many European countries (Generesch, 2010) and EU food regulations prohibit any detectable levels of antibiotics in commercial honey (EEC Regulation 2377/90, 26 June 1990). Still, regulations vary among countries and for example antibiotic use is permitted in the UK for EFB only (not AFB) under some conditions, depending on the level of infection and the size of the colony (Wilkins *et al.*, 2007). Antibiotic treatment remains legal in several other countries including the USA (e.g., under several NADA—New Animal Drug Application—and ANADA—Abbreviated New Animal Drug Application—numbers under the US Food and Drug Administration: NADA 008-622, NADA 008-804, NADA 095-143, NADA 138-938, ANADA 200-026, ANADA 200-247). In addition to incomplete infection clearance, an additional issue with antibiotic use is resistance. Tetracycline-resistant AFB was first reported in the US 15 years ago (Miyagi *et al.*, 2000), and a subsequent intensive survey has since found widespread antibiotic resistance in the gut microbiota of honey bees, including at least 10 different resistance genes (Tian *et al.*, 2012).

6.4.4.1.1.2.3.3 Fungi

The primary fungal pathogens of managed bees are *Nosema*, chalkbrood, and stonebrood. *Nosema* includes *N. apis* and *N. ceranae,* which typically infect bees in the genus *Apis* (e.g., Fries, 2010), as well as *N. bombi*, which infects a wide range of bumble bee species (Tay *et al.*, 2005). Chalkbrood includes: *Ascosphaera apis*, which typically infects *Apis* (Aronstein and Murray, 2010); *A. aggregata* and other species that typically infect *Megachile* (Vandenberg and Steven,1982; Bissett, 1988); and *A. torchioi* and other species that typically infect *Osmia lignaria* (Torchio, 1992; Sedivy and Dorn, 2013). Stonebrood is caused by several *Aspergillus* species that infect honey bees (Foley *et al.*, 2014) as well as other bee species (Goerzen, 1991).

The primary treatment for *Nosema* in honey bees in many countries, including Canada and the USA, is the antifungal treatment agent fumagillin dicyclohexylammonium ("fumagillin"; Williams *et al.*, 2008; Fries, 2010), though its use is illegal in the EU (Fries, 2010; Botías *et al.*, 2013) given its toxicity to mammals including humans (Huang *et al.*, 2013). While fumagillin can reduce *Nosema* levels in honey bee colonies in some circumstances (Webster, 1994; Williams *et al.*, 2008), it appears to have some direct toxicity to honey bees, and low levels of fumagillin may also enhance, rather than reduce, *N. ceranae* reproduction in honey bees (Huang *et al.*, 2013). Fumagillin was not shown to be effective in controlling *N. bombi* in bumble bees at either the recommended fumagillin dose for honey bees (26 mg/L in sugar syrup) or double that concentration (52 mg/L; Whittingdon and Winston, 2003).

A single study has also shown that RNAi, using gene transcripts for an ATP/ADP transporter specific to *N. ceranae*, when fed to worker bees, reduced infection levels and parasite reproduction within adult honey bee hosts (Paldi *et al.*, 2010). We are unaware of field implementation of RNAi therapy targeted to *Nosema*. There has been no assessment of the risks of RNAi technology or the costs of this technology relative to its benefits. The lack of proven options other than fumagillin for *Nosema* treatment (Fries, 2010) represents an important knowledge gap.

Chalkbrood and stonebrood, irrespective of host bees that are infected, also have few direct treatment options (Bosch and Kemp, 2001; Aronstein and Murray, 2010; Sedivy and Dorn, 2013). As Hornitsky (2001) noted, "A wide range of chemicals has been tested for the control of chalkbrood. However, none has proved efficacious to the point where it has been universally accepted. A chemical which is effective against chalkbrood, does not produce residues in bee products and is not harmful to bees is yet to be found." Still, there have been some promising developments including the use of formic acid and oxalic acid (also used in the treatment of *Varroa* mites), which reduced growth of *Ascosphaera apis* chalkbrood in vitro, but was not tested in live bees (Yoder *et al.*, 2014). Similarly, a range of essential oils showed promise in reducing stonebrood growth in *in vitro* assays, but showed challenges in translating that antifungal activity to pollinator management situations (Calderone *et al.*, 1994). A cultural practice for chalkbrood management in alfalfa leafcutting bees, *Megachile rotundata*, is that populations are often managed as loose cells (rather than entire natal nests) to prevent emerging adults from being dusted during emergence with chalkbrood spores from infested larval cadavers (Richards, 1984).

6.4.4.1.1.2.3.4 Protozoa

The primary protozoan parasite of managed bees is *Crithidia bombi*, which infects bumble bees (Shykoff and Schmid-Hempel, 1991). There is no known treatment for *Crithidia* (Schweitzer *et al.*, 2012). At least two lines of promising evidence point toward treatment options in the future. First, gelsamine, a nectar alkaloid, has been found to reduce *Crithidia* levels in bumble bees (Manson *et al.*, 2009), and second, horizontally-transmitted gut microbiota also have been shown to protect against *Crithidia* (Koch and Schmid-Hempel, 2011).

6.4.4.1.1.2.3.5 Parasitic mites

Mites are among the most destructive parasites of managed bees. The primary parasitic mites of managed honey bees are in the genera *Varroa, Tropilaelaps,* and *Acarapis* (reviewed in Sammataro *et al.*, 2000; Rosenkranz *et al.*, 2010), while *Locustacarus* impacts bumble bees (e.g. Shykoff and Schmid-Hempel; 1991; Otterstatter and Whidden, 2004). The negative health impacts of mites are exacerbated by a range of viruses that mites vector (Sammataro *et al.*, 2000; Rosenkranz *et al.*, 2010). Treatment of mites is challenging because bees and mites are both arthropods, and thus compounds that are toxic to mites are likely also to be harmful to bees. A range of different mite treatment and control methods have been developed for honey bees (but not for other managed pollinators), likely due to the substantial parasite pressure that mites exert on honey bees and their economic importance. Because of the particular importance of *Varroa*, the bulk of treatment methods focus on it. *Tropilaelaps* mites have a very similar natural history and thus many of the treatments used in *Varroa* have potential for use in *Tropilaelaps* (Sammataro *et al.*, 2000). Existing treatment classes include: 1) acaricides / miticides; 2) RNAi; 3) organic acid vapors; 4) aromatic and essential oils; 5) biological / cultural controls.

The primary groups of acaricides / miticides are the organophosphate coumaphos, two pyrethroids (tau-fluvalinate and fluvalin), and amitraz, a formamidine (Sammataro *et al.*, 2000; Rosenkranz *et al.*, 2010). Amitraz is illegal in the US (Sammataro *et al.*, 2000) and many other countries. While these compounds can greatly reduce mite populations, they have several drawbacks. First, they can harm bees because these compounds have insecticidal, not just acaricidal, impacts. Second, there is the potential for these products to contaminate hive products including honey. Third, and perhaps most important, *Varroa* resistance to all of these compounds is well documented in a very widespread geographic area (reviewed in Sammataro *et al.*, 2000; Rosenkranz *et al.*, 2010). These compounds are lipophilic and thus can become integrated and accumulate in beeswax for long periods, which exacerbates all three of the drawbacks to their use (Rosenkranz *et al.*, 2010).

Interference RNA (RNAi) has been targeted against *Varroa*, and injection or soaking of double-stranded RNA directly into *Varroa* strongly and specifically reduced the transcription target in a laboratory context (Campbell *et al.*, 2010). In addition, double-stranded RNA fed to bees was found to be passed intact to *Varroa*, and then back to developing bee brood (Garbian *et al.*, 2012). This RNAi method also reduced *Varroa* counts in laboratory colonies (Garbian *et al.*, 2012). As with other RNAi methods utilized in the treatment of managed bee parasites and pathogens (with the exception of Hunter *et al.*, 2010, working on Israeli Acute Paralysis Virus), RNAi for *Varroa* control has not been tested in field beekeeping scenarios and there has been no assessment of the risks or the costs of this technology relative to its benefits.

The main organic acid vapors used to control *Varroa* and *Acarapis* are formic, oxalic, and lactic acids. Multiple studies have evaluated the efficacy of these acids as well as different methods for administering them, and they are effective in reducing *Varroa* and *Acarapis* populations, though they do not necessarily provide complete clearance of mites from colonies (reviewed in Sammataro *et al.*, 2000; Rosenkranz *et al.*, 2010). Formic acid is the only known method of *Varroa* control that kills both adult phoretic mites and developing mites within sealed honey bee brood cells. Additional advantages of organic acids are that they are hydrophilic and do not accumulate in beeswax, and that to date there is no evidence of mite resistance to them (Rosenkranz *et al.*, 2010). Disadvantages of organic acid use include contamination of hive products, and the suggestion (for oxalic and lactic acids) of use in honey bee colonies during broodless periods, which is not possible in all geographic areas and limits use to particular times of year. In addition, results are dependent on vapour pressure and other within-hive conditions, meaning that the effects of treatment are more variable than with some other control measures (Rosenkranz *et al.*, 2010). There is some evidence of harm to bees from use of organic acids, and they can be hazardous to human applicators if not handled properly (Sammataro *et al.*, 2000).

The primary essential oil used in control of *Varroa* is thymol, which can reduce mite populations by up to 90% (Rosenkranz *et al.*, 2010). Other essential oils have been tested against *Varroa* but none with the consistent success of thymol, though more research is needed (Rosenkranz *et al.*, 2010). For *Acarapis* tracheal mites, menthol has been shown to be an effective control measure, and the only other effective treatment besides formic acid (Sammataro, 2000). As with organic acids, treatment effects are variable and vapour pressure within colonies is an important consideration. Essential oils are lipophilic and can become integrated into beeswax, heightening potential for contamination of hive products (Rosenkranz *et al.*, 2010).

Biocontrol of *Varroa* and other parasitic mites is a control strategy with some preliminary investigations, including laboratory demonstrations of lethality to *Varroa* of several different bacterial strains (Shaw *et al.*, 2002), but other attempts have shown less impressive results, and no commercial products or field beekeeping trials have used this strategy (reviewed in Rosenkranz *et al.*, 2010, Meikle *et al.*, 2012). Biocontrol of parasitic mites (and other parasites and pathogens) thus represents an important knowledge gap.

Parasitic mites, especially *Varroa*, are also controlled by beekeeping practices and other cultural controls. One such practice that has shown efficacy is the use of "trap frames". Gravid *Varroa* females prefer to lay their eggs in drone (male) brood cells relative to worker (female) brood cells. After the drone cells are capped, the drone brood can be removed, thus greatly reducing *Varroa* populations within a colony (Sammataro *et al.*, 2000; Rosenkranz *et al.*, 2010). Similarly, swarming management can provide some level of *Varroa* control given that departing swarms leave infected brood behind (Sammataro *et al.*, 2000; Rosenkranz *et al.*, 2010). Another method involves heating colonies to 44ºC, a temperature that bee brood can survive but which kills developing mites (Sammataro *et al.*, 2000; Rosenkranz *et al.*, 2010). A cultural practice used in the control of *Acarapis* tracheal mites is the addition of patties of vegetable shortening and sugar to colony boxes, which may disrupt the "questing" behavior of female mites searching for new hosts (Sammataro *et al.*, 2000). These cultural practices are often labour intensive and difficult to implement in large apiary operations (Rosenkranz *et al.*, 2010). In solitary bees, thermal shock treatments applied during the most resistant bee stage (dormant prepupa) are used in Japan to reduce numbers of *Chaetodactylus* mites in *Osmia cornifrons* populations (Yamada, 1990).

6.4.4.1.1.2.4 Support social immunity mechanisms in eusocial taxa

These are mechanisms by which social organisms help to prevent and treat pathogens and parasite infestations at a social (not individual) level (Cremer *et al.*, 2007; Sadd and Schmid-Hempel, 2008; Evans and Spivak, 2010; Parker *et al.*, 2011). This is a recently emerging area of study with limited, but growing evidence that it can have a large impact on disease pressure. Management to support social immunity could include provision of resin-producing plants so that honey bees can gather propolis and not removing propolis from colonies (Simone *et al.*, 2009; Simone-Finstrom and Spivak, 2012), and dietary management to support honey hydrogen peroxide production (Alaux, 2010). A possible trade-off is that some practices interfere with typical beekeeping practices (e.g., removal of propolis). More field-scale trials of supporting social immune mechanisms would assist pollinator managers and policy makers in evaluating their implementation.

6.4.4.1.1.2.5 Manage pathogen and parasite evolution

This category includes two broad responses. First, development of resistance to insecticides and antibiotics is a well-known phenomenon in agriculture (Brattsten *et al.*, 1986; Perry *et al.*, 2011) and medicine (e.g., Neu, 1992), respectively, which has also been documented in honey bees in terms of resistance of *Varroa* mites to acaricides (Milani, 1999). There is a body of evolutionary theory on managing insecticide and antibiotic resistance, and lessons from this work could be applied to treatment of disease and parasites in managed pollinators. For example, the length of treatment, treatment rotations, and treatment combinations could be applied in ways to reduce resistance (e.g., Comins, 1977; Lenormand and Raymond, 1998). Second, there is a well-described relationship in evolutionary theory between transmission of pathogens and virulence (harm to the host), such that increased transmission tends to select for increased virulence (e.g., Ewald, 2004). While there is no direct evidence of such a relationship in managed pollinators, this pattern has been detected in a broad range of other host-pathogen systems (reviewed in Alizon *et al.*, 2009). Steps could be made to assess this relationship in managed pollinators and potentially to alter management to select for less-virulent parasites and pathogens by reducing parasite transmission rates.

6.4.4.1.1.3 Genetic management

Genetic management, similar to general management, is focused on multiple goals. There are four main methods of genetic management: 1) traditional trait-focused breeding; 2) maintenance or enhancement of genetic diversity; 3) genetic engineering, i.e. development of transgenic pollinators; and 4) high-tech breeding. The first of these is traditional breeding for desirable traits, and in *A. mellifera* there have been extensive breeding efforts, in particular (though not exclusively) focused on hygienic behavior to reduce disease and parasites (Spivak and Reuter, 1998, 2001; Ibrahim *et al.*, 2007; Büchler *et al.*, 2010). These objectives have been successful in terms of target trait modification, but there is limited knowledge of how bees originating from such breeding programs perform relative to other lines, in managed apiary contexts, in terms of outcomes such as colony survival and productivity. While there is at least one report of bees from "hygienic" breeding programs outperforming typical (non-hygienic) stocks in terms of both disease resistance and honey production (Spivak and Reuter, 1998), other studies have not seen consistent advantages of bees bred for *Varroa* resistance

(Rinderer *et al.*, 2014). Maintaining the traits selected for in such breeding programs may be difficult in typical apiary settings for *A. mellifera*, given high levels of polyandry (queen mating with multiple, sometimes dozens of males) in honey bee queens and relatively large-scale movement of honey bee drones, especially given that trait maintenance appears to demand primarily drones expressing the traits of interest (Danka *et al.*, 2011). In solitary bees, there were unsuccessful attempts in the late 1970s and early 1980s to select univoltine *Megachile rotundata* strains as a means to avoid an undesired partial peak of emergence in late summer (Parker, 1979; Rank and Rank, 1989).

The second strategy is maintaining and/or increasing genetic diversity, as this is known to reduce disease threats and to promote colony health and productivity at a colony level in both *Apis* (Tarpy, 2003; Mattila and Seeley, 2007) and *Bombus* (Baer and Schmid-Hempel, 1999). By contrast, other reports show mixed effects of diversity on colony performance, depending on the origin of single versus mixed lines (Oldroyd *et al.*, 1992; Baer and Schmid-Hempel, 2001). In addition, beyond just social taxa, all currently managed pollinators are bees (Hymenoptera: Apoidea), which are haplodiploid with a single-locus sex determination system (Beye *et al.*, 2003); it is thought that this system might make bees particularly susceptible to deleterious effects of inbreeding (e.g., Zayed, 2009). Still, to our knowledge there are no systematic efforts to increase genetic diversity in any managed bees that have been assessed in a rigorous way. A related issue is not just genetic diversity *per se*, but maintenance of locally adapted strains. There is recent evidence that local (geographically specific) strains of honey bees outperform non-local strains, which is a distinct argument for conserving and maintaining geographic genetic diversity in managed pollinators (Büchler *et al.*, 2014).

There are trade-offs between these strategies in that breeding and genetic engineering are typically focused on replacing, or increasing the prevalence of particular alleles at particular loci. This goal is usually in direct conflict with maintenance of diversity. Still, multiple programs could exist with different goals, such as complementing existing *A. mellifera* bee breeding efforts with a program focused on enhancing genetic diversity.

The third method is the development of transgenic pollinators, (i.e., "genetic engineering"), which has been recently shown in principle with *A. mellifera* (Schulte *et al.* 2014), though not yet in full honey bee colonies, or to our knowledge in any other managed pollinator. There are risks associated with such an effort, and in polyandrous species such as *A. mellifera*, transgene containment might prove to be extremely difficult. These risks should be carefully assessed in the context of potential benefits before development of such transgenic pollinators.

The fourth method, which we describe as "high-tech breeding" can be thought of as a middle-ground approach between traditional breeding and transgenic approaches. For example, marker-assisted selection is an approach where genetic, phenotypic, and other markers associated with desired traits are identified in early stages of organismal development, speeding up the process of traditional breeding (e.g., Lande and Thompson, 1990; Collard and Mackill, 2008). This approach has been proposed for honey bee breeding (Oxley *et al.*, 2010; Oxley and Oldroyd, 2010), but has not been conducted to our knowledge. Speculatively, additional approaches could include up- or down-regulation or particular genes already present in the genome of managed pollinators.

6.4.4.1.1.4 Reduce pesticide threats

In this section, reduction of pesticide threats is specifically focused on beekeeping management strategies; more general and holistic treatment of managing pesticide threats to pollinators (including reducing exposure of bees) is covered in section 6.4.2. Beekeeping strategies to address pesticide threats remain largely speculative, but include improved nutrition, which has been shown to reduce the negative impacts of exposure to some classes of pesticides (Wahl and Ulm, 1983; Schmel *et al.*, 2014); and speculatively, the development of chemical antidotes or chemical (or possibly even microbial) prophylaxis against pesticides. Still, such strategies are likely to be expensive and difficult to implement compared to better management of pesticide application.

6.4.4.1.1.5 Manage symbionts and commensals

This is very much an emerging topic in pollinator management. Commensal or symbiotic macro-organisms have been documented in social bee colonies, including chelifers ("pseudoscorpions") (Gonzalez *et al.*, 2007; Read *et al.*, 2013) and non-parasitic mites, which could potentially have positive impacts on colony health and fitness (for example, cleaning detritus from the colony) (e.g., Walter *et al.*, 2002). The technical development of next-generation DNA sequencing has also revealed that most macro-organisms, including pollinators, host diverse communities of endosymbiotic microorganisms, and relatively recently work has shown that different communities of such microorganisms can have important effects on the health of honey bees and bumble bees, including disease resistance (e.g., Evans and Armstrong, 2006; Hamdi *et al.*, 2011; Kwong *et al.*, 2014) as well as nutrient availability (Anderson *et al.*, 2011). There is significant potential for developing ways to manage these communities to support pollinator health, including among many others, probiotics. While this is a very active area of research, there remains a poor mechanistic understanding of how different microorganisms affect pollinator health, alone and in combination, and development of effective management may take several years.

6.4.4.1.2 Improve pollination efficacy of managed pollinators (crop-focused)

In contrast to sections 6.4.4.1.1-6.4.4.1.6, this section is focused on improving crop pollination by managed bees, rather than focusing on the health and productivity of the pollinators themselves. Nearly all work in this area has been with honey bees, and to a limited extent with bumble bees, the latter especially in greenhouse / glasshouse / polytunnel contexts. This is an area with some limited evidence, with more study needed. Work to improve provision of crop pollination could include: optimization of stocking densities and configuration of colonies / nests (in conjunction with crop configuration) (Delaplane *et al.*, 2013); floral attractants such as pheromones; (Ellis and Delaplane, 2009; Sivaram *et al.*, 2013); feeding adjuvants such as caffeine, which can improve bee memory of particular flowers (Wright *et al.*, 2013); and combining pollination with delivery of other materials such as biofungicidal compounds (Mommaerts *et al.*, 2009; 2011) to plants. In a greenhouse / glasshouse / polytunnel context in particular, work could focus on optimization of lighting (Johansen *et al.*, 2011), as well as environmental parameters such as temperature, humidity, and airflow. A particular research need is assessment of potential trade-offs between pollination activity in the short term and individual pollinator / colony lifespan or other measures of health, particularly in the case of feeding adjuvants.

6.4.4.1.3 Develop alternative managed pollinators

A very small number of pollinator species are actively managed, especially relative to the diversity of pollinator species worldwide. There is potential to develop alternative pollinators, which could help to offset ongoing declines of managed pollinators. Within this realm, there are two main categories, first the use of existing managed pollinators on crops where they have not previously been in use. There is recent evidence for this with use of managed bumble bees in crops in which they had not previously been used, e.g., blueberry (Stubbs and Drummond, 2001). Second, there is potential for developing management techniques and practices for pollinators that had not previously been managed. Bumble bees for example, have only been commercially managed relatively recently (Goulson *et al.*, 2008). Social stingless bees (meliponines) are one taxonomic category with potential for increased domestication (e.g., Heard, 1999), along with species of *Osmia* beyond *O. lignaria*, *cornifrons, cornuta*, and *bicornis* (Torchio, 1990; Drummond and Stubbs, 1997; Cane, 2005), extending to other solitary leafcutter bees such as *Eumegachile pugnata* (Parker and Frohlich, 1985). For both of these categories, a potential trade-off is that it increases the density and/or distribution of newly managed species, which could lead to disease issues such as pathogen and parasite spillover to other species of pollinators (Otterstater and Thomson, 2008), as well as competition for resources with local pollinator taxa (e.g., Huryn, 1997; Thomson, 2004; see Chapter 3, section 3.3.3 and Chapter 2, section 2.4.2.2).

6.4.4.1.4 Provide resources for managed pollinators (food/nesting)

Two general limiting factors for managed pollinators are food (flowering plants) and nest sites. See sections 6.4.1.1.1 and 6.4.3.1.1 for more on provision of nesting and flowering resources for wild pollinators. There is little concrete evidence that increasing food or nesting sites leads to long-term positive effects on managed pollinator populations. Still, a major issue for large migratory beekeepers in the USA is the lack of flowering plant forage along migration routes. An additional component of forage availability is evidence that diversity of forage plant sources plays a role in bee health (e.g., Alaux, 2010). The issue of forage availability is relevant at a range of scales, from local scales surrounding sites of active pollinator management, to larger scales that could benefit from landscape/regional coordination (see section 6.4.4.3 of this chapter). A possible trade-off is that managed pollinators could usurp resources from wild pollinators in such areas, and potentially even contribute to pathogen spillover (see Chapter 2).

6.4.4.1.5 Boost native pollinators by translocation

Increasing crop pollinators by translocation (i.e., moving pollinators to an area where they are not found naturally or where their abundances are low), is distinct from migratory pollinator management practiced by migratory beekeepers in the USA, and does not include moving pollinator species to entirely new regions, which is not recommended (see Chapter 3, section 3.3.3). There are anecdotal reports of almond growers in California, USA, conducting relatively large-scale translocation of *Osmia lignaria* from states such as Utah in the interior western USA where *O. lignaria* abundances are higher. This strategy could potentially be broadened and might also be used as an adaptive response to climate change, if flowering crops and their pollinators become mismatched in space and time (see Chapter 2, section 2.6.2.3, and this chapter, section 6.4.1.1.12). We found no studies of its effects on pollination. As with any response that involves large-scale pollinator movement, two potential trade-offs are the increased risk of disease issues, including pathogen and parasite spillover, and potential for competitive effects on local pollinator taxa (see Chapter 3, section 3.3.3 and Chapter 2, section 2.4.2.2).

6.4.4.2 Legal responses

Two key policy responses are first, registration and inspection of managed pollinators, and second, regulation of managed pollinator movement, for example related to imports of hive pests and trade in managed pollinators at a single country level, or movement restrictions related to diseases. A list of such regulations around the world is included in the reference list (Annex 1). In Australia, this has so far prevented the introduction of *Varroa* mites of honey bees (Cook *et al.*, 2007).

As an example of within-country movement, in the UK, beekeepers whose colonies are infected with American Foulbrood (caused by *Paenibacillus larvae*) are mandated with standstill orders by the 1980 Bees Act, under the UK Bee Diseases and Pests Control Orders 2006, SI 2006/342. This policy mandate thus prevents spread of this highly contagious hive pathogen.

In dealing with multiple countries, there is significant potential for regional coordination of policies surrounding movement of managed pollinators, both within and between countries. Many countries and regions have regulations in place (e.g., in the UK, The Bee Diseases and Pests Control Order 2006 [2006 No. 342]; European Union Council Directive 92/65/EEC), though a key component of their success is border enforcement infrastructure. In addition, general biosecurity, beyond specific control of managed pollinators, is necessary to limit accidental introductions of managed bees and/or their parasites and pathogens (e.g., Cook *et al.*, 2007).

An additional policy concern is the potential for mandated registration of managed bees, which again is common in many countries and regions for honey bees (e.g., the state of Maryland, USA, under Maryland code 15.07.01.02), but could be done for bumble bees, *Osmia*, and other species. Registration would potentially assist with monitoring efforts and pathogen containment. There is very limited systematic evidence on how either regulation of pollinator movement or mandated registration of colonies affects tangible outcomes related to managed pollinators.

6.4.4.3 Economic responses

Economic responses for managed pollinators include access to markets and market building, incentives for beekeepers and other pollinator managers, and product certification. Access to markets, as well as building existing markets, is particularly relevant for alternative or newly managed pollinators. Economic incentives including supports could potentially play an important role in markets, such as for pollination contracts, where there is year-to-year variability that may discourage particular beekeepers or other pollinator managers from entering the market.

Product certification involves three areas of consideration: the targeted product; the pollinator species involved; and the certification type. Product targets currently include honey and other hive products (including wax, propolis, royal jelly), as well as bees themselves (colonies, packages, pupal cases, queens, or even bee semen for breeding purposes); for example EU Council Regulation No 1804/1999, of 19 July 1999 includes provisions for certifying any beekeeping product. While to our knowledge there is no thorough accounting of pollinator-related certification at a global level, at a species level honey bees and their products appear to account for the vast majority of certified products. Thus, there is a particular opportunity for developing certification for other species. Meliponine honey is a good example in that it already commands a price premium for its potential/perceived medicinal effects in parts of the world (Cortopassi-Laurino *et al.*, 2006). In terms of types of certification, these include: organic; trademark; quality; floral source; and geographic provenance. Again, while exhaustive surveys of certification types is lacking, organic certification and monofloral honey certification are very likely (but speculatively) the largest players. Product certification could also potentially be useful to protect indirectly biodiversity and traditional knowledge (Avril, 2008).

An example of protected monofloral honey is Manuka honey, produced from *Leptospermum scoparium* trees that grow in parts of New Zealand and Australia. Manuka honey commands a strong price premium for its perceived medicinal properties. The New Zealand Ministry for Primary Industries regulates labeling of Manuka honey, and in addition there are two Manuka honey trade groups that have licensed trademarks for Manuka honey meeting particular biochemical standards, though labeling of honey in New Zealand is under review at the time of this writing (http://archive.mpi.govt.nz/food/food-safety/manuka-honey, last accessed 11 December 2014).

An example of trademark-protected bees are Buckfast™ honey bees, which were bred at Buckfast Abbey in the UK in an isolated, treeless moor that lacks honey bee nesting habitat, thus allowing for careful selection and breeding, in particular against tracheal mites (Osterlund, 1983). The abbey has held various UK and EU trademarks, e.g., trademark EU003089224, to the Buckfast bees (http://www.ipo.gov.uk/tmtext, search for "buckfast bees", 13 April 2015).

While various certification schemes for products from *A. mellifera* are well established and very likely enhance beekeeper livelihoods in some contexts, there is no direct evidence to our knowledge that such certification improves colony or crop pollination outcomes. In addition, to our knowledge there is no evidence for the efficacy of market-building responses.

In France, an agri-environment scheme under the European Common Agricultural Policy provides economic support directly to beekeepers who place hives in areas of high biodiversity (le dispositif apiculture (API); see section 6.4c).

6.4.4.4 Social and behavioural responses

The two main social and behavioural responses for managed pollinators are community engagement through participatory processes, and voluntary codes of practice.

Community engagement could specifically include better coordination of growers with beekeepers and other managers of pollinators, especially in terms of pesticide use (e.g., providers of *Osmia* spp. to orchards, and alfalfa seed farmers who manage *Nomia melanderii* in the USA and Canada). It could also include provision of forage for managed bees at relatively large scales, including, for example, along beekeeper migration routes.

An example of the benefits of communities working together comes from Kenya (Rose *et al.*, 2014). In 2009, the Kenyan Ministry of Agriculture, Livestock and Fisheries in partnership with World Neighbours, a development organization, began working with farmers to introduce beekeeping as a way to diversify livelihoods. Women were provided with new beehives and received training and technical support from Ministry of Agriculture extension workers (Atakos and Recha, 2013). Women's groups formed to support and empower each other and average honey yields doubled from about 5 kg per beehive/year to 10 kg and above (Macoloo *et al.*, 2013). Some groups split earnings among the group or reinvest them into group functions. In addition to the economic benefits from honey production, neighbouring farmers have also experienced improved yields with their mango trees (Atakos and Recha, 2013). This case study offers an example of a government programme that not only promotes pollination, but also reduces poverty and empowers rural women.

There are examples of community-based voluntary codes of practice relating to managed pollinators. In the Mbulu highlands (Tanzania), there is a general agreement that bees and beehives should not be disturbed (Tengo & Belfrage, 2004). In the Kobo system in Ethiopia, families own groups of trees in which they can place their bee hives. These trees cannot be cut down and no one else can use these trees for beekeeping (Abebe and Lowore, 2013). The community tradition was recognized and strengthened by a forest protection agreement developed as part of participatory forest management, under the Ethiopian Government's Non-Timber Forest Product and Participatory Forest Management (NTFP-PFM) project (Abebeand Lowore, 2013). Similar practices could be enacted as part of a bio-cultural community protocol in the future (Bavikatte and Jonas, 2009).

6.4.4.5 Knowledge responses

There are four primary knowledge responses associated with managed pollinators. The first two are related to improved data on general properties of managed pollinators, first, monitoring and evaluation to give a big-picture idea of threats at large scales, and second, work to quantify the economic dimensions of managed pollinators, in particular their benefits. Previous work has shown that large-scale monitoring is very valuable in identifying threats at large spatial and temporal scales (e.g., Genersch *et al.*, 2010; Pettis and Delaplane, 2010). Economic valuation efforts have been helpful but have tended to give very large ranges in valuation estimates, in part depending on the valuation methodology used (see Chapter 4).

A third knowledge response is improvement in technical knowledge transfer, in particular to farmers and beekeepers. While there is significant agreement that such knowledge transfer could improve pollinator management, there are few if any data on the effects of, e.g., beekeeper education on tangible outcomes such as large-scale colony health.

The fourth response is maintaining and documenting traditional and indigenous knowledge surrounding managed pollinators, including its application to modern pollinator management practices and incorporation into global markets (see Chapter 5, section 5.4.10). Such knowledge is focused on management of social stingless bees (meliponines) and honey bees (including both *A. mellifera* and *A. cerana*).

6.4.5 Urban and transport infrastructure

This section considers responses that specifically take place in urban or suburban contexts, or are associated with built infrastructure such as roads, railways and powerlines. The impacts of urbanization, and patterns of pollinator diversity and abundance in urban areas are discussed in section 6.2.1.1.

6.4.5.1 Technical responses

6.4.5.1.1 Conserving pollinators' habitat

Urbanization has been demonstrated as a threat to pollinator conservation by causing habitat loss and fragmentation (McKinney, 2008). In a 2009 review, Hernandez *et al.* suggested that conserving larger fragments

TABLE **6.4.4**
Summary of evidence for responses relating to pollinator management and beekeeping

Response (section of chapter 6)	**Main driver(s) (section of chapter 2)**	**Type of response**	**Status**	**Scientific evidence**
Improve managed bee husbandry: general management (6.4.4.1.1)	Pollinator management (2.3.3)	Technical	Established, tested, or proposed depending on specific response	Management techniques can reduce losses of managed bees and increase production of hive products (**WELL ESTABLISHED**), but many specific techniques remain untested or poorly tested, especially in bees other than honey bees
Improve managed bee husbandry: manage disease threats (6.4.4.1.1.2)	Pollinator parasites and pathogens (2.3.1 And 2.3.2)	Technical	Established, tested, or proposed depending on specific response	Disease management techniques can reduce morbidity / mortality of managed pollinators (**WELL ESTABLISHED**), but many specific techniques and treatments remain untested or poorly tested
Improve managed bee husbandry: genetic management (6.4.4.1.1.3)	Pollinator management (2.3.3)	Technical	Established, tested, or proposed depending on specific response	Successful honey bee breeding programs have been carried out for disease resistance and other traits (**WELL ESTABLISHED**); strong evidence that genetic diversity enhances disease resistance in social bees (**WELL ESTABLISHED**); some evidence that locally adapted strains can outperform non-local strains of honey bees (**ESTABLISHED BUT INCOMPLETE**); and preliminary work has been done in creation of transgenic honey bees (**INCONCLUSIVE**). Maintenance of breeding efforts in typical apiary situations is challenging and there remains no testing of management for genetic diversity or of transgenic bees.
Improve managed bee husbandry: manage pesticide threats (at the level of the beekeeper or pollinator manager, distinct from general management of pesticide threats) (6.4.4.1.1.4)	Pesticides (2.2.1)	Technical	Established	Improved diet confers some pesticide resistance to bees (**ESTABLISHED BUT INCOMPLETE EVIDENCE**); veterinary prophylaxis or treatment (i.e. antidotes) to limit or prevent pesticide damage could be developed. **N/A** (**INCONCLUSIVE**)
Improve managed bee husbandry: management of pollinator symbionts (6.4.4.1.1.5)	Pollinator management (2.3.3)	Technical	Proposed	Gut bacterial communities of bees can help to support health (**ESTABLISHED BUT INCOMPLETE**), and macro-symbionts such as mites and pseudoscorpions could potentially improve colony or individual pollinator health (**INCONCLUSIVE**). No known explicit testing of management interventions.
Improve pollination efficacy of managed pollinators (6.4.4.1.2)	Pollinator management (2.3.3)	Technical	Established, tested, or proposed depending on specific response	These actions are focused on improving plant pollination outcomes, rather than on pollinator outcomes. They include optimizing pollinator stocking densities and configurations (**ESTABLISHED BUT INCOMPLETE EVIDENCE**); chemical attractants and feeding adjuvants (**INCONCLUSIVE**); and adjustment of glasshouse / polytunnel environmental parameters such as lighting, temperature, and humidity (**ESTABLISHED BUT INCOMPLETE**) to increase pollination and crop production.
Develop alternative managed pollinators (both existing and new) (6.4.4.1.3)	Pollinator management (2.3.3)	Technical	Established and proposed; unclear how established information would transfer to new developments	Management strategies for several previously unmanaged pollinator species have been developed over the last 30 years. While there is high confidence that previous efforts were successful, it is unclear how that will translate to new developments. **ESTABLISHED BUT INCOMPLETE**
Provide resources for managed pollinators (nectar/nesting) (6.4.4.1.4)	Land use and its changes (2.1.1)	- Technical-social / behavioural	Tested	While there is strong evidence that enhanced resource provision on farms can increase pollinator diversity and abundance, and widespread agreement among migratory beekeepers for the need for greater access to floral resources, there is no direct evidence as yet that increased resource provision will improve outcomes for managed pollinators **ESTABLISHED BUT INCOMPLETE**
Boost native pollinators by translocation (6.4.4.1.5)	Pollinator management (2.3.3)	Technical	Proposed	Pollinators could be moved between locations to enhance plant pollination or pollinator population outcomes (distinct from migratory beekeeping) **INCONCLUSIVE**
Regulate import of hive pests & trade in managed pollinators (6.4.4.2)	Pollinator management (2.3.3)	Legal	Established; proposed	Can prevent or limit the spread of parasites and pathogens of managed pollinators. **ESTABLISHED BUT INCOMPLETE**
Product certification for products from managed pollinators (6.4.4.3)	Pollinator management (2.3.3)	Economic	Proposed	Certification improves livelihoods for beekeepers and other pollinator managers, but no formal assessment if certification improves pollinator or plant pollination outcomes **ESTABLISHED BUT INCOMPLETE**

TABLE **6.4.4**
Summary of evidence for responses relating to pollinator management and beekeeping

Response (section of chapter 6)	Main driver(s) (section of chapter 2)	Type of response	Status	Scientific evidence
Build markets for managed pollinators (6.4.4.3)	Pollinator management (2.3.3)	Economic	Proposed	Limited assessment **ESTABLISHED BUT INCOMPLETE**
Community engagement through participatory processes (6.4.4.4)	Pollinator management (2.3.3)	Social / behavioural	Tested	Limited assessment of effectiveness, but widespread agreement that collaborative engagement would be beneficial **ESTABLISHED BUT INCOMPLETE**
Voluntary codes of practice (6.4.4.4)	Pollinator management (2.3.3)	Social / behavioural	Tested (ILK)	Limited assessment of effectiveness. Some examples from indigenous and local knowledge. **INCONCLUSIVE**
Better education (farmers, beekeepers) (6.4.4.5)	Pollinator management (2.3.3)	Knowledge	Tested	While there is widespread agreement that better education could lead to improved pollinator and pollination outcomes, this concept has not been formally tested. **ESTABLISHED BUT INCOMPLETE**
Maintain and document traditional and indigenous knowledge surrounding beekeeping and honey hunting (6.4.4.5)	Pollinator management (2.3.3)	Knowledge	Tested	There is strong agreement of the value of such a proposition, but it needs more concrete assessment **ESTABLISHED BUT INCOMPLETE**
Monitor and evaluate managed pollinators (6.4.4.5)	Pollinator management (2.3.3)	Knowledge	Established	Large-scale monitoring programs have been shown to effectively collect and synthesise information on threats to honey bees, allowing coordinated responses (**WELL ESTABLISHED**), but such programs remain untested in other pollinator species
Quantify the benefits of managed pollinators (valuation incentives) (6.4.4.5)	Pollinator management (2.3.3)	Knowledge	Proposed	Large-scale efforts to quantify the economic value of managed pollinators are useful but inherently give large value ranges **ESTABLISHED BUT INCOMPLETE**

is positive for conservation because smaller urban habitat fragments generally harboured lower bee species diversity than larger (Viana *et al.*, 2006; Nemésio and Silveira, 2007; Hinners, 2008). This has been further supported in studies from Germany (Dauber *et al.*, 2003), Brazil (Zanette *et al.*, 2005; Martins *et al.*, 2013), Sweden (Ahrné *et al.*, 2009), UK (Bates *et al.*, 2011), Switzerland (Sattler *et al.*, 2010) and USA (Tonietto *et al.*, 2011; Hostetler and McIntyre, 2001), but there are huge remaining knowledge gaps for other countries. Restoring grasslands, even if not targeted specifically for pollinators, can provide valuable habitat (Tarrant *et al.*, 2013). For instance, Cane *et al.* (2006) found that bee species diversity in Tucson, Arizona in the USA was reduced in small and older desert fragments, but bee abundance was similar to that found in continuous desert patches outside the urban area, which confirms the value to conserve remnant habitat. Also, the diversity of pollinator traits such as nesting habits, diet or body size were affected by habitat loss due to urbanization, which may alter the role of pollinators for ecosystem functioning (e.g., Banaszak-Cibicka and Zmihorski, 2012; Zanette *et al.*, 2005; Bates *et al.*, 2011, Sattler *et al.*, 2010).

Little is known about how the flow of genes might be supported by maintaining habitat in urban settings. Conserving remnant habitat in urban landscapes may enhance genetic flow among pollinator populations. In a unique study, Jha and Kremen (2013) examined regional genetic differentiation of *Bombus vosnesenskii* across a landscape mosaic of natural, agricultural, urban and suburban habitats. They found that *B. vosnesenskii* regional gene flow is most limited by commercial, industrial and transportation-related impervious cover linked to urbanization. Importantly though, the effects of urbanization are not common across all studies; several show no negative impact of urbanized landscape on local pollinator communities (Bates *et al.*, 2011), and urban areas can become important habitat for pollinators in intensively managed landscapes (Baldock *et al.*, 2015). Also, when a statistically significant relationship has been found, some of the previously mentioned studies show that urbanization explains a low proportion of the variation in pollinator community composition compared with other local and landscape factors. Conservation of pristine habitat should, thus, be combined with other actions to support pollinators in urban landscapes (e.g., Bates *et al.*, 2011; Sattler *et al.*, 2010).

6.4.5.1.2 Urban landscapes

Conservation of pollinators in cities depends on the composition of the surrounding landscape. Strong relationships between landscape heterogeneity and bee species richness have been found, indicating that the availability of diverse resources for the pollinators in the landscape play a great role to maintain a rich local community (Sattler *et al.*, 2010). Certainly, habitat connectivity can bolster a species-rich pollinator community within an urban area. For example, bee abundance on green roofs and in managed green spaces in Zurich, Switzerland was positively correlated with connectivity to surrounding habitat (Braaker *et al.*, 2014). Managing for a less hostile "softened" matrix where some resources and habitat stepping stones are available in urban or ruderal areas, may increase conservation of pollinators in remnant high quality habitats and in the landscape. This was demonstrated in southeastern Brazil, where generalist stingless bee diversity in urban forest fragments was driven by forest composition as well as the heterogeneity and quality of the surrounding landscape (Antonini *et al.*, 2013). In fact, several recent studies emphasize the importance of considering both the quality of local urban habitats as well as the surrounding landscape for the successful conservation of pollinators (Jules and Shahani, 2003; Bates *et al.*, 2011; Ahrné *et al.*, 2009). We also see reciprocal effects, with urban habitats influencing bee communities in surrounding natural areas (Hinners *et al.*, 2012; Neame *et al.*, 2013). For example, Hinners *et al.* (2012) studied diversity, abundance, and community composition of bees in remnant grassland fragments surrounded either by suburban residential areas or by extensive, continuous grassland in Colorado, USA. They found that bee species richness was positively related to grassland habitat area, and that bee species density was higher and more variable in suburban sites probably by means of habitat complementation or supplementation between grassland remnants and the surrounding suburbs.

Researchers have also begun to study how landscape context influences the pollination provided by bees in cities. Verboven *et al.* (2014) examined flower visitation and seed set of the obligatory outcrossing *Trifolium repens* (white clover) in public lawns in an urban-peri-urban gradient around Leuven, Belgium. They found that pollination was not compromised by urban land use. Greater abundance of *T. repens* in lawns and increasing urban area in the surrounding landscape both had a positive effect on both flower visitation rates and seed set. In this and many studies, however, a lack of mechanistic understanding of the population processes causing these patterns limits advancement in urban-focused conservation. For instance, this finding could be due to urban areas supporting an increased abundance of bumble bees, thus demonstrating a value for conservation, or due to urban sites concentrating bumble bees onto a small number of lawns due to a lack of alternative forage. The structure of landscape elements can also influence pollinator movement and directly affect plant reproductive success. Both hedgerows and artificial linear landscape features can influence the flight directions of bumble bees (Cranmer *et al.*, 2012). Pollinator activity, pollen receipt and subsequent seed set on sentinel plants increased in patches with more connections (Cranmer *et al.*, 2012). This knowledge has yet to be translated into specific actions.

Thus, managing the surrounding landscape to be more hospitable has potential to mitigate the negative impact of habitat loss and fragmentation. Despite the demonstrated negative impacts of urbanization, it's important to note that relatively intact pollinator communities can be maintained in urban areas, both in boundaries between urban and rural areas such as in sub- and pen-urban landscapes (e.g., Hostetler and McIntyre, 2001; McFrederick and LeBuhn, 2006; Kearns and Oliveras, 2009; Carper *et al.*, 2014). These ideas have not yet been widely tested or implemented, but an effort to create "Pollinator Pathways" in cities is underway, with a significant pilot study partially installed in Seattle, Washington, USA (Bergmann, 2015).

6.4.5.1.3 Urban green spaces

Urban green spaces are in focus when managing for a more pollinator-friendly landscape. Greenspaces may be privately owned yardscapes, allotments, parks, public gardens, cemeteries, golf courses, infrastructure right-of-ways, or green roofs (Kadas, 2006). They vary in their value for pollinator conservation depending on the availability of pollen, nectar and nesting resources, all of which are important factors for designing landscapes that support plant pollinator assemblages (Cane, 2005). An opportunity to maintain rich pollinator communities in urban settings lies in the appropriate management of gardens and allotments.

Increasing the abundance of flowering plants and floral area of blooms in urban green spaces can increase pollinator diversity and abundance (Dicks *et al.*, 2010). For example, establishing a strip of meadow vegetation, a sunflower patch, or reducing weeding in small French public gardens tripled the abundance of residential butterflies and increased the abundance of other pollinators by nearly 50% (Shwartz *et al.*, 2014). Richness of both butterflies and bees was positively related to garden floral area in New York City, New York, USA (Matteson and Langellotto, 2010). Researchers have also investigated whether the origin and structure of flowering plants influences their attractiveness. Native plants support both generalist and specialist bees (Isaacs *et al.*, 2009; Tuell *et al.*, 2008), but they represent only a fraction of available floral resource within a complex city landscape, often dominated by non-native weedy species and ornamentals (Gardiner *et al.*, 2013). Addition of native or locally-adapted vegetation has given variable results. The addition of native plants to urban food gardens did not influence the pollinators in New York City gardens (Matteson and Langellotto, 2010). In Phoenix, Arizona, engaging in locally-adapted dry desert landscaping practices in residential landscapes gave a more diverse bee community than irrigated yards (Hostetler and McIntyre, 2001). Clearly, non-native plants also offer important resources to pollinators (Frankie *et al.*, 2009; Woods, 2012; Frankie *et al.*, 2013; Hanely *et al.*, 2014; Garbuzov and Ratnieks, 2014). In Puebla, Mexico, local plants with many different uses are cultivated in home yards (Blanckert *et al.*, 2004). In Moscow, Russia, lawn management for conserving pollinators has been performed recently by sowing native wild herbs as well as imitating Russian traditional meadow management with mosaic mowing about half of the lawn one time per year (Volkova and Sobolev, 2004). While not specifically for pollinators, this preserves natural habitat for pollinators.

Schemes exist to help people select appropriate plants for urban green spaces such as gardens. For example, the UK Royal Horticultural Society's Perfect for Pollinators scheme (https://www.rhs.org.uk/science/conservation-biodiversity/wildlife/encourage-wildlife-to-your-garden/plants-for-pollinators) provides regularly-updated plant lists to help gardeners identify plants that will provide nectar and pollen for bees and other pollinating insects.

6.4.5.1.4 Retain unmanaged urban land

Retaining unmanaged areas in urban landscapes can provide important habitat for bees in cities (Tommasi *et al.*, 2004; McFredrick and LeBuhn, 2006; Gotlieb *et al.*, 2011; Gardiner *et al.*, 2013). Unmanaged areas include forest, grassland or desert fragments as well as vacant land or brownfields that were formerly residential or industrial space. In a review, Gardiner *et al.* (2013) found that urban vacant lots or brownfields are valuable for beneficial arthropods and that these habitats also support a significant diversity of rare and threatened species including pollinators. Bumble bee abundance was positively correlated with the abundance of unmanaged undeveloped areas, or areas not actively landscaped, in the parks in the city of San Francisco, US, and there was a positive correlation with the openness of the surrounding matrix illustrating that these pollinators colonize urban parks from surrounding habitats (McFrederick and LeBuhn, 2006). Gotlieb *et al.* (2011) compared bee communities in natural desert and garden habitats in the Jordan Rift Valley in Israel, and found that bees in gardens were more abundant and general in their diet, whereas rarefied bee species richness was greater in the natural habitat.

6.4.5.1.5 Adding artificial nests and food

Urban residents may also add shelter and artificial food sources, and significant efforts have been made in some cities to add nesting habitat in the form of "bee hotels". Artificial nest sites for cavity-nesting solitary bees have good occupancy rates and have been shown to enhance local populations over time (Dicks *et al.*, 2010). The value of several types of artificial nests for solitary and social bees has been tested. Sections of bamboo, paper tubes and wooden blocks with holes ranging from 4-10 mm in diameter were added to gardens as nesting sites for bees and wasps and it was found that both design and placement influenced colonization. Nest boxes for bumble bees have much lower success rates, with underground boxes the most effective, and no evidence that they lead to increasing colony densities over time (Dicks *et al.*, 2010). In Toronto, Canada, introduced bees occupied larger proportion of nests and were less parasitized compared with native bees (MacIvor and Packer, 2015). Bundles of twigs and plastic tubes were colonized by Megachilidae in gardens in Liege (Jacob-Remacle, 1976). Canes from *Spathodea campanulata*, *Ficus*, and bamboo have been found to support *Xylocopa* (carpenter bees) in urban greenspaces (Charves-Alves, 2011). Although many of these artificial nests were colonized by bees, their effects on species richness or population-level abundances of bees in the urban landscape have not been measured. It is possible that placement of artificial nests increases awareness about pollinators among citizens, but this has not been tested. Artificial nests need to be managed; otherwise, disease(s) and parasites may build up over time (Mader *et al.*, 2010).

There is little research to date into how the addition of artificial food may influence pollinator communities. One study by Arizmedi *et al.* (2007) found that the addition of nectar feeders can influence visitation and subsequently the pollination of native plants by hummingbirds. Therefore, impacts of practices aimed to supplement food should be investigated further, given their ability to alter important ecological relationships.

6.4.5.1.6 Management of right-of-way infrastructure

Early successional habitat created by right-of-way management is increasingly considered valuable for pollinator conservation (Wojcik and Buchmann, 2012). The areas these habitats occupy are huge (Wojcik and Buchmann, 2012). Several studies have examined right-of-way linear elements such as road verges, power lines and railroad corridors as areas for active pollinator management, and they are often found to be valuable (Way, 1977; Bhattacharya *et al.*, 2003; Tischendorf and Treiber, 2003; Desender, 2004, Russell *et al.*, 2005; Noordijk *et al.*, 2009; Osgathorpe, 2012; Berg *et al.*, 2013). Butterflies benefit from the presence of native plants on roadsides, as shown by North American and European studies (Ries *et al.*, 2001). Berg *et al.* (2013) found that power-line corridors harbored more butterfly species, higher abundances and a tendency for more individuals of red-listed species than road verges, clear-cuts, or pastures. Byrne *et al.* (2007) found that road verges were important in maintaining landscape-scale genetic connectivity of a bird-pollinated shrub. A replicated controlled trial in Kansas, US found that road verges planted with native prairie grasses and flowers supported a greater number and diversity of bees than paired conventionally managed verges (Hopwood, 2008). Moroń *et al.* (2014) found that railway embankments positively affected bee species richness and abundance, but negatively affected butterfly populations. Importantly, management efforts to encourage pollinators must also satisfy the highway engineers, and must be developed in a collaborative manner (Way, 1977). Further, the limitations of these habits should be considered as the presence of cars may disrupt or kill foragers (Hirsch, 2000). Also the potential for contamination within these habitats exists. Jablonski *et al.* (1995) found metal (Pb, Cd, Cu) contamination of nectar, honey and pollen collected from roadside plants. In many countries there is an interest in managing these habitats for biodiversity, but this response must be considered to be proposed but with great potential. There are right-of-way management programs for pollinator conservation underway such as the "B-lines" project in the UK (https://www.buglife.org.uk/campaigns-and-our-work/habitat-projects/b-lines), aiming to restore 150,000 ha of flower-rich habitat in the UK. In the US, Iowa installed in 1989 a program to establish roadside native vegetation funded partly by road use tax, by which 50,000 ha of roadsides have been planted with native vegetation (Brandt *et al.*, 2011) that benefits pollinators (Ries *et al.*, 2001). In the US state of Minnesota restored native plant habitat has been established along roadsides (The Xerces Society, 2011).

6.4.5.2 Legal responses

Some national pollinator strategies (see section 6.4.6.2.2) have specific actions to enhance pollinator habitat in towns and cities. A focus of these is on providing evidence-based guidance to local authorities, landscape planners and architects. We found no examples of strict regulations relevant to managing pollinators associated with urban areas or infrastructure developments.

Having said that, urban green space habitats are often ignored in conservation plans despite their value, an issue that must be addressed (Harrison and Davies, 2002; Muratet *et al.*, 2007; Kattwinkel *et al.*, 2011).

6.4.5.3 Economic responses

We know of no economic incentive programs similar to those present within agricultural landscape that support conserving habitats for pollinators and other beneficial biodiversity in cities or infrastructure.

6.4.5.4 Social and behavioural responses

6.4.5.4.1 Community engagement

Urban residents are interested in conserving and enhancing pollinators by assisting with monitoring networks, construction of pollinator gardens and addition of artificial food and nesting resources (see section 6.4.6.3.4). There are plenty of examples of NGOs that promote private and public land managers to support pollinators in the urban landscape by decreasing pesticide use and providing flowers and nests in their gardens *etc.* (e.g., http://www.xerces.org/wp-content/uploads/2008/06/Pollinator-Conservation-in-the-Portland-Metro-Area.pdf, http://www.sef.nu/smakrypsguiden/smakryp-som-hobby/skapa-din-egen-insektstradgard/), but we found no applied policies to stimulate this kind of action at the community level. Many green-space habitats are ignored in conservation plans despite their value, an issue that must be addressed (Harrison and Davies, 2002; Muratet *et al.*, 2007; Kattwinkel *et al.*, 2011). One step in that direction came in 2014 when the US President, Barack Obama, established the Pollinator Health Task Force. One of the key goals of this initiative is the development of plans and policy to establish or protect pollinator habitats. The U.S. government has subsequently issued a National Strategy to Promote the Health of Honey Bees and Other Pollinators (https://www.whitehouse.gov/sites/default/files/microsites/ostp/Pollinator%20Health%20Strategy%202015.pdf), which outlines actions that various federal agencies are taking as well as identifying research to address uncertainties; a key element of this strategy is the development of public/private partnerships.

Urban food production has grown rapidly worldwide with citizen groups constructing food gardens that include pollinator resource plants (Gardiner *et al.*, 2013). Management of these small-scale gardens and farms may include the addition of managed honey bees or rely solely on existing pollinator communities for crop pollination.

6.4.6 Policy, research and knowledge exchange across sectors

This section explicitly reviews responses that cut across sectors, such as large-scale land use planning, education and engagement, and community engagement through participatory processes. It compiles global experience of developing broad pollinator policy or actions and considers how research and monitoring needs have been met, and could be met in the future.

6.4.6.1 Summary of experience across sectors

Across the policy sectors in this section (agriculture, pesticides, nature conservation, managed pollinators and urban/transport infrastructure), some common themes emerge about available responses and the evidence for their effectiveness.

Technical responses are the most widely established and the most scientifically tested. For many of those relating to land management, such as planting flowers, or restoring semi-natural habitat, there is high confidence in positive effects on pollinators themselves, with many studies showing that pollinators make use of new resources provided for them (biodiversity). There is much less evidence of longer-term effects on pollinator populations, and limited evidence of effects on pollination.

Economic and legal responses tend to be established, with some evidence of impacts on pollinators and pollination. Regulatory control through obligatory registration and standards (legal responses) are most strongly established in the pesticides sector (6.4.2), and there is evidence they reduce risks to pollinators. Among economic market-based instruments, voluntary incentives such as certification or agri-environment schemes are established in some regions in the agriculture and managed pollinator sectors (6.4.1 and 6.4.4). Taxes, which are obligatory market-based instruments, have been proposed to discourage pesticide use, but not tested.

Social/behavioural responses, even those that are established, seldom have robust evidence of effectiveness. Many examples come from indigenous and traditional knowledge, such as voluntary codes of practice among farming and beekeeping communities and community groups working together (6.4.1 and 6.4.4).

TABLE **6.4.5**
Summary of evidence for responses relating to nature conservation

Response	Main Drivers	Type of response	Status	Scientific evidence
Manage or restore native habitat patches to support pollinators	Land use and its changes (2.1)	Technical 6.4.3.1.1.	Established	Increases diversity and abundance of pollinating insects **WELL ESTABLISHED**
Increase connectivity of habitat patches	Changes in land cover and spatial configuration (2.1.2)	Technical 6.4.3.1.2.	Tested	Some evidence that habitat connections help pollinator movement and gene flow **ESTABLISHED BUT INCOMPLETE**
Manage invasive species (plants, pests, predators or pollinators) that diminish pollinators or pollinator habitat	Invasive species	Technical 6.4.3.1.4.	Tested	Case study evidence of some benefits to pollinator species, but eradication is difficult to achieve **ESTABLISHED BUT INCOMPLETE**
Targeted conservation of specific pollinator species or groups of species (includes ex situ conservation of threatened species, includes species of special cultural value)	Multiple, interacting threats	Technical 6.4.3.1.5.	Tested	Examples exist for a limited range of taxa **ESTABLISHED BUT INCOMPLETE**
Targeted conservation of pollinators associated with specific plant species threatened by pollination deficit	Multiple, interacting threats	Technical 6.4.3.1.5.	Tested	One European example known, for dittany (*Dictamnus albus*) **INCONCLUSIVE**
Establish protected areas or improve the quality of existing ones (including protected areas of cultural value)	Land use and its changes (2.1)	Legal 6.4.3.2.2	Established	Protected areas host species diversity, but it is difficult to determine the impact of legislation in achieving protection **WELL ESTABLISHED**
Payment for ecosystem services	Land use and its changes (2.1)	Economic 6.4.3.3.	Tested	Ecosystems services payments have been established for other services (watershed protection, carbon sequestration) but no examples for pollination **ESTABLISHED BUT INCOMPLETE**
Maintain sacred and other culturally protected areas that support pollinators	Land use and its changes (2.1)	Social/Behavioural 6.4.3.2.2	Established	Protected areas host species diversity, but few case studies **ESTABLISHED BUT INCOMPLETE** (see also 5.4.2.4)
Increase taxonomic expertise on pollinator groups (formal education/training) and technology to support discovery and identification	All	Knowledge 6.4.3.5.	Tested	Significant training has been achieved in a number of countries **WELL ESTABLISHED**

Knowledge responses related to ongoing research are generally known to be effective in enhancing knowledge and improving responses, whereas those related to education and awareness-raising usually have limited evidence to demonstrate effectiveness. Exceptions to this are the evidence on ability of Farmer Field Schools to change pest management practices (see section 6.4.2.4.2) and evidence that outreach programmes led by the Xerces Society for Invertebrate Conservation in the USA have created pollinator habitats (Xerces Society, 2014).

Indigenous and local knowledge particularly enhances scientific knowledge in the area of diversified farming systems (5.2.8 and 6.4.1.1.8), knowledge responses in agriculture (6.4.1.5), non-timber forest products (6.4.3.1.3), species-focused conservation actions (6.4.3.1.5), and protected areas and conservation (6.4.3.2.2). It also complements scientific knowledge by adding significantly to scientific information on husbandry techniques and habitat management for managed pollinators other than *Apis mellifera* (sections 5.3.4, 5.3.6 and 6.4.4.1.1, 6.4.4), such as adding artificial nests and food for pollinators (6.4.5.1.5), or related to social and behavioural responses (6.4.3.4 and 6.4.4.4).

6.4.6.2 Legal integrated responses

6.4.6.2.1 Large-scale land-use planning

There is an extensive literature regarding how an understanding of ecosystem services in general could be used to improve land-use planning (for example, Chan *et al.*, 2011; Goldstein *et al.*, 2012). There are a few examples where an understanding of ecosystem services has been used to influence land use planning outcomes, such as the often cited example of the New York City water management (Kremen and Ostfeld, 2005). We were unable to find an implemented example where pollination or pollinator protection has been one of the primary drivers in land-use planning. There are, however, a number of research projects that have used pollination as one of the key ecosystem services in analyses of the cost impact of different land-use change scenarios (Olschewski *et al.*, 2006; Olschewski *et al.*, 2010; Ricketts and Lonsdorf, 2013).

Land-use planning is more likely to build on an understanding of multiple overlapping benefits (and costs) associated with different land-use scenarios rather than a single ecosystem service, such as crop pollination. This approach is also more likely to detect economic advantages associated with habitat protection, because the sum of multiple benefits will be greater than that from any single service unless there are strong trade-offs between services (Olschewski *et al.*, 2010) (see section 6.8 for a discussion of the evidence for specific trade-offs). Whereas some land-use analyses have applied a total valuation approach, decision making is generally guided by the marginal change in value associated with an action (i.e., the value added or lost for each small piece of land changed). Ricketts and Lonsdorf (2013) show that some patches of habitat have a much higher value under marginal valuation (i.e., assessing stepwise loss in cover) than they would in an average or total valuation across the whole landscape.

6.4.6.2.2 High-level initiatives, strategies and policies focused on pollinators

The North American Pollinator Protection Campaign (NAPPC; http://pollinator.org/nappc), was established in 1999. This initiative focuses on North America, including Canada, USA, and Mexico. It has members and 120 partner organizations from all three countries, and is co-ordinated by The Pollinator Partnership. The biggest achievements of the NAPPC so far have been the 2007 Status of Pollinators report (National Academy of Sciences, 2007), the production of 31 Web-based regional planting guides covering the entire US, to help farms, schools, parks and businesses grow pollinator-friendly landscapes, and the 11 major pollinator-protection agreements signed between the Pollinator Partnership and federal government agencies responsible for land management.

The International Pollinators Initiative, facilitated by the Food and Agriculture Association of the United Nations (FAO), was formally established by the Convention on Biological Diversity in 2000 (Convention on Biological Diversity, 2012), as part of a Programme of Work on Agricultural Biodiversity developed in 1996. Its aim was to coordinate action worldwide to: monitor pollinator decline; address the lack of taxonomic information on pollinators; assess the economic value of pollination; and promote the conservation and sustainable use of pollinator diversity. It has developed a number of useful tools and guidance, including a protocol for detecting and measuring pollination deficit in crops tested in at least eighteen countries (Vaissiere *et al.*, 2011, see section 6.4.1.1.10)), a guide to help farmers evaluate the costs and benefits of applying pollinator-friendly practices (Grieg-Gran and Gemmill-Herren, 2012), and a spreadsheet-based tool for assessing pollination value and vulnerabilities to pollinator decline at national scale (Gallai and Vaissiere, 2009). The International Pollinators Initiative also maintains the Pollination Information Management System (see *Decision Support Tools* in section 6.4).

Several national or regional pollinator initiatives have been established under the umbrella of the FAO International Pollinators Initiative (http://www.fao.org/pollination/en/). One that preceeded it was these include the African Pollinator Initiative and the Brazilian Pollinators Initiative. The Brazilian Pollinators Initiative was started in 2000 by scientists. It became an official Government initiative in 2009, led by the Brazilian Ministry of the Environment, and established research networks focused on 11 valuable crops including cashew, Brazil nut and apple. These networks were funded by the Brazilian Research Council (CNPq; costing US $2 million in total) and supported by a range of international institutions (http://www.polinizadoresdobrasil.org.br/index.php/pt/). In 2010, the African Pollinator Initiative published a guide for the identification of tropical bee genera and subgenera of sub-Saharan Africa, in both English and French. This is available free to download at http://www.abctaxa.be/volumes/vol-7-bees, and hardcopies are freely available for people in developing countries. Between 2010 and 2014, 349 free copies of the book were distributed to people in 16 countries, including Cameroon, Ethiopia, Sri Lanka and Malaysia.

More recently, several countries have initiated strategic policy initiatives on pollinators at the national level. They include the Welsh Pollinator Action Plan, the National Pollinator Strategy for England, and the US National Pollinator Health Strategy.

There is no doubt that these integrated actions and strategies can lead to policy change with the potential to influence pollinator management on the ground. There are examples of both non-Governmental Pollinator Initiatives (the North American Pollinator Protection Campaign) and national pollinator strategies (The National Pollinator Strategy for England) leading to specific consideration of pollinators in agricultural policy. In the US, the NAPPC worked with other organisations to ensure that the 2008 Farm Bill included pollinator programs. In England, a new agri-environmental scheme being designed for the latest reform of the Common Agricultural Policy, to start in 2016, will include an optional package of measures targeted to pollinators, as a direct result of Government signing up to a National Pollinator Strategy for England. In both cases this was possible because action on pollinators was demanded at the appropriate time, during a development stage in the agricultural policy cycle (Dicks *et al.*, 2015; see section 6.1 for explanation of the policy cycle).

6.4.6.3 Integrated knowledge responses

6.4.6.3.1 Changing behaviour through engagement and education

Education and outreach programs focused on pollinators and pollination have increased in recent years globally, in both school curricula and informal settings (museums, websites, conservation programs, entertainment media such as TV and radio). For example, in Mexico, scientific information on pollination and the role of bats is included in a fourth-grade text book issued by the Government to all 9-10 year old school children (Secretaría de Educación Pública, Mexico, 2014).

We found no published evidence of pollinator education programs leading to impacts on pollinator populations through behaviour change.

Environmental education (EE) research, drawing on the fields of environmental psychology and sociology, provides evidence of particular outreach and education strategies that result in behaviour changes in the audience. The early and persistent assumption that environmental knowledge leads to environmental attitudes, which then lead to pro-environmental behaviour, is no longer accepted (Kollmuss and Agyeman, 2002). Instead, numerous evidence-based theories involving meta-analyses of existing studies have identified variables associated with pro-environmental behaviour. Some of these variables are relevant to the specific behaviours necessary to enhance pollinator populations: knowledge of the issue and action strategies to address it, perception of one's own ability to affect change (internal locus of control), pro-environmental attitudes, verbal commitment to the behaviour, sense of personal responsibility for the environment, and social and institutional constraints to the desired behaviour. Key behaviour-change strategies that influence these variables can be drawn from standard techniques in social marketing (Monroe, 2003). They include: tailor the message and the types of information provided to the audience, including understanding barriers and benefits to the behaviours for that audience; use methods that create commitment to the behaviours, including providing vivid, meaningful procedural information about the action desired (Monroe, 2003).

Pollinators, unlike many targets of environmental education, allow the public to make a direct link between learning and specific behaviours. The two main strategies of pollinator education campaigns expected to be effective in producing behaviour change are: 1) *Building awareness and concern* about the declines in populations of some pollinator species and their role in food production; 2) *Practical training and real opportunities for action,* such as planting a garden or reducing pesticide use.

Many public programs around the world use these education strategies. Conservation organizations such as the Xerces Society (USA), Bumblebee Conservation Trust (UK), and the Pollinator Partnership (USA) offer conferences, workshops and/or training that specifically provide information and hands-on practice with pollinator habitat enhancement techniques, as well as online educational materials, for landowners, farmers, teachers and the broader public. University programs aimed at post-graduates and professionals in agriculture and environmental sciences provide courses on pollinator biology, management and conservation. For example a two-week Pollination

Course is provided by government, university and NGO partners in Brazil. This has run every year since 2008 (every other year 2003-2008), and has intensively trained nearly 300 professionals (http://pollinationcourse.wix.com/2014english). Pollinator citizen science programs are numerous (see Citizen Science section) and in addition to producing monitoring data, are also effective education programs, engaging thousands of volunteers by providing information about the role of pollinators in ecosystems and food production, and providing an opportunity for action by monitoring the pollinators in their local area (Toomey and Domroese, 2013).

6.4.6.3.2 Research and monitoring

There are funding programmes dedicated to pollinators or pollination research in Australia, the UK, USA, Brazil, India, Kenya and South Africa. For example, between 2003 and 2009, the Brazilian Government invested US$ 3.3 million in development of management plans for native pollinators of plants of economic value, including West Indian cherry, guava, tomato, mango, passion fruit, cashews, Brazil nuts, melons, and cotton (http://www.cnpq.br/web/guest/chamadas-publicas;jsessionid=22C71C12E78764DEB8534068636DF7AC?p_p_id=resultadosportlet_WAR_resultadoscnpqportlet_INSTANCE_0ZaM&idDivulgacao=76&filtro=resultados&detalha=chamadaDetalhada&exibe=exibe&id=116-16-938&idResultado=116-16-938 and http://www.mma.gov.br/biodiversidade/projetos-sobre-a-biodiveridade/projeto-de-conserva%C3%A7%C3%A3o-e-utiliza%C3%A7%C3%A3o-sustent%C3%A1vel-da-diversidade-biol%C3%B3gica-brasileira-probio-i/processos-de-sele%C3%A7%C3%A3o-finalizados, see Edital PROBIO 01/2004).

The Australian Honey Bee and Pollination Programme is a joint Government and industry program that invests over US$1 million a year in research on sustainable beekeeping and crop pollination. Analyses of its research investments showed that it provided positive returns, with benefit: cost ratios ranging from 2.05 to 28.61 (Rural Industries Research and Development Corporation, 2012). These numbers were based on economic, environmental and social benefits accrued, relative to a scenario without the research, for three case study projects. Potential societal benefits included the maintenance of rural livelihoods through beekeeping, and reduced impacts of chemical handling through biological control of chalkbrood. The AmericanHort Bee and Pollinator Stewardship Initiative http://americanhort.org/AmericanHort/Shop/Be_In_The_Know/AmericanHort/Knowledge_Center/beespoll.aspx is a similar collaborative funding scheme for the US horticulture industry. The UK Government, through its National Bee Unit (www.nationalbeeunit.com), and the US Department of Agriculture (www.ars.usda.gov/main/site_main.htm?modecode=80-42-05-40) dedicate research funding to honey bee health and monitoring. The USDA Colony Collapse Action Plan (http://www.ars.usda.gov/is/br/ccd/ccd_actionplan.pdf) directed $1 million USD per year from 2008-2012, which contributed to understanding the causes of Colony Collapse Disorder, and the programme was continued in 2015 (USDA, 2013; USDA, 2015; see section 2.3).

The UK Insect Pollinators Initiative invested a total of £9.65 million in nine projects through a partnership of six research funders between 2009 and 2014. The research covered the health, ecology and conservation of both managed and wild pollinators, as well as crop pollination. It led to a number of important new findings, including spatial evidence for pathogen transfer between wild and managed bees (Furst *et al.*, 2014), empirical evidence of negative interactive effects between pesticides (Gill *et al.* 2012), and maps of current and future pollination for the UK (Polce *et al.*, 2013; Polce *et al.*, 2014). The final outcomes and impact of this research effort are yet to be reported.

The European Commission has funded a series of international research projects focused at least partly on pollinators (ALARM http://www.alarmproject.net/, STEP http://www.step-project.net/) and more recently on pollination as an ecosystem service (LIBERATION http://www.fp7liberation.eu/TheLIBERATIONproject; QUESSA http://www.quessa.eu) or measuring farmland biodiversity (BIO-BIO http://www.biobio-indicator.org). Each cost several million euros. These projects either have generated, or are expected to generate, globally important findings and datasets. The ALARM project, completed in 2009, compiled the first detailed quantitative assessment of pollinator decline (Biesmeijer *et al.*, 2006) and a Europe-wide climate change risk atlas for butterflies (Settele *et al.*, 2008). The STEP project is continuing this work, with greater focus on mitigation. It has produced, for example, a meta-analysis on the effects of agri-environmental management for pollinators (Scheper *et al.* 2013) and new analyses of the pollinator decline data for Europe (Carvalheiro *et al.*, 2013). The BioBio-project identified wild bees and bumble bees as one of 23 indicators for measuring farmland biodiversity (Herzog *et al.*, 2013).

These examples demonstrate that dedicated funding for pollinator research is effective at delivering robust, peer-reviewed scientific evidence and societal benefits.

6.4.6.3.3 Centres of information, research and knowledge exchange

Knowledge exchange must take place alongside research to ensure that the research answers the right questions and has a chance to be incorporated into policy and practice quickly. See Chapter 5 (section 5.2.4.7) for a discussion on co-production of knowledge across different knowledge systems.

Cook *et al.* (2013) described four institutional frameworks to achieve effective knowledge exchange in conservation science – i) boundary organisations spanning science and management, ii) scientists embedded in management agencies, iii) formal links with decision-makers at research-focussed institutes and iv) training programmes for practitioners. At least three of these approaches can be identified in one or more of the many networks or centres for information and knowledge exchange on pollinators that have been established around the world. Prominent examples are shown in **Table 6.4.6.2**. All examples are providing information or resources to a broad set of target audiences, usually including researchers, beekeepers, farmers, policymakers and members of the public. The effectiveness of this activity is hard to quantify. Most of the centres have not actively reported performance indicators, or direct or indirect measures of their impact. Even so, some of the resources they have produced, even very recently, are widely used and well known.

Several international biodiversity information centres carry information on pollinators although their remit is far broader. For example, the International Union for the Conservation of Nature (IUCN; www.iucn.org) holds a number of conservation databases, including the Red List of threatened species, which has assessed the threat status of all European bee species (Nieto *et al.*, 2014). The Global Biodiversity Information Facility (GBIF; http://www.gbif.org/) collates global biodiversity data for over 1.5 million species and has been used to investigate spatial patterns in plant-pollinator interactions, such as oil-collecting bees in the genus *Centris* and flowers that produce oil (Giannini *et al.*, 2013). The Integrated Taxonomic Information System has a checklist of the world's bee species, providing details of all synonyms and subspecies (ITIS; http://www.itis.gov/beechecklist.html).

Ensuring transfer of indigenous and local knowledge, or biocultural traditions, from elders to new generations is a different challenge. In New Zealand, the Tuhoe Tuawhenua Trust (http://www.tuawhenua.biz/index.html) publish online videos of elders demonstrating traditional knowledge, such as methods for gathering honey, as if in conversation with younger people.

6.4.6.3.4 Use of citizen science for pollinator research and monitoring

Long-term monitoring of pollinator populations, and pollination, is greatly needed all over the world (see Chapter

TABLE **6.4.6.2**
Centres of information, research and knowledge exchange around the world

Name	Purpose	Location	Institutional framework	Website
International Bee Research Association IBRA	Provides information and educational material on bee science and beekeeping worldwide.	UK	Boundary organisation	http://www.ibra.org.uk/
International Commission for Plant Pollinator Relationships (ICPPR)	Promotes and coordinates research on plant-pollinator interactions by organising meetings and networks	International	Formal link between researchers and decision makers	http://www.uoguelph.ca/icpbr/index.html
Apimondia	The International Federation of Beekeeper's Associations. Organises international meetings for scientists, beekeepers, honey traders, regulators and development professionals.	Italy	Boundary organisation	http://www.apimondia.org/
COLOSS Network	A network of over 350 scientists from 64 countries. To coordinate research efforts and facilitate transfer of scientific information about honey bee health. It was initially funded as a European COST Action (COST FA0803).	Switzerland	Formal link between researchers and decision makers	http://www.coloss.org
SuperB	A new research network, SuperB (Sustainable pollination in Europe) set up in 2014, also funded by COST (COST Action FA1307). Already has members from 30 countries	Netherlands	Formal link between researchers and decision makers	http://www.superb-project.eu/
Centre for Pollination Studies in India	A Government-funded field research station focused on capacity building and making use of pollinator research (see case study box).	India	Formal link between researchers and decision makers Training for practitioners	http://cpscu.in/
Bee Health eXtension network	An online 'learning environment', linking research users directly with the American Land Grant Universities. Bee health is one of many resource areas.	USA	Formal link between researchers and decision makers Training for practitioners	http://www.extension.org/bee_health
Honey and Pollination Centre, University of California, Davis	Exchanging knowledge between pollination researchers and the wider community of research users.	USA	Formal link between researchers and decision makers	http://honey.ucdavis.edu

2). Appropriate methods and costs of a global monitoring scheme have been discussed (Lebuhn *et al.*, 2013) and the UK Government is currently funding research to design a cost-effective pollinator monitoring programme for the UK, as part of the National Pollinator Strategy for England (Defra, 2014).

Citizen science projects to monitor pollinator populations have been established in many regions. We have gathered some prominent examples in **Table 6.4.6.3**.

As an indication of the scale of citizen science activity for pollinators, the Xerces Society (USA) provides a catalogue of 15 pollinator citizen-science projects in the US (http://www.xerces.org/citizen-science/pollinator-citizen-science/). A database of biodiversity monitoring projects across Europe collected by the EU MON project (http://eumon.ckff.si/index1.php; accessed 22 October 2014) lists 34 different butterfly, moth or wild bee monitoring schemes involving volunteers, in 18 different European countries. Most of these monitor butterflies (30 of the 34 schemes), ranging from single species (*Maculinea rebeli*) annual egg counts on a few sites by a single volunteer in Italy, to 2000 volunteers doing standardised weekly transect counts of 64 species at 1,200 sites in the UK.

Kremen *et al.* (2011) tested the quality of citizen-science data by comparing the results of flower visitor monitoring between trained citizens and professional insect ecologists. Overall coarse trends in pollinator abundance, richness and community structure matched between citizens and scientists. Citizens could reliably distinguish between native bees and honey bees (which are not native in the US), allowing them to provide important data on the overall abundance of wild bees, for example. Such data could potentially be used as proxies to track trends in pollination, or ecosystem health (Munoz-Erickson *et al.*, 2007) as required by policy makers, although their correlations with actual pollination or measures of ecosystem resilience are untested. In Kremen *et al.*'s study, the citizens missed over half the groups of bees collected. The authors concluded that citizen science data collected by inexperienced members of the public could not reliably reflect patterns in occurrence of specific pollinator species or groups.

Some citizen science projects have generated globally important datasets. For example, data from long-running insect recording schemes in the UK, Belgium and the Netherlands are the basis of important analyses of pollinator trends in Europe (Biesmeijer *et al.*, 2006; Carvalheiro *et al.*, 2013). The data held by these insect recording schemes (see **Table 6.4.6.3**) are usually validated for obvious anomalies and verified by experts to check species identities. While there is often no information on sampling effort, and a possibility of bias towards attractive, unusual or easy to find species (Ward, 2014), statistical techniques have been developed to account for these issues (Morris, 2010; Hill, 2012; Carvalheiro *et al.*, 2013).

National-level trends and spatial patterns are discernible from citizen-science data. Here we highlight a few studies to illustrate this. Deguines *et al.* (2012) found degraded insect flower-visitor communities in urban areas across France, relative to agricultural or natural areas, based on data from the SPIPOLL project. Hiromoto et al*.* (2013) are using a participatory monitoring project to gather information about the numbers of invading *Bombus terrestris* in Hokkaido, Japan. Stafford *et al.* (2010) showed that photographic

BOX **6.3**

CASE STUDY: Farmers, researchers and Government working together in Tripura, India

As part of a Darwin Initiative project '*Enhancing the Relationship between People and Pollinators in Eastern India'* the Centre for Pollination Studies, based at University of Calcutta, established a field station for researchers in the north eastern state of Tripura (http://cpscu.in/). This was initially funded by the UK and Indian Governments and the University of Calcutta, with ongoing support from the local Government of Tripura. Local field staff joined the project to support researchers and facilitate engagement with farmers. In the first year a network of 15 long-term monitoring stations was established. Many farmers have been keen to engage by running long-term monitoring on their farms, sharing their local knowledge or taking part enthusiastically in training events. The project has run a series of well-attended farmer events, referred to as 'festivals' because they include a celebratory meal and some cultural events. At festivals, project staff provide training on pollinators and their role in agriculture. Local officials and prominent community members have increasingly lent their support, attending and speaking at these events. From the outset the Tripura State Department of Agriculture was very supportive, providing staff at no charge and helping to keep farmers informed. Recently a Memorandum of Understanding was signed between the Centre for Pollination Studies and the Tripura State Department of Biotechnology to mainstream the findings of the project research programme and to work together to engage and build capacity in local communities. The first jointly-run festival event attracted 150 people. The next joint venture will be to create exhibits in a public space.

records collected via popular social media sites could quickly generate records from across the UK, which could be used for species identification if clear instructions were given on important body parts to include in the photo. Trained members of the public in New South Wales, Australia monitored the extent of a small invading non-native bee species, *Halictus smaragdulus* (Ashcroft *et al.*, 2012). Data from the North American Bird Phenology Program were used to show that ruby-throated hummingbirds (*Archilochus colubris*) are arriving 11-18 days earlier from their migration in the Eastern USA than in the early to mid-twentieth century (Courter *et al.*, 2013). There are many other examples, covering pollinators in general, or specific to bees, moths or birds.

Where citizen science data have been systematically collected with standard methods, they can also enable scientists to begin to distinguish the relative importance of possible drivers of decline. For example, Bates *et al.* (2014) showed a negative effect of degree of urbanization on the diversity and abundance of moths in gardens, based on the citizen science Garden Moth Scheme in the UK (www.gardenmoths.org.uk).

TABLE **6.4.6.3**

Centres of information, research and knowledge exchange around the world Global examples of citizen science projects that monitor pollinators. This Table gives examples to illustrate the range of possibilities. It is not exhaustive (see text for indication of the number of pollinator monitoring schemes that involve volunteers).

Project name	Geographic scope	Number of participants	Brief description and reference
The Great Sunflower Project	US	Over 100,000 people signed up. Data submitted from 6,000 sites.	Volunteers count insects and birds visiting flowers in their back gardens, following a standard methodology. Data are used to map urban pollination services. www.greatsunflower.org
Insect recording schemes. Example: Bees Wasps and Ants Recording Scheme (BWARS)	Schemes in several countries, including the UK, Netherlands, Belgium.	BWARS (UK): About 50 regular recorders	Volunteer recorders, often highly skilled amateur entomologists, submit ad-hoc records of species, which are validated and verified by experts, and collated in national distribution maps. www.bwars.com
New Zealand Nature Watch Hymenoptera project.	New Zealand	25 members in the first year. (Ward 2014)	Online community of volunteer recorders. Identifications are open to be validated and queried by others; anyone can be an expert. http://naturewatch.org.nz/
Seiyou status	Hokkaido, Japan	Over 140 participants in the years 2007-2011.	Participants monitor and destroy spring queens of the invasive bumblebee Bombus terrestris. Scheme running 2006-2014. (Horimoto *et al*. 2013) http://www.seiyoubusters.com/seiyou/en/
Social wasp and bumblebee monitoring in Poland	Poland	50 volunteers	Standard transect counts to monitor bumblebee and wasp community composition (50 species) at 40 agricultural or garden sites, every 20 years. Operating 1981-2020.
SPIPOLL (France)	France	1,137	Following a standard protocol, volunteers photograph all insects visiting a flower of their choice over a 20 minute period. Pictures are identified online by volunteers (Deguines *et al*. 2012) www.spipoll.org.
Monarch Larva Monitoring Scheme	USA, Canada, Mexico	Over 1000 sites since inception in 1996, multiple volunteers per site	MLMP volunteers collect data on monarch egg and larval densities, habitat characteristics, and parasite infection rates. (Oberhauser and Prysby 2008) http://www.mlmp.org/
Iingcungcu Sunbird Restoration Project	City of Cape Town, South Africa	Eight schools	The aim is to relink broken migration routes for sunbirds across nectar-less urban areas by planting bird-pollinated plants on school grounds and involving learners in restoration and bird monitoring. http://academic.sun.ac.za/botzoo/iingcungcu/
Earthwatch: Butterflies and bees in the Indian Himalayas	Kullu Valley, Himachel Pradesh, India.	Three expeditions a year since 2012. So far 88 volunteers have taken part.	Volunteers monitor bees and butterflies visiting fruit crops at different elevations and the diversity of other flower resources. http://earthwatch.org/expeditions/butterflies-and-bees-in-the-indian-himalayas
People, Plants and Pollinators: Uniting Conservation and Sustainable Agriculture in Kenya	Kenya: Kerio Valley, Kakamega Forest, Taita Hills	> 50 farmers and >100 schoolchildren involved in direct monitoring	Volunteers document and monitor flower-visiting insects on specific crops and plants that of high value to the community and/or for pollinators. Over 1000 pollinator species documented on some farms.
“Guardiões da Chapada” Chapada Guadians	Brazil: Chapada Diamantina, Bahia	>50 tour guides and > 100 volunteers in 2015 (the first year)	Volunteers upload pictures of flower-visitor interactions to the project webpage and/or identify the species. The information will be used to build a database on the distribution of plants and flower visitors in the Chapada Diamantina region. http://www.guardioesdachapada.ufba.br/ https://www.facebook.com/Guardi%C3%B5es-da-Chapada-486135114871905/timeline/

6.5 EXPERIENCE OF TOOLS AND METHODOLOGIES FOR ASSESSING RESPONSES

This section describes the available tools and methods for mapping, modelling and analysing options for action on pollinators and pollination, and reviews experience of their use.

6.5.1 Summary of tools, methods and approaches

Many of these tools and methods aim to incorporate existing knowledge and stakeholder or policy preferences into environmental decisions. Often, they can be applied in conjunction with one another. For example, models can be used to build maps that are used in participatory assessments or decision support tools. Evidence synthesis can be used to identify best practice, to define parameters in models or to quantify performance criteria for multi-criteria analysis. Some, not all, of these tools employ economic valuation methods discussed in Chapter 4 (Sections 4.4, 4.5 and 4.6).

6.5.1.1 Case study/best practice approach

Case studies are often used to exchange knowledge and experience, or communicate best practice. An advantage of case studies is that they can be a quick, low-resource option providing localised guidance. For example, the International Pollinators Initiative has collected online written case studies, including reports on pollination requirements of particular crops, monitoring methods and data recording sheets (www.internationalpollinatorsinitiative.org).

The FAO published an initial survey of best pollination practices for at least eight crops in Africa, Asia, North America and South America (FAO, 2008), including mango, papaya and cardamom. This resource is currently being updated. Costs and benefits of the practices are described, but not quantified.

The Pollinator Partnership in the US has published a set of Best Management Practices for four US crops: almond, apple, melon and corn (Wojcik *et al.*, 2014). 'Best' practices were identified by reviewing scientific literature, printed and online resources available to growers and interviews with farm advisers and producers. Some identified best practices were commonly promoted across the industry, such as night spraying and providing outreach material to growers. Others were not mentioned or missing from practice. For example, 'pesticide label instructions in Spanish' was identified as a best practice, but missing from industry practice for all four crops.

Strictly, best practices should be identified by benchmarking, based on outcome metrics that compare practices carried out in a similar context, to find out which perform best. We do not know any examples of this involving pollinators or pollination.

TABLE **6.4.6.1**
Summary of evidence relating to policy, research and knowledge exchange across sectors.

Response (section of chapter 6)	Main driver(s) (section of chapter 2)	Type of response	Status	Scientific evidence
Large scale land use planning (6.4.6.2.1)	Land use change	Legal	Proposed	No specific evidence of use
High level initiatives, strategies and policies focused on pollinators (6.4.6.2.2)	All	Policy	Established	Some evidence of direct influence on policy, but not of actual impacts on biodiversity, food production or cultural value. (**ESTABLISHED BUT INCOMPLETE**)
Outreach and education (6.4.6.3.1)	All	Knowledge	Established	Well-designed activities can change practices, although there is no evidence yet of direct effects on pollinators, or food production. **ESTABLISHED BUT INCOMPLETE**
Fund scientific research on pollinators (6.4.6.3.2)	All	Knowledge	Established	Dedicated funding delivers high quality scientific outputs (**WELL ESTABLISHED**) and societal benefits (**ESTABLISHED BUT INCOMPLETE**).
Knowledge exchange between researchers or knowledge holders and stakeholders (6.4.6.3.3	All	Knowledge	Established	Many examples around the world. Effectiveness for pollinators and pollination unknown. (**INCONCLUSIVE**)
Employ citizen science for pollinator monitoring (6.4.6.3.4)	All	Knowledge	Established	Can discern trends and spatial patterns for some pollinator species or groups (**WELL ESTABLISHED**) No specific evidence of use.

6.5.1.2 Evidence synthesis

Systematic, hierarchical synthesis of evidence is the basis of evidence-informed policy and practice (Dicks *et al.*, 2014a). For pollinators and pollination, a number of systematic reviews, meta-analyses and systematic maps have analysed relevant evidence (Humbert *et al.*, 2012; Randall and James, 2012; Scheper *et al.*, 2013).

In 2010, global evidence on the effects of interventions to conserve wild bees (all species) was summarised in a collated synopsis, covering 59 different responses to a range of threats, with 162 scientific studies individually summarised (Dicks *et al.*, 2010). These summaries are available in an open-access online resource (www.conservationevidence.com). The synopsis has been used for reference in developing the National Pollinator Strategy for England (Defra, 2014) and the FAO International Pollinators Initiative (Convention on Biological Diversity, 2012).

This resource needs updating to cover all pollinators, pollination and evidence from 2011 onwards. The approach has been applied to other ecosystem services, such as pest regulation and soil-related services (www.conservationevidence.com).

The evidence in the bee conservation synopsis was scored for certainty by a group of experts (Sutherland *et al.*, 2011) and their scores used to identify research priorities considered important by conservationists but with little scientific certainty about effects. Research priorities included investigating effects on wild bees of restoring species-rich grassland, and increasing the diversity of nectar and pollen plants at landscape scale. A similar assessment of summarised evidence on interventions to enhance farmland biodiversity (Dicks *et al.*, 2014c) recommended one action specific to pollinators – planting nectar flower mixtures – on the basis of existing evidence.

We know of no examples where this unbiased synthesis of evidence has been employed in decision-support systems relevant to pollinators or pollination (see *Decision support tools* below).

Scanning for alternative options, or solutions, is an important element of organising synthesized evidence to link it with decision-making approaches (such as *Multi-criteria analysis* below). Thirty-one management actions for enhancing biodiversity-mediated pollination were listed by Sutherland *et al.* (2014), and incorporated in the list of responses developed for this report.

6.5.1.3 Risk assessment

Risk assessment is a way of quantifying the likelihood of specific threats or hazards, and is used to help decide whether mitigation is needed. Risk assessment uses a well-established and constantly developing set of methods, and is widely used to support decision making in policy and business. For pollination and pollinators, risk assessment is most widely used in the context of predicting the risk from pesticides and GMOs. It is discussed as a Technical response in section 6.4.2.

The Causal Analysis/Diagnosis Decision Information System (CADDIS; http://www.epa.gov/caddis/) is a formal approach to elicit and organize expert opinions on risk factors, designed by the US Environmental Protection Agency for environmental problems where multiple causes are suspected. It was used to identify '*Varroa* mites plus viruses' as the probable cause of reduced survival in honey bee *Apis mellifera* colonies in California almonds orchards (Staveley *et al.*, 2014).

6.5.1.4 Multi-criteria analysis

Multi-criteria Analysis (MCA; also called multi-criteria decision analysis MCDA, multi-criteria decision-making – MCDM, or multi-criteria evaluation – MCE) is an approach to decision-making that evaluates multiple objectives against multiple attributes or performance criteria (see section 4.2.7.5). MCA is designed to take account of trade-offs. It often involves participatory engagement with stakeholders (42% of examples included stakeholders in a recent review by Estevez *et al.* 2013) and was strongly advocated over purely economic valuation for making decisions about ecosystem services (Spangenberg and Settele, 2010). It has very frequently been applied to environmental decision domains such as land-use planning, biodiversity conservation, water resource management, and energy systems, and a range of methods and approaches are well developed (see Moffett and Sarkar, 2006; Hajkowicz and Collins, 2007; Huang *et al.*, 2011; Estevez *et al.*, 2013).

Multi-criteria evaluation was used to derive a map of suitability for honey bee hives in La Union Island, the Philippines (Estoque and Murayama, 2011). Criteria for good hive placement were suggested and weighted by experts. The results showed high correlation between the landscape suitability index and real honey yields. We could find no cases where pollination was explicitly considered as part of a Multi-criteria Analysis.

A broader approach advocated for environmental decisions is called Structured Decision Making (SDM) (Gregory *et al.*, 2012). This expands on Multi-Criteria Analysis with more focussed effort and guidance on defining the initial objectives and performance measures with stakeholders, as well as monitoring and review stages to incorporate learning into the ongoing decisions. SDM practitioners employ various Multi-Criteria analysis tools, when formal quantitative analysis of trade-offs is required to make a decision.

6.5.1.5 Cost-benefit analysis

Cost-benefit and cost-effectiveness analyses (section 4.1.1.4) have both been used to address decisions about pollinators (Morandin and Winston, 2006; Olschewski *et al.*, 2007; Breeze *et al.*, 2014a). A range of valuation methods can be employed (see **Table 4.2**).

Marginal Abatement Cost (MAC) curves are a popular tool to illustrate cost-effectiveness information. They show the cost associated with the last unit (marginal cost) for varying amounts of reduction in something bad for the environment (such as greenhouse gas emissions), or supply of an environmental good (such as clean water or pollination). They are used to select a cost-effective set of responses to an environmental problem and have mostly been employed to inform climate change mitigation policy (Kesicki and Strachan, 2011). MAC curves have not yet been employed to inform decisions on actions to enhance pollination, or other ecosystem services, because the analysis required to do so it still at an early stage. Ricketts and Lonsdorf (2013) estimated marginal losses of pollination value from removal of forest patches in a Costa Rican landscape, and showed that the marginal pollination value of a hectare of forest is highest when the density of surrounding forest cover is low. To develop a MAC curve, this marginal value information would be combined with the cost associated with keeping each hectare of forest, the amount of forest available to keep, and then compared to similar marginal pollination values generated by other responses, such as retaining or restoring other habitat types.

6.5.1.6 Environmental Impact Assessment

Environmental Impact Assessment (EIA) is a set of well-defined methods for evaluating the environmental impact of particular projects or activities. In Europe, regulation requires that EIAs be carried out on all projects involving certain defined process. When applied to policies, it is called Strategic Environment Assessment.

We found no examples of EIA taking explicit account of pollinators or pollination. A review of Environment Impact Assessment methods applied to the fruit sector doesn't mention pollination (Cerutti *et al.*, 2011). Crist *et al.* (2013) describe a process for assessing the likely impacts of a development on regional ecosystem services, which focuses on the process of consultation and decision-making around major projects. The guidance does not mention pollination as a possible service.

6.5.1.7 Vulnerability assessment

Vulnerability Assessment, or vulnerability analysis, describes an analytical exercise in which the goal is to identify areas, sectors or groups of people particularly vulnerable to adverse effects of environmental change (see definition of vulnerability in Chapter 4, Section 4.6.1). It might be thought of as a broader, generic form of risk assessment. Several different approaches and frameworks have been used. Indicator-Based Vulnerability Assessment (IBVA) is a widely used method that combines quantitative and qualitative indicators, and has been used to inform climate change adaptation in the contexts of public health and water management (Tonmoy *et al.*, 2014). These authors warn that methodological problems such as inappropriate scales and aggregation methods are frequent.

Given the emerging ability to identify areas of potential pollination deficit, vulnerability analysis could be a useful tool for policy on pollinators and pollination. A spreadsheet-based tool developed by the Food and Agriculture Organisation of the United Nations (Gallai and Vaissiere, 2009) allows a simple economic vulnerability assessment for a national economy (see *Decision support tools*, 6.5.1.12).

6.5.1.8 Environmental accounting

In environmental accounting, pollinators can be considered as a natural capital asset, and pollination as an input to production (see Chapter 4, Section 4.4). The recently developed System of Environmental-Economic-Accounting (European Commission *et al.*, 2012) accounts for 'environmental goods and services', which are flows of products within the economy, rather than flows of services from the environment to the economy. This system is designed to accord with the established System of National Accounts (an international statistical standard for compiling national accounts). It treats pollination as an input to the growth of a mature crop, flowing in fixed proportion to the quantities of harvested product, therefore assuming that the production function is stable (European Commission *et al.*, 2013). The level of pollination can be accounted for as a function of the abundance of pollinators.

We found no example of pollination actually being accounted for in a national accounting framework, but steps have been taken towards doing so. For example, Dickie *et al.* (2014) assessed which characteristics of pollination need to be understood to allow its appraisal as a natural capital asset in national accounts. They identified a need to monitor common wild pollinators for ongoing trends, given the option value (possible future value) provided by diversity in the stock of wild pollinators.

Bateman *et al.* (2013) outline a different approach to taking account of ecosystem service values in national decision-making, based on welfare changes as a consequence of specific scenarios. These authors did not illustrate their approach with pollination as an example.

6.5.1.9 Mapping pollination

Most maps of ecosystem services so far produced do not consider pollination as a service, focusing instead on services with clearer links to spatial data such as land use on a regional or larger scale, such as recreation, or primary production. For example, in a 2012 review, Martinez-Harms and Balvanera (2012) identified just five studies that had mapped pollination at that time, from a total of 41 studies mapping ecosystem services.

A blueprint for mapping and modelling ecosystem services published by the thematic working group on mapping ecosystem services of the Ecosystem Services Partnership (ESP) in 2013 (Crossman *et al.*, 2013) suggests pollination is not often mapped because it is delivered at small scale. **Table 6.5.1** summarises all the published maps of pollination that we identified based on our searches (see *Methods* section). It serves to illustrate the range of methods that have been used. Where pollinators themselves (estimates or probability of abundance, for example) have been used to derive maps, only bees have been considered. We know of no pollination maps that take account of other (non-bee) pollinators.

As demonstrated by **Table 6.5.1**, all the currently available maps of pollination are based on relative measures or proxies of the pollination and most lack empirical validation. Whilst these studies represent good steps along the way to developing a validated tool for mapping pollination services, most overplay their utility, in the way they are presented in the primary literature. Using these maps as tools for decision-making poses serious problems if they are not accurate.

Eigenbrod *et al.* (2010) warned against the use of secondary proxy data, demonstrating that such maps provided a poor fit to primary data for three services – biodiversity, recreation and carbon storage. The estimates of bee abundance in the InVEST pollination module have been validated against empirical field data for some sites (see section on *Modelling* below), but the relationship between bee abundance and pollination is not straightforward (see Aizen *et al.* (2014), for an example where over-abundant bees reduced fruit set in raspberries).

Most maps of pollination supply or demand have not been validated against empirical (primary) data. Only two of the seventeen pollination maps in **Table 6.5.1** have been validated. Some of the proxy measures used are very indirect, such as land cover variables. The 'supply' of pollination services map in **Figure 6.2**, for example, does not really show the pollination, but the distribution of habitat types such as grassland and forest edge assumed to support wild bees (Schulp *et al.*, 2014). This map implicitly assumes that habitat is the only driver of wild bee abundance (see Chapter 2 for discussion of other possible drivers), and that wild bees are the only pollinators.

6.5.1.9.1 Indicators of pollination, as a basis for mapping

One approach to mapping ecosystem services is to define indicators of service status that can be estimated spatially. Layke *et al.* (2012) evaluated ecosystem service indicators from over 20 ecosystem assessments at multiple scales and many countries. They did not find any indicators for pollination, and considered that "regulating or cultural services such as pollination [and others]….were not assessed by enough… assessments to draw or permit an analysis of indicators" (Layke *et al.*, 2012). A 2011 report on ecosystem service indicators published by the Convention on Biological Diversity (CBD) Secretariat proposes three possible indicators of pollination that could be mapped (UNEP-WCMC, 2011) – percentage of planted crop area dependent on (wild) pollinators, status of pollinating species and landscape configuration, and suitability for pollinators. It does not include evidence that these have been used, either for mapping or any purpose, for actual policy decision or in sub-global ecosystem assessments. As pointed out above, all three indicators suggested by the CBD rely on secondary proxies that have never (crop areas; status of pollinating species), or seldom (landscape configuration) been validated against empirical data to check whether they reliably represent pollination delivery.

Maskell *et al.* (2013) used the number of species of nectar-rich plants preferred by bees and butterflies from a UK Countryside Survey dataset as indicators of pollination. A decision-support tool developed by a partnership of agricultural co-operatives in France (see section on *Decision support tools* below: 6.5.1.12) has also used pollinator forage plants as a proxy for pollination.

TABLE **6.5.1**

Maps of pollination services according to the methods used. The validation column shows whether the maps were validated with empirical data from mapped landscapes. Scale categories are as defined in chapter 4, with maps encompassing the whole of Europe classed as 'Global'. References marked* mapped other ecosystem services as well as pollination. The Lonsdorf index and InVEST model are described in section 6.5.10.

Method to map ecosystem services	Proxy data used to represent or derive pollination service estimates	Validation	Scale	Study area	Reference
Index of bee abundance based on the availability of nest sites and floral resources (from land cover data) and bee flight ranges (Lonsdorf index).	Land cover	No	Regional	The Baiyangdian watershed. China	Bai *et al.* (2011)*
	Land cover	No	Global. 25x25m pixel size.	Europe	Maes *et al.* (2012)*
	Land cover	Yes	Regional. 30x30m pixel size.	California, Costa Rica and New Jersey	Lonsdorf *et al.* (2009)
Pollination service value, estimated using an index of pollination service based on proportion of pollinator habitat, and quantity and pollination dependence of crops grown in each pixel.	Land cover Crop areas	No	Regional. 30x30m pixel size.	California	Chaplin-Kramer *et al.* (2011)
Functional diversity of wild bees.	Bee distribution data (presence/absence)	No	National 10x10km pixel size	Great Britain	Woodcock *et al.* (2014)*
Probability of presence for ten pollinating bee species (from species distribution models) for field bean Vicia faba.	Bee distribution data (presence/absence)	No	National. 1x1km pixel size.	Great Britain	Polce *et al.* (2013)
Changes to expected crop yield based on index of bee abundance (InVEST model) per hectare of deforested land.	Land cover Crop areas	Yes	Regional. 30x30m pixel size.	Costa Rica	Ricketts and Lonsdorf (2013)
Economic value of crops weighted by the value of animal pollinated crops and total agricultural area.	Land cover Crop areas	No	Regional. 500 ha pixel size.	Central Coast ecoregion of California. USA	Chan *et al.* (2006)*
Area of pollinator dependent crops, potential wild bee habitat and the visitation probability based on distance from nesting habitats.	Land cover Crop areas	No	Regional. 10x10m pixel size.	Leipzig, Germany.	Lautenbach *et al.* (2011)*
	Land cover Crop areas	No	Global. 1x1km pixel size.	Europe	Schulp *et al.* (2014)
Modeling onset of flowering plants with explanatory variables (soil, climate and land use data).	Soil, climate, land cover	No	Regional. 20x20 m pixel size.	Central French Alps, France.	Lavorel *et al.* (2011)*
Percentage fruit set based on the distance of crops to forest.	Forest cover	No	Regional. 250m pixel size	Central Sulawesi, Indonesia	Priess *et al.* (2007)*
Model exponential decline in pollination (pollinator species richness) as a function of distance from nearest natural habitat.	Land cover	No	Global	Global	Ricketts *et al.* (2008)
Model spatial relationship between the diversity of nectar providing plants and explanatory variables (soil, climate and land use data).	Soil, climate, land cover	No	National. 1x1km pixel size.	Temperate ecosystems of Great Britain.	Maskell *et al.* (2013)*
Crop yield per area considering crops depending on pollination.	Crop yield	No	Global. 10x10km pixel size.	Global	Lautenbach *et al.* (2011)
Number of honeybee colonies divided by the total number of colonies demanded.	Honey bee colony numbers Crop areas	No	Global	Europe	Breeze *et al.* (2014b)
Landscape suitability for bees based on the quantification of desired land cover types (grasslands) within forage distance from potential nesting sites.	Land cover	No	National. 100x100m pixel size.	North Dakota, USA	Gallant *et al.* (2014)

6.5.1.10 Modelling pollinators and pollination

For this report, modelling is the process of making an abstract, usually mathematical, representation of an ecosystem or socioeconomic system, in order to understand and predict the behaviour and functioning of the modelled system.

6.5.1.10.1 Spatially explicit models of pollinators and pollination, as a basis for mapping

A range of quantitative, spatially-explicit modelling approaches have been used to quantify and map the supply or demand of pollination **(Table 6.5.1)**. The most widely used is part of The Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) suite of models (Sharp *et al.* 2015).

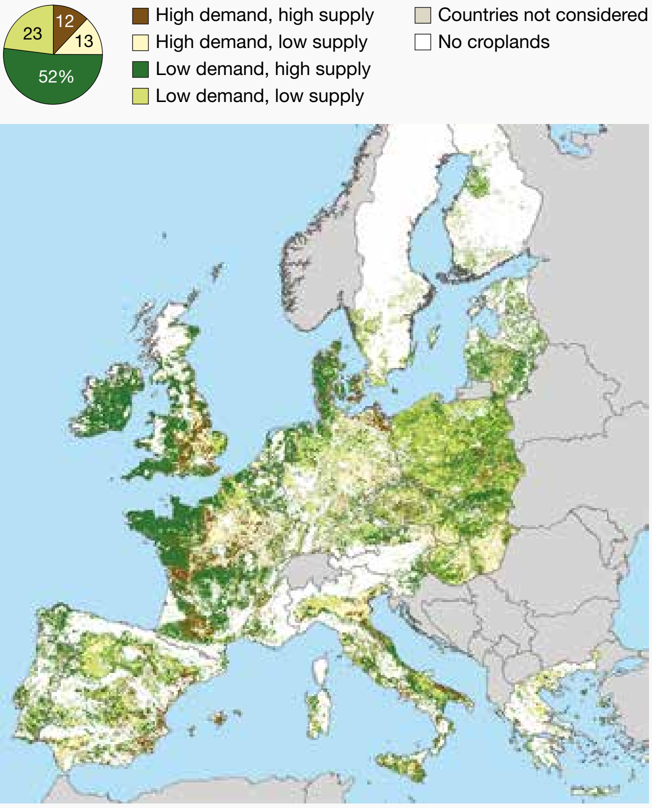
The InVEST pollination module uses modelled estimates of wild bee abundance as a proxy for the supply of pollination. It employs the 'Lonsdorf model', in which different land use or cover types are assessed, using expert judgement, for their nesting and forage potential for wild bees (Lonsdorf *et al.*, 2009). Each land cover type is mapped and a wild bee abundance index (the Lonsdorf Index) derived for every pixel, based on the foraging and nesting potential of the surrounding cells and the foraging ranges of the local bee species. The model must be implemented at scales within the foraging ranges of individual bees. Pixels of 30 x 30 m have been used in the cases where the model has been validated with empirical wild bee abundance data (Lonsdorf *et al.*, 2009; Kennedy *et al.*, 2013). A value of the pollination supplied to agriculture from each pixel is calculated as the economic impact of pollinators on crops grown in pixels within the relevant foraging ranges of each pixel in the pollinator source map, using dependence ratios and a simple saturating crop yield function, which assumes that yield increases as pollinator visitation increases, but with diminishing returns (see Chapter 4 for more on production functions). This model is well documented here: http://ncp-dev.stanford.edu/~dataportal/invest-releases/documentation/3_0_0/croppollination.html. The model provides relative, not absolute, abundance estimates and economic values, but these can be calibrated with real data on bee abundance data and effects on crop yield.

Other well-documented modelling platforms for spatially-explicit assessment of ecosystem service trade-offs (at least 15 identified by Bagstad *et al.* (2013)) have not yet incorporated alternative pollination modules, although some use the InVEST pollination module (see *Decision*

FIGURE **6.2**

Estimated pollination supply and demand for Europe.

WARNING: this map, and others like it, use proxy measures of the *potential* for landscapes to generate pollination. Such measures are unvalidated, and may not reflect real pollination supply.
Source: Schulp *et al.* (2014).



support tools). This would be a valuable development, as some of the other modelling platforms place more emphasis on non-economic values and different groups of beneficiaries. For example, the Artificial Intelligence for Ecosystem Services modelling framework (ARIES; http://www.ariesonline.org) maps ecosystem service flows with an emphasis on the beneficiaries of each service. Pollination is suggested as a service suitable for ARIES modelling (Villa *et al.*, 2014), but to our knowledge this has not been developed.

Spatially-explicit modelling of bee nesting and foraging resources in agricultural landscapes was used by Rands and Whitney (2011) to show that increasing the width of field margins would provide more food resources to wild bees whatever their foraging range.

6.5.1.10.2 Other modelling techniques

Various modelling techniques have been used to predict effects of future land-use change and climate change and on pollinators or pollination demand (see sections 2.1.1 and 2.5.2.3 respectively). These could provide information to inform crop management or conservation decisions, but we know of no specific examples where they have. For example Giannini *et al.* (2013) showed a substantial reduction and northward shift in the areas suitable for passion fruit pollinators in mid-Western Brazil by 2050. This information could be used by the passion fruit industry to target conservation effort for these pollinators and their food plants, although there is no evidence it has been used for this purpose.

Population dynamic models have been built for honey bees (for example, DeGrandi Hoffman *et al.*, 1989). An integrated model of honey bee colony dynamics that includes interactions with external influences such as landscape-scale forage provision has recently been developed (Becher *et al.*, 2014), which accurately generates results of previous honey bee experiments. Bryden *et al.* (2013) used a dynamic bumble bee colony model to demonstrate multiple possible outcomes (success or failure) in response to sublethal stress from exposure to neonicotinoids, while a spatially-explicit model of individual solitary bee foraging behaviour has recently been developed (Everaars and Dormann, 2015). All these models have great potential to be used for testing effects on bees of different mitigation options, such as enhancing floral resources in the landscape, or reducing pesticide exposures.

A stochastic economic model was employed to quantify the potential cost of *Varroa* mites arriving in Australia, in terms of lost crop yields to due reduced pollination (Cook *et al.*, 2007). This model has been used as a guide to how much the Government should spend trying to delay the arrival of *Varroa* (Commonwealth of Australia, 2011).

6.5.1.11 Participatory integrated assessment and scenario building

Participatory Integrated Assessment involves a range of stakeholders in scenario building or use of models to consider and decide on complex environmental problems. Its techniques have been extensively used in climate-change policy development at local and regional levels (Salter *et al.*, 2010) and are sometimes used to develop scenarios for multi-criteria analysis. The underlying assumption is that participation improves the assessment, and the final decision. Salter *et al.* (2010) provide a review of methods and issues.

Future scenarios were built using a deliberative approach by the Millennium Ecosystem Assessment and UK National Ecosystem Assessment (Haines-Young *et al.*, 2011). Those from the UK NEA were used to develop pollination futures to 2025 in a recent assessment of evidence for the UK Government (Vanbergen *et al.*, 2014).

6.5.1.12 Decision support tools

Decision support tools are increasingly being used in environmental management to help decision-making (Laniak *et al.*, 2013). They are distinct from the analytical mapping and modelling tools discussed above because they are designed around a particular decision or decision-making context, and ideally developed collaboratively with end-users. Most decision support tools are software based, and assist with decisions by illustrating possible outcomes visually or numerically, or leading users through logical decision steps (see section 4.6.3 for an example of stepwise decision trees). Some rely on complex models, only operable by their developers (see *Modelling pollinators and pollination*). Others have simple interfaces designed to be used by non-experts. Costs are variable, but can be relatively high (Dicks *et al.*, 2014a).

A variety of decision support tools have emerged for systematic assessment of ecosystem services, in order to examine trade-offs and assist policy decisions. Bagstad *et al.* (2013) identified 17 different tools, ranging from detailed modelling and mapping tools (including InVEST, discussed in *Models for mapping the pollination* above) to low-cost qualitative screening tools developed for business, such as the Ecosystem Services Review (Hanson *et al.*, 2012), and others have been developed since then. Many include carbon storage, sediment deposition, water supply and the scenic beauty of landscapes, among other services. Only a few such tools currently include pollination (for example, InVEST, Envision [using the InVEST pollination module (Guzy *et al.*, 2008)] Ecometrix and the Ecosystem Services Review).

The Ecosystem Services Review includes pollination as one of a list of 31 possible goods and services, and business dependence on pollination is assessed qualitatively by stakeholders. Sandhu *et al.* (2012) developed this further into a risk analysis tool for three land-based businesses, but the case studies did not include a company with dependence on any pollination.

A great range of decision support tools can be applied in agriculture, agroforestry, pollinator management and land management. For example, the Danish decision support tool Crop Protection Online, sold commercially, presents users with relative risk quotients for bees and other beneficial insects, to help them choose crop protection products according to their toxicity (Gyldenkaerne and Secher, 1996). At least one commercial decision support tool in development uses field-scale estimates of pollinator food sources to generate advice on honey bee management for commercial farms (pers. comm., Jeremy Macklin, Hutchinson's Ltd, UK).

A spreadsheet-based tool developed by the Food and Agriculture Organization of the United Nations (Gallai and Vaissiere, 2009) has been used to assess the vulnerability of several countries to pollinator decline, based on the proportion of GDP dependent on pollination. This highlighted, for example, a dependence of over 7% of Ghana's GDP on pollinators, as a result of the high value and high dependence of cocao (Convention on Biological Diversity, 2012).

6.5.1.12.1 Accessible data sources

There are at least three online sources of data specific to pollinators and pollination that could be used for decision support tools, mapping, modelling and accounting. The Pollinator Information Network of the Americas (http://pollinator.org/PINA.htm) provides digitized pollinator records, contacts, and other plant-pollinator interaction datasets from across the Americas. Other more general sources of biodiversity data are discussed in the integrated responses section, under Centres of information, research and knowledge exchange (6.4.6.3.3).

The Pollination Information Management System managed by the FAO is an online database of pollination studies and basic crop dependence information based on Klein *et al.* (2007) (http://www.internationalpollinatorsinitiative.org/pims.do). The crop dependence information requires updating to take account of developments in the literature since 2007. For example, its entry on papaya does not identify the importance of hawkmoths (Sphingidae), demonstrated to be the primary pollinators of papaya in Kenya (Martins and Johnson, 2009).

Finally, there are accessible databases of toxicology information for specific pesticides. For example, the US Environmental Protection Agency maintains a database of ecotoxicology information (http://cfpub.epa.gov/ecotox/).

6.5.1.13 Ecosystem Approach

An 'Ecosystem Approach' is the primary framework for action under the Convention on Biological Diversity. It is defined as "the integrated management of land, water and living resources to promote conservation and sustainable use", with a priority to maintain ecosystem services (COP 5, Decision V/6 http://www.cbd.int/decision/cop/default.shtml?id=7148). In practice, this means taking account of the stocks and flows of ecosystem services, including pollination. Potschin & Haines-Young (2013) classify three major ecosystem assessment frameworks – habitat-based, system- or process-based, and place-based. The pollination examples they use fall into systems- or process-based (using the InVEST model to map supply and value of pollination, for example). They argue that all ecosystem assessments could be place-based at some scale, overlain with habitat, system- or process-based assessments.

6.5.2 Building an effective toolkit

Table 6.5.2 summarises the global experience of use of all these tools and methods for assessing responses and making decisions about pollinators and pollination. In general, we see that while many tools are available or in the process of being developed, only some have been used, and very few incorporated into real decisions in policy or practice. There is great potential to enhance the consideration of pollinators and pollination in environmental decisions through increased use of these tools.

The following tools and methods are well developed and appropriate for application to policy decisions about pollinators and pollination: evidence synthesis, environmental accounting, modelling, multi-criteria analysis and participatory integrated assessments.

For other tools, methods relevant to pollinators and pollination are not yet well developed enough for immediate application to decisions, but there is strong potential: identifying best practice, risk assessment, vulnerability assessment, mapping pollination, and decision support tools.

Enhancing the consideration of pollinators and pollination in policy requires **engaging** and **communicating** with people from all relevant sectors, so they understand the importance and value of pollinators to them (Cowling *et al.*, 2008; Maes *et al.*, 2013). It also requires **designing** and **resourcing** appropriate responses at appropriate scales. The tools discussed here can enable these different elements of mainstreaming pollination in policy, as shown in **Table 6.5.3**.

The literature on environmental decision support systems is informative on how to increase the use of particular tools and methods (McIntosh *et al.*, 2011). The importance

TABLE **6.5.2**

Estimated pollination service supply and demand for Europe. WARNING: this map, and others like it, use proxy measures of the potential for landscapes to generate pollination services. Such measures are unvalidated, and may not reflect real pollination service supply. Source: Schulp *et al.* (2014).

	Purpose	Use for pollinators	Strengths	Weaknesses
Case study/ best practice approach	To exchange knowledge and guide practice	Many organisations share case studies online. Best pollinator management practices identified for some crops.	Relatively quick. Relatively cheap. Easily understood. Can be locally relevant.	Performance metrics for identifying best practice not quantified.
Evidence synthesis	To inform decisions with the best available evidence	Systematic reviews and synopses of evidence have informed decision-making on wild bees and agricultural interventions.	Systematic, explicit review and meta-analysis methods are well established. High confidence in conclusions. Demonstrates knowledge gaps.	Relatively expensive (Dicks *et al*. 2014). Interpretation in decisions requires judgement. Evidence may not be relevant locally.
Risk assessment	To identify and prioritise risks of a product or activity	Established in several continents for pesticide regulation. Has led to restrictions of chemicals identified as a risk to the environment. Some evidence that it reduces overall environmental toxicity of pesticide use in agriculture over time.	Well established in many countries. Relatively quick and cheap if relevant data are available. Can be done at a range of scales.	Established methods only consider direct toxicity to honeybees and/or aquatic invertebrates. Rigorous methods specific to non-Apis pollinators, and sublethal effects, still under development. Relevant data are not always available.
Multi-criteria analysis	To evaluate multiple objectives against multiple attributes or performance criteria	Very little used for decisions about pollinators. Could be used to address trade-offs between pollination and other services.	Effective at addressing trade-offs. A range of methods well developed. Involves stakeholders. Can be locally relevant.	Can be time-consuming.
Cost-benefit analysis	To compare the costs and benefits of different responses, and provide a single indicator of net benefit	A few simple examples have compared actions to benefit pollinators.	Compares costs and benefits. Can account for non-use values. Relatively quick and cheap if relevant data are available.	Standard methods to calculate costs and benefits not established for pollinators. Data on costs of alternative responses usually not available. Discount rates used to actualize future cost and benefit flows are a source of controversy.
Environmental impact assessment	To evaluate impacts of a project or activity	None found.	Methods well established. Always locally relevant.	Only applies to specific projects.
Vulnerability assessment	To identify areas, sectors or groups vulnerable to adverse effects of environmental change	None found. Could be used to identify areas with pollination deficit.	Can be done at regional, national and global scales. Takes economic and ecological information into account.	Varied methods, not well developed and often mis-used.
Environmental accounting	To monitor stocks and flows of environmental goods and services	Pollination not included in ‘environmental footprint’ calculations, but included in international Environmental-Accounting Guidance. No experience of use yet.	Potential for high impact, by incorporating pollination into national accounts.	Recommended accounting method depends on a static production function uniform across crop varieties, extrapolated from empirical evidence. Requires a lot of data.
Mapping pollination services	To visualise pollination service supply and/or demand for a specific area, or set of conditions	Many maps of pollination service drawn around the world. A range of methods used. None incorporated directly into policy or practice decisions yet.	Estimates of wild bee abundance underlying one method (the Lonsdorf model, used in InVEST) have been validated empirically. Most useful on a regional scale (several farms or a landscape)	No validated measures of actual pollination service. Validated measures are data intensive and time-consuming.

TABLE **6.5.2**

Estimated pollination service supply and demand for Europe. WARNING: this map, and others like it, use proxy measures of the potential for landscapes to generate pollination services. Such measures are unvalidated, and may not reflect real pollination service supply. Source: Schulp *et al.* (2014).

	Purpose	Use for pollinators	Strengths	Weaknesses
Modelling	To quantify and/or visualise the possible behaviour of environmental systems in response to sets of conditions or variables	Various approaches to modelling pollinators and pollination service supply demonstrated, including future effects of environmental change. Global scale models not yet developed. None incorporated directly into policy or practice decisions yet.	Most modelling approaches for pollinators and pollination are validated, tested for sensitivity and explicit about sources of uncertainty.	Methods are complex, with many assumptions that must be understood by users. Usually expensive.
Participatory integrated assessment and scenario building	For experts and stakeholders to consider and decide on complex environmental problems	Some pollinator scenarios developed in the UK.	Enables alternative futures to be considered. Involves stakeholders. Can be done at a range of scales.	Based largely on judgement. Appropriate methods of consultation must be documented.
Decision support tools	To assist with decisions by illustrating possible outcomes, or leading users through logical decision steps	Few decision support tools assessing ecosystem services or supporting land management decisions have incorporated pollination so far. Two examples of these being incorporated directly into policy or practice decisions.	Tools may refer to empirical data sets, such as toxicity data or crop dependence ratios. Specific to a decision-making context, can be at any scale.	Can be expensive. Link to evidence or real data is seldom explicit.
Ecosystem approach	To maintain ecosystem services through integrated management of land, water and living resources	Pollination can be included, using any of the above methods. No specific experience identified.	Considers multiple ecosystem services and trade-offs. Locally relevant. Works best at regional scale (landscape or catchment).	Can be an expensive and time-consuming. Requires large amounts of data.

TABLE **6.5.3**

Utility of tools and methods for decision-making on pollinators at different levels of governance – an example for the food industry. ENGAGE = a tool to engage and communicate with users of the pollinator-related services. DESIGN = a tool to design or select appropriate responses.

Scale	Farm	Regional	National	Global
Actors (examples from the food industry)	Farmers	Suppliers Processors	Retailers Manufacturers Government	International agri-businesses Government
Case study/best practice approach	ENGAGE	ENGAGE	DESIGN	ENGAGE
Evidence synthesis		DESIGN	DESIGN	DESIGN
Risk assessment			DESIGN	DESIGN
Multi-criteria analysis	ENGAGE	ENGAGE + DESIGN	ENGAGE + DESIGN	ENGAGE + DESIGN
Cost-benefit analysis	ENGAGE + DESIGN	ENGAGE + DESIGN	ENGAGE + DESIGN	ENGAGE + DESIGN
Environmental impact assessment			DESIGN	DESIGN
Vulnerability assessment		ENGAGE + DESIGN	ENGAGE + DESIGN	ENGAGE + DESIGN
Environmental accounting			ENGAGE + DESIGN	ENGAGE + DESIGN
Mapping pollination services	ENGAGE + DESIGN	ENGAGE + DESIGN	ENGAGE + DESIGN	ENGAGE + DESIGN
Modelling	DESIGN	ENGAGE + DESIGN	ENGAGE + DESIGN	ENGAGE + DESIGN
Participatory integrated assessment and scenario building			ENGAGE + DESIGN	ENGAGE + DESIGN
Decision support tools	DESIGN	DESIGN	DESIGN	DESIGN
Ecosystem approach			DESIGN	DESIGN

of involving end users in design and implementation is repeatedly emphasized, and the development of agricultural DSSs has tended to shift towards participatory approaches to both design and implmentation (Jakku and Thorburn, 2010; Valls-Donderis *et al.*, 2013).

6.6 DEALING WITH ECOLOGICAL UNCERTAINTY

Knowledge about the natural world and its complex relationships is inherently uncertain. Decision-makers faced with uncertain information need to know as much as possible about how much uncertainty there is and why it exists, in order to choose a course of action.

For scientific information, there has been considerable effort to clarify and manage uncertainty across different research fields (e.g., Elith *et al.*, 2002; Regan *et al.*, 2002; Walker *et al.*, 2003; Norton *et al.*, 2006; Li and Wu, 2006; Beale and Lennon, 2012; Kujala *et al.*, 2013; Riveiro *et al.*, 2014). Among the proposed taxonomies, frameworks, and modelling approaches, there is neither a commonly shared terminology (Walker *et al.*, 2003) nor a comprehensive framework (see Mastrandrea *et al.*, 2011 and Moss, 2011 for general uncertainties guidance). We therefore take a pluralist view and use all the available information to suggest how to improve the treatment of uncertainty in pollination research and management strategies.

Uncertainty assessment is not something to be added only a posteriori to interpret scientific results, management decisions or policy options. It is better to recognize it from the outset (Refsgaard *et al.*, 2007). Perceiving, defining and analysing different sources of ecological uncertainty can increase the accuracy of risk estimation, improve models and predictions, and consequently improve control over the system. Although future drivers, effects or events cannot always be anticipated, environmental management or restoration of pollinators and pollination services can be performed in ways that tolerate ecological and economic uncertainty.

Table 6.6.1 summarises a general view of uncertainty. It is divided into four main sources: *linguistic, stochastic, scientific* and *epistemic*. Two or more types of uncertainty are identifiable within each source. This list of sources and types of uncertainty is not exhaustive.

For each type of uncertainty, we use examples from pollinator and pollination research to illustrate how its extent can be monitored, and/or how it can be reduced. For instance, incomplete knowledge of the ecological system (a type of epistemic uncertainty) and mistakes in observations (a type of scientific uncertainty) will always lead to uncertainty in predictions, but the extent of these types of uncertainty can be accounted for and potentially reduced in different ways. **Table 6.6.2** suggests policy responses and applicable tools for the different sources of uncertainty.

The sources of uncertainty in **Table 6.6.1** help to explain why there is uncertainty, rather than how much uncertainty there is. The overall amount of uncertainty, or level of confidence in a particular finding, combines different sources together and does not distinguish among them. This report defines the amount of uncertainty with consistent, well-defined terms based on authors' evaluations of the quantity, quality and consistency of the evidence and level of agreement for each finding (see IPBES Guidance on a Common Approach to Applying Uncertainty Terms, in preparation). These terms (well established, established but incomplete, unresolved, and inconclusive) are generally selected using expert judgement, although probabilistic or statistical information would be used if it were available.

Table 6.6.1 clearly shows that the study of pollinators and pollination is a multi-dimensional social construct, and includes dimensions that involve the entire process (generation and communication) of the production of scientific knowledge.

The major area of discussion about uncertainty in the scientific literature concerns modelling processes and model selection, just one of the sources of uncertainty in **Table 6.6.1** (e.g., Walker *et al.*, 2003; Wintle *et al.*, 2003; Li and Wu, 2006; Pappenberger and Beven, 2006; Rivington *et al.*, 2006; Refsgaard *et al.*, 2007; Ascough II *et al.*, 2008; Cressie *et al.*, 2009; Reilly and Willenbockel, 2010; Hildebrandt and Knoke, 2011; Keenan *et al.*, 2011; Beale and Lennon, 2012; Rinderknecht *et al.*, 2012; Mosadeghi *et al.*, 2013; Riveiro *et al.*, 2014; Sileshi, 2014).

Other sources of uncertainty are prominent in the use of pollinator and pollination science for policy and decision-making. For example, uncertainty surrounding the impact of sublethal effects of pesticides on pollinators might be considered an example of data uncertainty (a type of scientific uncertainty), because the true levels of field exposure are poorly known and the sublethal effects are only characterised for a small selection of pollinator species (see section 2.2.1.4). Maxim and Van der Sluijs (2007) also demonstrated epistemic uncertainty in the debate surrounding the insecticide imidacloprid in France, through the use of 'contradictory expertise' leading to different interpretations; epistemic uncertainty includes variations in the interpretation of scientists about concepts, methodologies, data sets, and ethical positions that may come from different epistemological positions or understandings of the world.

Another area of uncertainty is the extent to which crop yields depend on pollination. There is stochastic uncertainty at local scales, because both yield and pollination, and their

TABLE **6.6.1**

Summary of sources and types of uncertainty in ecological studies and ideas to quantify and/or diminish uncertainties, with examples for pollinators and pollination (modified from Elith *et al.* 2002, Regan *et al.* 2002, Li and Wu 2006, Keenan *et al.* 2011, Kujala *et al.* 2013, Mosadegui *et al.* 2013). Uncertainty is divided into four main sources, each given a plain English (and a technical) name in bold font. Two or more types of uncertainty are identifiable within each source.

Sources and types of uncertainty	Brief explanation and examples	Ideas for dealing with it in pollinator and pollination research
1. Imprecise meanings of words (Linguistic uncertainty)	Uncertainty about language and meaning of expression.	Can be reduced through research and communication. Cannot easily be quantified.
1.a. Vagueness	Nature does not always arrange itself into strict classes, so sharp boundaries and homogenous classes do not represent reality. For example, categories for plant compatibility systems, or degrees of dependence on biotic pollination, are defined arbitrarily. Describing crop dependence ratios according to crop type, without specifying variety, ignores the variation among varieties.	Can be reduced exposing clearly the meaning of categories, terms, and measurements, and the scale at which they are defined (e.g., Ruiz Zapata and Kalin Arroyo 1978, Chautá-Mellizo *et al*. 2012, Liss *et al*. 2013).
1.b. Ambiguity	Words can have more than one meaning. For example, plant reproductive success can mean fruit set, seed set, pollen removal, pollen load, pollen tube growth or number, overall male and female reproductive output, and all can be used as measurements of pollination service.	Can be reduced by exposing clearly the meaning of terms (concepts), indicators and dimension of the variables (e.g., Aguilar and Galetto 2004).
2. Inherently unpredictable systems (Stochastic uncertainty)		Cannot be reduced through more research. Can be quantified and its potential impacts understood.
2.a. Randomness of nature	Chaotic or aleatory nature of natural phenomena. For example, global climate change, extreme rainy/dry years, differences in pollination rates within the season, among sites, etc.	Can be identified through large-scale (spatial and temporal) studies (e.g., Brosi *et al*. 2008, Winfree *et al*. 2008, Aizen *et al*. 2009, Cameron *et al*. 2011, Garibaldi *et al*. 2011, Holzschuh *et al*. 2012) or by meta-analyses (e.g., Aguilar *et al*. 2006, Ricketts *et al*. 2008, Winfree *et al*. 2009). Competing factors can be clarified through experimental design. For example, effects of wind/bee pollination within the season (Hayter and Cresswell 2006).
2.b. Economic fluctuations	The economic costs of employing managed pollinators can fluctuate strongly depending on availability and projected benefits. The value of pollination services to crops is strongly tied to the sale price of the crop. This may be influenced by market forces such as stochastic variations within the supply chain or agricultural subsidies.	An example for econometric analysis of the price of pollination service provision is Rucker *et al*. (2012). Crop price fluctuations can be analysed by statistical averaging or medians of prices over a series of years (Leonhardt *et al*. 2013).
3. Limits of methods and data (Scientific uncertainty)		Can be reduced through better quality research. Can be quantified and impacts understood.
3a. Measurement error	Imperfect measurements or techniques, e.g. available methodology may not record data precisely. For example, uncertainty in land cover maps can propagate into ecosystem services maps (Eigenbrod *et al*. 2010, Schulp and Alkemade 2013).	Selection of the best available measurements or techniques, and acknowledgement of this source of uncertainty.
3.b. Systematic error	Methods produce biased data, e.g. sampling of pollinators in a crop is always close to main roads; pan trap samples of pollinator communities systematically underestimate social bee abundance.	Experimental designs should include a reasonable heterogeneity for the experimental unit. For example, to evaluate the effects of the forest on Macadamia pollination, treatments were applied in orchards that varied in distance from rainforest, to compare the effects of the contrasting pools of available pollen vectors (Blanche *et al*. 2006). Bias in measurement techniques to evaluate the diversity of pollinators of different communities can be tested and controlled for (e.g., Popic *et al*. 2013).
3.c. Model uncertainty	Models are simplifications of real processes, and several alternative models may fit the same data. For example, there are different models for pollen dispersal in Brassica napus (Lavigne *et al*. 1998, Klein *et al*. 2006, Hoyle *et al*. 2007, Ceddia *et al*. 2007, 2009)	Models can be improved through their structure (i.e., modelling processes and formulation by equations and algorithms) or parameters (i.e., estimation, calibration).
3.d. Data uncertainty (or input uncertainty for modelling) and low statistical power	Studies of low data quality, low sample size, low number of replications or not fully representing relevant variation. For example, native bees provide pollination services but how this varies with land management practices can be unknown.	Data sets can be improved through increasing sample size or replications, controlling heterogeneity, reducing missing data, etc. For example, native bee communities providing pollination services for a crop (watermelon) with heavy pollination requirements (Kremen *et al*. 2002).

TABLE **6.6.1**

Summary of sources and types of uncertainty in ecological studies and ideas to quantify and/or diminish uncertainties, with examples for pollinators and pollination (modified from Elith *et al.* 2002, Regan *et al.* 2002, Li and Wu 2006, Keenan *et al.* 2011, Kujala *et al.* 2013, Mosadegui *et al.* 2013). Uncertainty is divided into four main sources, each given a plain English (and a technical) name in bold font. Two or more types of uncertainty are identifiable within each source.

Sources and types of uncertainty	Brief explanation and examples	Ideas for dealing with it in pollinator and pollination research
4. Differences in understanding of the world (Epistemic uncertainty)	Incomplete knowledge through available theory (web of concepts) and data. Uncertainty from subjective human judgments and beliefs. This might also be called decision uncertainty.	Can be reduced through further research. Can also be quantified and its potential impacts understood.
4.a. Natural and anthropogenic variations	Natural and agro-ecological systems are complex and hard to characterise because processes vary across space, time, etc. For example, crop pollination studies measuring fruit set or seed set have seldom taken account of the effects of nutrients, water and other limiting resources, also important for seed set (Bos *et al*. 2007).	
4.b. Confusing reasoning	Uncertainty due to lack of clarity or differences in argument structure, derived hypothesis and/or predictions and/or experimental design. For example, pollinators may deliver services locally, but their individual behaviour, population biology and community dynamics could also be affected by a landscape scale.	
4.c. Subjective judgement or context dependence uncertainty	The same data set or the meaning of a concept can be differentially interpreted by experts from different research fields. For example, whether pollinator diversity and crop pollination services are at risk depends on how you interpret the evidence, while different methods for assessing the economic value of pollination services capture different values of different benefits (Chapter 4).	
4.d. Human decisions under economic uncertainty	For example, non-Market values are difficult to assess and subject to a number of complexities in their elicitation (see Chapters 4 and 5). Different groups of people can experience different values from the same element of an ecosystem, or at a different time – beekeepers, almond growers and citrus growers in the same landscape view honey bee pollinators differently, for example (Sagoff, 2011).	

TABLE **6.6.2**

Suggested policy responses and applicable tools to account for or reduce different sources of uncertainty

Source of Uncertainty	Qualities	Available policy responses and applicable tools
Imprecise meanings of words	Reducible Not quantifiable	• Clear, common definition of terms (such as the IPBES conceptual framework) • Develop and communicate standardised methods (such as the COLOSS Bee Book Neumann *et al*. 2013; 6.4.6.3.3)
Inherently unpredictable systems	Not reducible Quantifiable	• Clear communication • Support large scale, long term multi-site studies to quantify the variation over space and time • Evidence synthesis (6.5.2) • Vulnerability assessment (6.5.7) • Participatory Integrated Assessment and scenario building (6.5.11) • Multi-criteria analysis (6.5.4) • Decision support tools (6.5.12) • Precautionary principle
Limits of methods and data	Reducible Quantifiable	• Improve experimental design • Expand data collection • Support detailed, methodological research • Evidence synthesis (6.5.2) • Develop and communicate standardised methods (such as the COLOSS Bee Book Neumann *et al*. 2013; 6.4.6.3.3) • Capacity building for scientists • Precautionary principle
Differences in understanding of the world	Sometimes reducible Sometimes quantifiable	• Support detailed, site-based and modelling studies to understand systems • Acknowledge existence of biases • Acknowledge differences in conceptual frameworks (within and between knowledge systems) • Multi-criteria analysis (6.5.4) • Decision support tools (6.5.12) • Capacity building for decision makers

interaction, are affected by soil and weather conditions (see Chapter 3). Liss *et al.* (2013) found considerable variation in how the pollination is defined (linguistic uncertainty) and measured (scientific uncertainty), and recommended that pollination measurements and metrics are explicitly clarified (reducing linguistic and scientific uncertainties).

Finally, the effects of organic farming on pollinators (see section 6.4.1.1.4) look different if you take the view that wild nature beyond farmland has a higher value than farmland biodiversity, or overall food production at a large scale is more important than local impacts, because organic farms tend to have lower yields than conventional farms. Debates around organic farming are therefore subject to uncertainty that comes from confusing reasoning, an element of differences in understanding of the world.

6.7 TRADE-OFFS AND SYNERGIES IN DECISIONS ABOUT POLLINATION

This section reviews what is known about trade-offs and synergies among responses or policy options related to pollinators and pollination. A trade-off is considered as the simultaneous enhancement of one aspect of pollination and the reduction in other ecosystem services or another aspect of pollination. Synergy here is when two or more services, or aspects of pollination, are concurrently enhanced by the same action. Trade-offs and synergies need to be understood and acknowledged at all steps of the decision-making process about pollination and food production.

6.7.1 Trade-offs and synergies between pollination and other ecosystem services

Ecosystem services and pollination encompass various natural processes and are surrounded by sociological systems, so trade-offs and synergies between them need to be well thought out. For instance, actions to maximize crop pollination and conservation of culturally important pollinators may be in conflict with the other. Research analyzing how a single focused response affects trade-offs and synergies among pollination and other ecosystem services, as well as the economic costs and benefits, should be considered. For example, Kleijn *et al.* (2015) recently demonstrated that simple actions such as planting flowers to support crop pollinators (see section 6.4.1.1.1) do not necessarily also support declining or specialised species of wild bee. They suggest that managing for pollinator diversity requires different actions, more focused on habitat protection or restoration.

It is important to understand whether multiple ecosystem services changing together are responding to the same driver or interacting with each other (Bennett *et al.*, 2009). It is also necessary to consider trade-offs and synergies among sectors, stakeholders, or constituents because each ecosystem service is used differently by diverse groups of humans.

Several reviews and meta-analyses have examined the trade-offs and synergies among multiple ecosystem services alongside pollination. Reviews have indicated that the creation and conservation of pollinator habitats, such as biologically diverse faming systems in agricultural landscapes, can enhance biodiversity and several ecosystem services such as natural pest control, soil and water quality, and rural aesthetics (Kremen and Miles, 2012; Wratten *et al.*, 2012). In coffee and cacao agroforestry systems, it has been shown that the presence of shade trees, which enhances the presence of pollinators, could lead to synergies such as pest control (Tscharntke *et al.*, 2011). Natural habitats provide pollinator habitats and facilitate the movement of organisms that can be providers of other ecosystem services (Mitchell *et al.*, 2013). In a meta-analysis, Shackelford *et al.* (2013) compared the abundance and richness of pollinators and natural enemies in agricultural landscapes and found that some pollinators and natural enemies seem to have synergetic responses, although the evidence is limited. An investigation of the relationship between the genetic diversity of crops and the delivery of ecosystem services implied that increasing crop genetic diversity was useful in pest and disease management, and might have the potential to enhance pollination (Hajjar *et al.*, 2008). Breeding crops to reduce pollinator dependence (see section 6.4.1.1.11) could reduce production uncertainty or instability in the short term, but this can reduce overall crop genetic diversity, thus increasing potential vulnerability to pests and diseases (Esquinas-Alcázar, 2005).

A case study on a *Cordia alliodora* plantation in Ecuador indicated that economic trade-offs do not necessarily occur among timber provision, regulation of carbon dioxide, and pollination of adjacent coffee crops with moderate silvicultural interventions (Olschewski *et al.*, 2010). A modeling study in the United States indicated trade-offs between income provision and other ecosystem services, including pollination, when replacing annual energy crops with perennial energy crops (Meehan *et al.*, 2013). Several spatially explicit frameworks to investigate the trade-offs of multiple ecosystem services, with pollination estimated mainly by the proxy of natural vegetation, found both negative and positive correlations between pollination and other ecosystem services. Pollination was weakly negatively correlated with forage production, and weakly positively correlated with carbon storage and water provision in the United States (Chan *et al.*, 2006). Positive relationships of pollination and water quality regulation with recreational and commercial fisheries were found in Australia (Butler *et al.*, 2013).

Using a spatially extensive data set of trade-offs and synergies for Great Britain, Maskell *et al.* (2013) demonstrated that nectar plants for bees were positively correlated with other services or service providers, such as plant species richness and soil invertebrate diversity. Additionally, trade-offs and synergies between pollination, indexed by the sampling of actual pollinators and/or the pollination success of plants and other ecosystem services, have been reported. A study conducted in the United Kingdom that examined the effects of grazing management showed that grazing intensity did not affect potential pollinators or total carbon stock, but affected some groups of pest-regulating invertebrates (Ford *et al.*, 2012). Another study in the United States, of perennial bioenergy crops that provide an alternative to annual grains, found that pollination, methane consumption, pest suppression and conservation of grassland birds were higher, whereas biomass production was lower in perennial grasslands (Werling *et al.*, 2014).

6.7.2 Trade-offs between pollination and food provisioning services (crop yield and honey)

Among ecosystem services, provisioning services, especially food production, are likely to be a priority for human societies. Therefore, trade-offs between pollination and provisioning services (e.g., crop yield and honey) warrant special consideration.

There is potentially a direct trade-off between using land to grow food and using land to provide pollinator habitat. To illustrate, using farmland to provide flower strips or other pollinator habitat (see section 6.4.1.1.1) takes land out of production and so overall yields may be lower. However, because there may be existing pollination deficits (see Chapter 3, section 3.8.3), and management for pollinators has been shown to enhance crop yields (6.4.1.1.1), it is important to calculate the net yield and economic outcomes of such management at both farm and landscape scales. There is a major knowledge gap about the net yield effects of managing for pollinators in different farming systems. Elements of it have been analysed for a few farming systems or contexts.

A model-based study of a low intensity agricultural system in northern Scotland examined the trade-off between the conservation of bumble bees and agricultural income, and showed that both agricultural profits and bumble bee densities can be enhanced (Osgathorpe *et al.*, 2011). A study of coffee production systems in India (Boreux *et al.*, 2013) found that management to enhance pollination (use of shade trees) slightly increased coffee yields, but much greater increases in production could be achieved through liming (no influence on pollination), or irrigation timed to promote flowering when other coffee farms were not flowering. Irrigation enhances the pollination without the light and nutrient costs of shade plants, but it is a very context-dependent solution. Another way to reduce the trade-off between providing habitat for pollinators and net yield is to provide pollinator habitat on low-yielding, sometimes called 'marginal' land, such as field edges or steep slopes.

Organic farming and diversified farming systems contribute to maintaining pollinator habitats and effective crop pollination, but many studies indicate that these farming systems are often, not always, less productive than conventional agricultural management (Badgely *et al.*, 2007; de Ponti *et al.*, 2012; Seufert *et al.*, 2012; Ponisio *et al.*, 2015) (see Chapter 2, 2.2.3). Here again there is apparently a direct trade-off between management to enhance pollination and yield. Yields on organic farms are on average around 20-25% lower than on conventional farms (Ponisio *et al.*, 2015: 19.2%; Seufert *et al.* 2012: 5-34%, depending on the system). We could not find any analysis to indicate how observed increases in pollinator abundance, diversity and pollination on organic or diversified farms (see section 6.4.1.1.4 and 6.4.1.1.8) contribute to reducing this trade-off. However, there is clear evidence that the trade-off can be reduced by practices that could be considered diversification, or ecological intensification (see Chapter 1 for definitions) on organic farms, such as multi-cropping and crop rotations (see section 6.4.1.1.8). These practices reduced the yield gap between organic and conventional farms to 9% and 8% respectively (Ponisio *et al.*, 2015). It has also been suggested that the trade-off could be minimised by encouraging organic farming in landscapes with low productivity due to soil or climate conditions, where yield differences between organic and conventional agriculture are lower (see section 6.4.1.1.4).

Elmqvist *et al.* (2011) emphasize the importance of incentives, institutions and governance in effectively managing trade-offs between provisioning services and regulating services, including pollination, in agricultural landscapes. For example, they suggest payments for ecosystem services (see section 6.4.3.3), or compensation through incentive payments or certification schemes (see section 6.4.1.3), can allow farmers to retain equivalent income with lower yields, in return for improvements to the landscape as a whole.

Honey bees are managed for honey production as well as crop pollination, and there is a trade-off between these if the best food sources or landscapes for honey production are not the same as the landscapes where pollination are needed (Champetier, 2010). For example, honey bees are taken to almond orchards for pollination, but this reduces production of honey. This trade-off is compensated for in pollination markets by increased pollination fees (Champetier, 2010).

6.7.3 Trade-offs between pollination and ecosystem dis-services

Food-producing ecosystems also generate ecosystem dis-services that reduce yield or increase production costs, in addition to providing ecosystem services. Ecosystem dis-services, such as pest damage caused by birds or insects, can potentially be enhanced when using an ecosystem approach to enhance pollination. The trade-offs between a pollination and ecosystem dis-service could depend on the sectors and the stakeholders or humans involved. To manage the potential trade-offs, it is necessary to analyze the economic and social costs and benefits and explore their interactions.

Review publications have assessed the trade-offs between pollination and ecosystem dis-services provided by potential pollinators and their habitats. The available evidence suggests that promoting bird species diversity in agricultural landscapes would enhance both pollination and pest control services and ecosystem dis-services such as the consumption of crops by birds, although more studies are needed to quantify the costs and benefits (Triplett *et al.*, 2012). Marshall and Moonen (2002) reviewed the ecological effects of field margins in Europe and reported that having semi-natural field margins can create habitats for pollinators, but some field margins will lead to some ecosystem dis-services in lower crop yield due to weed and pest species that spread into cropland. Another review reported that having non-crop habitat for pollinators may result in competition for pollination from flowering weeds and non-crop plants, which would reduce crop yields (Zhang *et al.*, 2007). Additionally, competition for pollinators between crops and wild plants might result in a potential threat to the fitness of concurrently-flowering wild plants (Holzschuh *et al.*, 2011).

6.7.4 The importance of spatial scale, location and timescale to trade-offs and synergies

Management of pollinators requires consideration not only at the local field scale, where services are delivered, but also at the larger surrounding landscape scale. This is because pollinators depend on habitats for nesting, larval development, mating or overwintering that are often spatially segregated from the flowers where they feed. There is a potential for trade-offs or synergies among spatial scales, because the effects of actions taken at one spatial scale to support pollinators can depend on what is happening at a different spatial scale. For example, a meta-analysis showed that pollinators benefit from agri-environmental management at a local scale in simple, but not in complex landscapes (Batáry *et al.*, 2011). This means actions at landscape scale to improve landscape complexity could potentially make local scale actions such as planting flower strips less effective (a trade-off). A case study in blueberry fields in the United States showed that the scale at which land cover had the strongest effect on bee abundance varied according to bee body size (Benjamin *et al.*, 2014). In this case, actions tailored to support larger bees would not be expected to benefit smaller bees, because they would be at an inappropriate scale.

There are cases where pollinators move between different countries. Then, conservation action in one country can either have synergy with conservation action in the other country, or trade off against habitat destruction or adverse management for pollinators in the other country. For example, long-nosed bats (genus *Leptonycteris*), which are pollinators of agave plants, move between Mexico and the United States (Lopez-Hoffman *et al.*, 2010).

In addition to the spatial trade-offs, there must also be trade-offs between the present and future pollination, although management decisions often focus on an immediate time frame (Power, 2010). Technical developments associated with pollinators, pollination systems, and pollination may increase future food production, whereas some practices used to provide foods confer economic benefits in the present, but might be costly in the future.

6.7.5 Trade-offs and synergies among responses

Different responses can have opposing or synergistic effects on different aspects of pollinators or pollination. For instance, using managed pollinators to promote crop pollination may have negative impacts on native biodiversity, including wild pollinators (see section 6.4). This could lead to economic consequences for producers that may be passed onto consumers (Rucker *et al.*, 2012). There can be trade-offs among responses for pollinators and responses designed to protect other elements of ecosystems (see case study: Eucalyptus trees and honey bees in South Africa).

Kitti *et al.* (2009) used an economic model to assess whether measures to reduce poverty (minimum wages for labourers) or protect forest (conservation payments for retaining forest) lead to conflicting outcomes in a coffee producing area of Costa Rica. Their model accounted for the positive impact of forest patches on pollination. In this context, minimum wages did not favour the production of 'sun coffee', and would not lead to a decrease in forest cover, so there was not a trade-off between forest protection and poverty reduction.

6.8 GAPS AND FUTURE RESEARCH

There have been four independent exercises to identify important research questions, or knowledge needs, relating to pollinators and pollination. One was a scientific exercise that defined 86 research questions in from evolution and ecology to implementing pollinator conservation (Mayer *et al.*, 2011). Two defined key questions related to pollinators from the perspective of end-users of research, involving policy makers, businesses and non-Governmental organisations (Ratamaki *et al.*, 2011; Dicks *et al.*, 2012). In both of these exercises, the role of pollinator diversity and the relative importance of wild and managed pollinators in crop production were identified as prominent and high priority questions. Sutherland *et al.* (2011) assessed synthesized evidence to identify ten research priorities on wild bee conservation (see section 6.5.2).

There is no published analysis of the extent to which the questions or research priorities are being addressed by current research effort. It is likely that many are, especially through the pollinator-focused research efforts described in section 6.4.6.3.2.

6.8.1 Agricultural, agroforestry and horticultural practices

More research is required to establish firmly the impact on food production of planting and managing new pollinator forage resources into agricultural landscapes. Such research could focus on: What flowering species are needed to support the nutritional needs of the required pollinator communities? When to sow, when to cut? How does the quantity (total and area margin/area of crop) and configuration (location, connectedness of patches) of field margins impact their effectiveness on pollinators and services? Studies should measure the effects of enhancing floral resources at local and landscape scales, on pollination and on populations of pollinators measured at larger spatial scales than individual fields.

The net yield and economic outcomes of such management, at both farm and landscape scales are a major knowledge gap that has been analysed for very few farming systems or contexts (see section 6.7.2).

Another research gap is in identifying crop mixes that can promote pollinator species and communities. A recent study suggested that abundance of pollinator communities is as enhanced by polyculture as it is by surrounding natural habitat (Kennedy *et al.*, 2013). Thus areas that are planted to productive crops could, in combination with margin enhancements, support pollination.

Similar attention needs to be paid to the possibilities of increasing nesting resources for pollinators, which could be a limiting factor in agricultural landscapes. These studies must be accompanied by investigations of farmers' acceptance and motivations to introduce such measures on their land.

Ecological intensification emerges as a priority strategy in countries where agricultural production is already approaching maximum exploitable yields, with the principal aim being to reduce environmental costs and erosion of ecosystem services that are now under pressure. A main priority for supporting food security should be directed at closing existing yield gaps around the world with ecological enhancement (Bommarco *et al.*, 2013). Findings ways to reduce the apparent trade-off between yield increases and pollinator benefits (as shown in studies on organic farming, for example) is an inherent part of this research programme (see section 6.4.1.1.4 and 6.7.2).

The effects of climate change on plant-pollinator interactions are still mostly unknown, so adapting farming methods to

BOX **6.4**
CASE STUDY: Eucalyptus in South Africa: bad for water, good for bees

The Working for Water programme in South Africa was founded in 1995 to clear non-native plants while providing social services and rural employment. Australian eucalyptus trees were a focus of the programme, because they are heavy water users. Beekeepers in all South African provinces depend heavily on eucalyptus trees as a forage resource for their honeybees and were very worried about large-scale removal of eucalyptus. The Department of Environmental Affairs funded the Honeybee Forage Project (http://www.sanbi.org/biodiversity-science/state-biodiversity/applied-biodiversity-research/global-pollination-honeybee-fo) to provide evidence about the importance of eucalyptus for honey bees and to search for indigenous replacements. This project has confirmed that the amount of bee forage provided by eucalyptus trees is not replaceable from indigenous plant communities. Negotiations between beekeepers and conservationists to resolve this issue are ongoing. One element of compromise is that landowners can apply for a permit to demarcate their listed eucalyptus trees as "bee-forage areas", as long as they are not in water courses or invading into natural vegetation.

deal with global warming requires substantial additional research, especially in the tropics.

Interdisciplinary research that combines ecological, economic, social and psychological research to elucidate the processes underlying successful agri-environmental policies is greatly needed around the world.

Finally, transdisciplinary work is essential to implement pollinator-supporting practices in real-world landscapes and support long-term yields of pollinator-dependent crops (Garibaldi *et al.*, 2014). Developing farmer-researcher platforms or networks, helping researchers to interact with farmers and understand farmer problems, and assisting researchers to work within the complexity of on-farm research (e.g. http://aeix3dev.devcloud.acquia-sites.com), are key ways of finding practical answers in a context that involves the participation of farmers.

6.8.2 Pesticides, pollutants and genetically modified organisms

Research is needed for more accurate predictions of exposure and risks, to inform approaches to reduce the exposure of pollinators to pesticides, and to help determine the impacts of pesticides on pollinators.

Risk assessment tools will need to be further developed and implemented. Impacts assessments need to address adverse sublethal effects and risks to wild bees. For instance, a risk assessment based on a literature review identified lack of exposure and toxicological information for pollinators other than the honey bee as the primary area of uncertainty (Cutler *et al.*, 2014b). Knowledge gaps include mitigation of negative impacts of pesticides on pollination (Nienstedt *et al.*, 2012), on actual population trends and dynamics of pollinators, and of combined effects of multiple environmental pressures and pesticides, or mixes of pesticides and other pollutants on pollinators (Gonzaléz-Varo *et al.*, 2013).

A development of specific risk indicators from exposure of pesticides to pollinators would be useful for evaluating possible impacts on pollinators of risk reduction programmes.

Higher-tier registration studies are costly to perform and process, and it is not necessary to repeat them in each country. Sharing information among countries can help raise and harmonise registration standards globally. Making registration studies available globally needs to be accompanied by raising the skills to interpret the studies and distinguish which studies may not be necessary to conduct locally.

There is no global overview of pesticides regulation among countries. Efforts to reduce risks need to be directed to regions and crops in which pollinators and pollination are most probably at the highest risk. Schreinemachers *et al.* (2012) give a nice overview of the pesticide use in the world related to economy type; it is highest in middle income economies. Most crop pollination values are generated in Asia while 58%, 8% and 10% are generated in Africa, and South and Central America, respectively (Gallai, 2009) where pesticide use is also high. If this information were matched with where regulation is weak, where and in which crops impact studies have been performed (probably mainly in field crops in Europe, North America and Brazil), there is a high probability to find clear mismatches and knowledge gaps.

Continual investments into agricultural research and development of technology are needed that reduce risk to pollinators. Research funding to develop IPM strategies and crop production systems with no or reduced use of pesticides, would provide options to decrease exposure and risks to pollinators. Cost-benefit comparisons of IPM or no-pesticide options against conventional pesticide use are also needed. Assessing pollination dependence in flowering crops that are now considered self-pollinated remains to be performed for major crops. For instance, pollinators contribute to crop yield in soy beans, but pest management is not considering pollination in soy beans (Chiari *et al.*, 2005; Milfont *et al.*, 2013).

It is clear that adverse effects for beneficial organisms such as pollinators from exposure to pesticides can be reduced. There are, however, few examples where the actual effectiveness of these efforts has been estimated specifically for pollinators.

Many pesticides are used in urban green spaces. Risk management and risk mitigation for pollinators is poorly developed for urban settings and amenity areas. Education and awareness-raising targeted at gardeners and professional managers of urban amenity areas (e.g., playing fields and golf courses) need more attention.

There is also a lack of standardized monitoring and research of GM-crop impacts on pollinators. Risk assessment of GM-crops on non-target organisms needs to be developed for bee species other than the honey bee, for GM organisms in combination with environmental stressors, and on populations and communities of pollinators (Arpaia *et al.*, 2014).

6.8.3 Nature conservation

Research is needed to understand better how the composition and configuration of the landscape affects plant-pollinator interactions. More studies are needed that address the diversity of pollinators and population attributes (e.g., density fluctuations and survival) and to evaluate changes in diversity and behavioural attributes (e.g., species mobility and foraging patterns) that could affect the efficiency of different pollinators. These knowledge gaps apply equally to crop pollinators and wild plant pollinators.

That type of research is particularly needed for tropical ecosystems, where the recent increase in the number of studies has been lower than in temperate regions and where the higher diversity of plants and pollinators impedes a more thorough knowledge of these systems. Due to the high worldwide importance of those regions for the production of food and primary agricultural goods, more attention should be given to the development of knowledge of pollinators and pollination processes in complex tropical landscapes (Viana *et al.*, 2012).

Lennartson (2002) states that habitat loss and fragmentation can lead to abrupt qualitative changes in landscape structure, limiting the survival and movement of pollinators. To conserve pollinator diversity properly, habitat loss should never reach threshold levels that lead to local extinctions of pollinator species (Radford *et al.*, 2005). However, the critical threshold levels of habitat loss that could lead to drastic increases in pollinator extinction rates and the collapse of plant-pollinator interaction networks (Viana *et al.*, 2012) are not known.

Understanding how pollen is dispersed and investigating the factors that affect pollinator mobility are essential, in order to design land management strategies that can secure crop and wild plant pollination. However, to complete this task, methodological and technical obstacles must be overcome. The development of better individual tracking technologies will inevitably lead to more detailed studies on pollinator movement through the landscape, which together with the knowledge already available in the literature will lead to the development of better tools and guidelines for the management and design of landscapes with highly-efficient ecosystem services, also ensuring the long-term conservation of pollination in agro-natural systems (Viana *et al.*, 2012).

Studies to evaluate the effectiveness of ecosystem service payments or stewardship mechanisms to protect pollinators and pollination are also needed for both developed and developing countries.

As taxonomic capacity is essential for pollinator monitoring, conservation and management, a targeted effort is needed to surmount the taxonomic impediment: the adequacy and accessibility of identification services, the status of taxonomic knowledge, and the provision of tools to assist non-experts in identification.

Policy makers need to have concrete, practical information on pollinator declines which can only be provided by a broad, collaborative global effort to monitor pollinator trends and status effectively. Then strategies are required for monitoring in the face of large expected natural pollinator population variation (FAO, 2008).

6.8.4 Pollinator management and beekeeping

There is a clear need for research on how to improve or optimise the pollinating abilities of managed pollinators, and to develop management techniques for new pollinator species suitable for different crops.

More research is needed on the effects of combined interventions in managing pollinators, to determine when and how different interventions interact. Such research could focus more generally on best practices for pollinator management; these practices in many cases should be developed to be regionally specific.

However, the most prominent knowledge gaps on managed pollinators are related to the control of parasites and pathogens. Major gaps are:

6.8.4.1 Detection / Diagnosis

1. Improvements are needed in terms of speed, reliability, cost, and accessibility of diagnostic tests.

2. From a policy perspective, a key knowledge gap is how best to link inspections of managed bees and detection of parasite / pathogen problems to legal responses.

6.8.4.2 Prevention

1. How to manage pollinator movement across multiple spatial scales to reduce the spread of infection, especially without greatly interfering with the delivery of pollination and farmer and beekeeper profitability, is a key policy challenge and knowledge gap.

2. Another key policy challenge and knowledge gap is how best to reduce infection spread and support best management practices in rearing facilities while maintaining profitability, especially for bumble bees, but potentially for other bee species in the future

6.8.4.3 Treatment

1. Overall, treatment of parasites and pathogens of managed pollinators is a major knowledge gap and there are few parasite / pathogen problems with effective treatment strategies.

2. Little is known about treatment options for managed pollinators other than honey bees, comprising another general knowledge gap.

3. Treatment of viral diseases is a key knowledge gap, as there are no known effective treatments for any viral diseases of managed pollinators.

4. Control of *Varroa* mites, the single largest cause of honey bee colony losses worldwide, is another major knowledge gap. This is particularly true given that *Varroa* has evolved resistance to miticide treatments that were previously very effective.

5. Interference RNA (RNAi) technology has been shown in laboratory, and limited field trials, to reduce viral diseases and Varroa mites, and to improve beekeeping outcomes in honey bees, but the optimization and commercialization of this technology represent a specific knowledge gap. An additional knowledge gap is the use of RNAi against parasites and pathogens other than viruses and *Varroa*.

6. Fungal diseases of managed bees, represented primarily by *Nosema*, stonebrood, and chalkbrood, have few treatment options. *Nosema* in honey bees (but not bumble bees) is controlled in some countries by the antifungal agent fumagillin, but it is expensive and toxic to mammals, and likely has toxicity impacts on honey bees as well. Alternatives to fumagillin and development of antifungal agents effective against chalkbrood and stonebrood present another knowledge gap.

6.8.4.4 Social Immunity

1. Social managed pollinators (including honey bees, bumble bees, and social stingless bees) have evolved elaborate defense mechanisms at a group (rather than individual) level. A knowledge gap is understanding these "social immunity" defense mechanisms, and how to protect and support them in managed taxa, especially given that there is some evidence of common management practices disrupting social immunity.

6.8.4.5 Management of pathogen and parasite evolution

1. Little is known about best management practices for reducing the evolution of resistance by parasites and pathogens of managed bees to treatments.

2. We know little about managing pollinators, and their parasites and pathogens, to select for less-virulent parasites or more-resistant pollinators.

6.8.5 Urban and transport infrastructure

Currently around half the world's population lives in urban areas and this is set to increase dramatically during the next 50 years (Grimm *et al.*, 2008), yet pollination and pollinator conservation are not a major focus of urban design or policy.

Many initiatives are underway to restore or create urban green space, but the success of these efforts often fails to evaluate the effect on pollinators (Lomov *et al.*, 2010).

Early successional habitats such as urban brownfields and vacant land provide valuable foraging habitat for pollinators, yet these areas are not considered important in conservation planning (Gardiner *et al.*, 2013). Determining how to manage these habitats to support pollinators is critical to sustaining needed pollination.

Studies conducted in developing countries, where urban food production is much more extensive, suggest that urban agriculture can provide extra nutrition and food security for households (Maxwell *et al.*, 1998; Drescher, 2004). However there is a great lack of knowledge from some of the most rapidly developing cities within China and India, addressing the importance of garden and allotment food production in both developing and developed world. The vast majority of studies have been performed in Brazil, USA and Europe (primarily Northern Europe) (Hernandez *et al.*, 2009).

Organizations and governments have identified right-of-way infrastructure as a key way to support pollinators and connect habitat patches, however, there are few policy strategies underway to institute these efforts for large-scale landscape management.

Finally, studies are essential to evaluate the impact of urban management on pollination, the value of pollination for food production in cities, and the efficient and economic options for managing right-of-way infrastructure to support pollinators.

6.8.6 Tools and methods

The most prominent knowledge gap when it comes to comparing responses is the lack of information on relative costs of different responses. There has been a great deal of research to assess the value of pollinators and pollination (see Chapter 4), and to measure the effectiveness of different measures. Researchers and policymakers must now work together to quantify the costs, and find viable measures of relative effectiveness, for the different responses discussed in this report.

We urge ongoing investment in method development for identifying best practice, risk assessment, vulnerability assessment, mapping pollination, and decision support tools. There are a number of specific gaps, or methodological uncertainties.

For example, it is necessary to analyse the strengths and weaknesses of methods for mapping pollination and validating pollination maps. Mapping techniques should be standardised to improve the use of pollination information in decision making. The pollination must be incorporated into global Integrated Assessment Models to accomplish new perspectives for stakeholders when deciding on complex environmental problems.

Risk assessment methods for wild pollinators and sub-lethal effects of current practices in agro-environments have still to be considered when quantifying and mapping the supply or demand of pollination.

The diversity of pollinators and pollination should be incorporated into a range of standard model sets for analysing trade-offs between ecosystem services, especially pollination with treatment of non-monetary values such as, for example, the value loss associated with a decrease of native pollinators.

6.9 CONCLUSION

The available strategic responses to the risks and opportunities associated with pollinators range in ambition and timescale, from immediate, relatively easy responses to reduce or avoid risks, to larger scale, long-term transformative responses. **Table 6.9.1** describes seven strategies, linked to actions responding to risks and opportunities, including a range of solutions that draw on Indigenous and Local Knowledge (ILK). These strategies can be adopted in parallel, and would be expected to reduce risks associated with pollinator decline in any region of the world, regardless of the extent of available knowledge about the status of pollinators or the effectiveness of interventions. The first two strategies ('Manage immediate risks' and 'Exploit immediate opportunities') are relatively short-term and low in ambition. Some, not all, of the specific responses involved would also be part of the longer-term, more ambitious strategies.

We envisage three possible strategies for moving towards more resilient, sustainable agriculture in the longer term, with an associated reduction in risks generated by pollinator decline: i) ecological intensification, ii) investing in ecological infrastructure and iii) strengthening existing diverse farming systems. These are not mutually exclusive, but each has a different focus. Definitions of ecological intensification, diversified farming, and other farming systems are provided in Chapter 1.

Ecological intensification (Bommarco *et al.*, 2013; Tittonell, 2014) emphasizes management that increases the intensity of ecological processes that support production, such as biotic pest regulation, nutrient cycling, and pollination. It involves making smart use of nature's functions and services, at field and landscape scales, to enhance agricultural productivity and reduce reliance on agro-chemicals. The end point of ecological intensification is a farming system that is likely to meet the definition of a diversified farming system.

Some specific actions that farmers or land managers may take to achieve ecological intensification are the same as those that would improve current conditions for pollinators, listed in the first two rows of **Table 6.9.1**, such as creating flower-rich field margins or road verges. In ecological intensification, these actions would be actively designed to support pollination of specific crops in the locality.

Strengthening existing diversified farming systems is an important strategic response because there is clear evidence that such systems support a higher diversity and abundance of pollinators. Diversified farms integrate the use of a mix of crops and/or animals in the production system. Many such systems are practised by indigenous peoples and local communities across the globe, and contribute to maintenance of pollinators and pollination resources (see Chapter 5, section 5.2.8).

The **ecological infrastructure** needed to benefit pollination comprises small to medium-sized patches of semi-natural habitat, providing nesting and floral resources, distributed throughout productive agricultural landscapes (see section 6.4.3.1.1). The same approach can also be expected to benefit the diversity of pollinators and pollination of food crops in urban areas (see sections 6.4.5.1.1 and 6.4.5.1.2). Such distributed ecological infrastructure may not be the same as the infrastructure needed for other ecosystem services or elements of biodiversity. For example wild species associated with natural habitats such as wetland or forest may benefit more from protection of larger areas of habitat (tens or hundreds of hectares), separated from agriculture (Phalan *et al.*, 2011), while other species, including some pollinators, rely on entire landscapes with diversified farming systems (Loos *et al.*, 2014; Sutcliffe *et al.*, 2014).

Finally, pollinators and pollination offer a real opportunity to begin to transform the relationship between humans and nature, because of their tangible values (Chapter 4), and the demonstrable benefits of sharing knowledge systems and working collaboratively across sectors (see **Table 6.9.1**).

TABLE **6.9.1**

Overview of strategic responses to risks and opportunities associated with pollinators and pollination. Examples of specific responses are provided, selected from chapter 5 and 6 to illustrate the scope of each proposed strategy. This is not a comprehensive list of available responses and represents around half of the available options covered in the entire report. Not all the responses shown for 'improving current conditions' will benefit pollinators in the long term, and those with potential adverse effects are marked with an asterisk (*). All responses from chapter 6 that are already implemented somewhere in the world and have well established evidence of direct (rather than assumed or indirect) benefits to pollinators are included in the table and are highlighted in **bold**.

AMBITION	STRATEGY	EXAMPLES OF RESPONSES	CHAPTER REFERENCES
IMPROVING CURRENT CONDITIONS FOR POLLINATORS AND/OR MAINTAINING POLLINATION	MANAGE IMMEDIATE RISKS	• **Create uncultivated patches of vegetation such as field margins with extended flowering periods**	2.2.1.1, 2.2.1.2, 2.2.2.1.1, 2.2.2.1.4, 6.4.1.1.1, 5.2.7.5, 5.2.7.7, 5.3.4
		• Manage blooming of mass-flowering crops*	2.2.2.1.8, 2.2.3, 6.4.1.1.3
		• Change management of grasslands	2.2.2.2, 2.2.3, 6.4.1.1.7
		• **Reward farmers for pollinator-friendly practices**	6.4.1.3, 5.3.4
		• Inform farmers about pollination requirements	5.4.2.7, 2.3.1.1, 6.4.1.5
		• Raise standards of pesticide and genetically-modified organism (GMO) risk assessment	2.3.1.2, 2.3.1.3, 6.4.2.1.1, 6.4.2.2.5
		• Develop and promote the use of technologies that reduce pesticide drift and agricultural practices that reduce exposure to pesticides	2.3.1.2, 2.3.1.3, 6.4.2.1.3, 6.4.2.1.2
		• Prevent infections and treat diseases of managed pollinators; regulate trade in managed pollinators	2.4, 6.4.4.1.1.2.2, 6.4.4.1.1.2.3, 6.4.4.2
		• Reduce pesticide use (includes Integrated Pest Management, IPM)	6.4.2.1.4
	UTILIZE IMMEDIATE OPPORTUNITIES	• Support product certification and livelihood approaches	5.4.6.1, 6.4.1.3
		• **Improve managed bee husbandry**	2.4.2, 4.4.1.1, 5.3.5, 6.4.4.1.3
		• Develop alternative managed pollinators*	2.4.2
		• Quantify the benefits of managed pollinators	6.4.1.3, 6.4.4.3
		• Manage road verges*	2.2.2.2.1, 6.4.5.1.4, 6.4.5.1.6
		• Manage rights of way and vacant land in cities to support pollinators	2.2.2.3, 6.4.5.1.4, 6.4.5.1.6, 6.4.5.4
TRANSFORMING AGRICULTURAL LANDSCAPES	ECOLOGICALLY INTENSIFY AGRICULTURE THROUGH ACTIVE MANAGEMENT OF ECOSYSTEM SERVICES	• **Support diversified farming systems**	2.2.1.1, 2.2.1.2, 2.2.2.1.1, 2.2.2.1.6, 5.2.8, 5.4.4.1, 6.4.1.1.8
		• Promote no-till agriculture	2.2.2.1.3, 6.4.1.1.5
		• Adapt farming to climate change	2.7.1, 6.4.1.1.12
		• Encourage farmers to work together to plan landscapes; engage communities (participatory management)	5.2.7, 5.4.5.2, 6.4.1.4
		• Promote Integrated Pest Management (IPM)	2.2.2.1.1, 2.3.1.1, 6.4.2.1.4, 6.4.2.2.8, 6.4.2.4.2
		• Monitor and evaluate pollination on farms	5.2.7, 6.4.1.1.10
		• Establish payment for pollination services schemes	6.4.3.3
		• Develop and build markets for alternative managed pollinators	6.4.4.1.3, 6.4.4.3
		• Support traditional practices for managing habitat patchiness, crop rotation and co production of knowledge between indigenous and local knowledge holders, scientists and stakeholders	2.2.2.1.1, 2.2.3, 5.2.7, 5.4.7.3, 6.4.6.3.3
	STRENGTHEN EXISTING DIVERSIFIED FARMING SYSTEMS	• **Support organic farming systems; diversified farming systems; and food security,** including the ability to determine one's own agricultural and food policies, resilience and ecological intensification	2.2.2.1.1, 2.2.2.1.6, 5.2.8, 5.4.4.1, 6.4.1.1.4, 6.4.1.1.8
		• Support "biocultural diversity" conservation approaches through recognition of rights, tenure and strengthening of indigenous and local knowledge and traditional governance that supports pollinators	5.4.5.3, 5.4.5.4, 5.4.7.2, 5.4.7.3
	INVEST IN ECOLOGICAL INFRASTRUCTURE	• **Restore natural habitats** (also in urban areas)	6.4.3.1.1, 6.4.5.1.1, 6.4.5.1.2
		• Protect heritage sites and practices	5.2.6, 5.2.7, 5.3.2, 5.4.5.1, 5.4.5.3
		• Increase connectivity between habitat patches	2.2.1.2, 6.4.3.1.2
		• Support large-scale land-use planning and traditional practices that manage habitat patchiness and "biocultural diversity"	5.1.3, 5.2.6, 5.2.7, 5.2.9, 6.4.6.2.1
TRANSFORMING SOCIETY'S RELATIONSHIP WITH NATURE	INTEGRATE PEOPLES' DIVERSE KNOWLEDGE AND VALUES INTO MANAGEMENT	• Translate pollinator research into agricultural practices	2.2.1, 2.2.2, 2.2.3, 2.2.1.2, 6.4.1.5, 6.4.4.5
		• Support knowledge co-production and exchange among indigenous and local knowledge holders, scientists and stakeholders	5.4.7.3, 6.4.1.5, 6.4.6.3.3
		• Strengthen indigenous and local knowledge that fosters pollinators and pollination, and knowledge exchange among researchers and stakeholders	5.2.7, 5.4.7.1, 5.4.7.3, 6.4.4.5, 6.4.6.3.3
		• Support innovative pollinator activities that engage stakeholders with attachments to the multiple socio-cultural values of pollinators	5.2.3, 5.3.2, 5.3.3, 5.3.4, 5.4.7.1, 6.4.4.5
TRANSFORMING SOCIETY'S RELATIONSHIP WITH NATURE	LINK PEOPLE AND POLLINATORS THROUGH COLLABORATIVE, CROSS SECTORAL APPROACHES	• Monitor pollinators (collaboration between farmers, the broader community and pollinator experts)	5.2.4, 5.4.7.3, 6.4.1.1.10, 6.4.4.5, 6.4.6.3.4
		• Increase taxonomic expertise through education, training and technology	6.4.3.5
		• Education and outreach programmes	5.2.4, 6.4.6.3.1
		• Manage urban spaces for pollinators and collaborative pathways	6.4.5.1.3
		• Support high-level pollination initiatives and strategies	5.4.7.4, 6.4.1.1.10, 6.4.6.2.2

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USA: United States Environmental Protection Agency (1996): Ecological Effects Test Guidelines: OPPTS 850.3040. Field Testing for Pollinators: http://www.epa.gov/pesticides/science/efed/policy_guidance/team_authors/terrestrial_biology_tech_team/honeybee_data_interim_guidance.htm.

USA: USDA APHIS (2013): Import into the US – Honey bees and other bees. https://www.aphis.usda.gov/aphis/ourfocus/planthealth/import-information/permits/

regulated-organism-and-soil-permits/sa_bees/ct_bees_general_requirements.

USA: USDA FSA – Conservation Programs: http://www.fsa.usda.gov/FSA/webapp?area=home&subject=copr&topic=crp.

USA – California: Food and Agricultural Code Section 29120-29128: http://www.leginfo.ca.gov/cgi-bin/displaycode?section=fac&group=29001-30000&file=29120-29128.

USA – California: Food and Agricultural Code Section 29120-29128: http://www.leginfo.ca.gov/cgi-bin/displaycode?section=fac&group=29001-30000&file=29120-29128.

USA/Canada: United States Environmental Protection Agency, Health Canada Pest Management Regulatory Agency & California Department of Pesticide Regulation (2014): Guidance for Assessing Pesticide Risks to Bees: http://www.epa.gov/pesticides/science/efed/policy_guidance/team_authors/terrestrial_biology_tech_team/GuidanceAssessingPesticideRisk2Bees.pdf.

USA/Canada/Mexico: NAPPO (2008): Guidelines for the Petition for Import and Release of Non-*Apis* Pollinating Insects into NAPPO Countries. RSPM No. 29: http://www.nappo.org/en/data/files/download/PDF/RSPM29-20-10-08-e.pdf.

APPENDIX A

Methods and approaches used in this Chapter 6

Ariadna Lopes

A1. Defining responses in each sector

Our list of responses was compiled from:

i) suggested responses from published lists related to bee conservation or pollination services (Dicks *et al*. 2010, Sutherland *et al*. 2014);
ii) items listed during a workshop session at the first author's meeting, July 2014; and
iii) a consultation with all authors, the pollination Technical Support Unit and the ILK Task Force.

Responses were then grouped according to policy sectors. The sectors are: a) Agricultural/horticultural/forestry practices; b) Pesticides and other pollutants; c) Nature conservation; d) Pollinator management and beekeeping; and e) Urban and transport infrastructure. These sectors were selected based on a combination of the Millenium Ecosystem Assessment and the important policy areas selected by an FAO policy workshop on pollinators.

We developed a section on **integrated response** types that could be applied across sectors, such as participatory processes, regional co-ordination of policies or trans-disciplinary research. The application and effects of integrated responses within each sector are still considered within the relevant sectors (for example, regional co-ordination of bumblebee importation policies would be in the managed pollinator section). The integrated response section looks across sectors and describes evidence gathered across sectors that cannot easily fit in the individual sectoral sections.

A2. Review methods

Our search methods followed the protocol outlined in the IPBES guidance document. The following databases were searched: Environmental Evidence Systematic Review Library; ISI Web of Science; Conservation Evidence synopses. Search terms for each sector are shown as in **Table A.1**. Search terms used for other sections of the chapter (also combined with All row from Table A.1) are in **Table A.2**.

A3. Examining the chosen responses

In each section we reviewed responses that have been **proposed** in response to evidence of drivers, status and trends in pollinators (see also Chapters 2 and 3). Then we asked which, if any, have been **tested** or are already **established**. Within each sector, responses were grouped according to the type of response (see List of Responses document).

For each chosen response or category of response, we reviewed what is known about its effectiveness at reducing the risks or enhancing the opportunities associated with pollinators and pollinators (see section 6.2).

For the main sectors (section 6.4), information about the effectiveness of each type of response is summarized in a table at the end of each subsection. In these tables, and to accompany summary statements in other parts of our chapter, we have used the confidence terms adopted by this IPBES assessment. The choice of terms has been made by consensus among the Lead and Co-ordinating Lead Authors of Chapter 6.

Knowledge gaps important for understanding the responses and issues discussed in Chapter 6 were identified by individual lead authors, in response to reviewing the literature. These are brought together in section 6.8. Separately, in section 6.6 we provide an overview of the research and activities that have focused on identifying knowledge needs across the whole of pollinator and pollination science. This is related to a discussion about how research and monitoring needs are being met overall.

TABLE **A1**

Search terms used for responses in each sector in section 6.5. In the initial search, terms from all the cells in the 'All' row and the appropriate sector row were combined in a single string of search terms, using AND. If no suitable review or synthesis studies were found, subsequent searches were conducted without the 'Review OR meta-analysis…' term.

Sectors	Search terms used for responses in each sector		
All	Review OR meta-analysis OR "systematic review"[1]	OUTCOME TERMS: (Pollinat* OR bee OR bees OR Apoid* OR syrphid OR ((butterfl* OR Lepidoptera OR moth OR moths OR beetle* OR Coleoptera OR bird* OR bat OR bats) AND pollinat*))	Option OR policy OR policies OR action OR intervention[2] OR trade-off OR sustainab* OR conserv* OR "ecosystem service" OR benefi* OR "pollinat* serv*"
Agricultural/ horticultural/ forestry	SECTORAL TERMS: agricultur* OR farm* OR farmland OR horticultur* OR crops OR arable OR livestock OR forestry OR Agroforestry OR organic	SECTOR SPECIFIC RESPONSE TERMS: "flower strip" OR "habitat" OR non-ag* OR non-crop OR non-timber OR off-field OR non-tillage OR "no till" OR "reduced tillage" OR "conservation agriculture" OR field margin OR heterogen* OR hedgerow OR crop rotation OR connect* OR meadows OR species-rich OR pasture OR "forest fragment" OR remnant OR Agri-environment* OR Agrienvironment* OR integrated pest management OR IPM OR fertilizer* OR "mass-flowering crop*" OR "variety" OR automatic OR mechanical OR robotic OR certificat* OR extension OR training OR "land abandonment"OR "not-dependent pollinat* crop*" OR "manual pollinat*" OR "manual-pollinat*" OR "mechanical pollinat*" OR "automatic pollinat*" OR "hand pollinat*" OR "hand-pollinat*"	SECTOR SPECIFIC OUTCOME TERMS:
Pesticides and other pollutants	SECTORAL TERMS: pesticid* OR insecticid* OR herbicid* OR algicid* OR molluscicid* OR miticid* OR rodenticid* OR biocid* OR agrochemical* OR agro-chemical* OR toxic* OR pollut*	SECTOR SPECIFIC RESPONSE TERMS:	
Nature conservation	SECTORAL TERMS: habitat* OR native veg* OR remnant OR grassland* OR woodland OR wildflower* OR veg*	SECTOR SPECIFIC RESPONSE TERMS: restor* OR manage* OR conserv* OR plant*OR reforest* OR afforest*	
Pollinator management and beekeeping	SECTORAL TERMS: beekeeping OR apicultur* OR "managed bees"		SECTOR SPECIFIC OUTCOME TERMS: Disease* OR varroa OR honey
Urban and transport infrastructure	SECTORAL TERMS: right-of-way or rights-of-way or urban* or road* or electrical* or power* or "transmission line*" or infrastructur* or infra-structur* or transport or garden*		

1. This term removed and search repeated if no reviews found
2. This term not used for searching Conservation Evidence synopses, which at present only include evidence relating to policies and actions.

TABLE **A2**

Search terms for other issues covered in Chapter 6. All cells from the appropriate row were combined with cells from the All row from Table A1. If no suitable review or synthesis studies were found, subsequent searches were conducted without the ‘Review OR meta-analysis…’ term.

Other issues covered in chapter 6	Search terms
Risks	(risk OR risks OR opportunit*) AND (“pollination deficit” OR yield* OR quality OR food OR biodiversity OR “farm income” OR “species richness” OR “seed production” OR honey OR “bee product*” OR “cultural value” OR “cultural service*” OR health) NOT (venom OR insecticide)[1]
Tools and methodologies	(“case study” OR model* OR evidence OR InVEST OR “cost benefit analysis” OR CBA OR “cost-benefit” OR “risk assessment” OR “multicriteria analysis” OR “multi-criteria analysis” OR “multicriteria decision analysis” OR “multi-criteria decision analysis” OR “multicriteria evaluation” OR “multi-criteria evaluation” OR MCDA OR MCA OR MCE OR “Vulnerability analysis” OR scenario* OR mitigation OR pathway* OR priorit* OR “natural capital account*” OR map* OR ”decision tree” OR “DSS” OR “Decision support” OR “Participatory Integrated Assessment” OR PIA OR “Ecosystem approach” OR “Environmental Impact Assessment” OR EIA)[2]
Uncertainty	“ecolog* uncert*” OR “ecolog* vagueness” OR “ecolog* ambiguity” OR “uncert* analysis”
Analyzing trade-offs	**Web of Science (Review OR meta-analysis):** (review* OR metaanalysis OR “meta-analysis”) AND (pollinat* OR bee OR bees OR Apoid* OR syrphid*) AND (policy OR policies OR action* OR response* OR intervention* OR service* OR conserv* OR sustainb*) AND (trade-off* OR “trade-off*” OR synerg* OR conflict* OR cost* OR benefit*) **Web of Science (Non review OR meta-analysis):** (pollinat* OR bee OR bees OR Apoid* OR syrphid*) AND (policy OR policies OR action* OR response* OR intervention* OR service* OR conserv* OR sustainb*) AND (trade-off* OR “trade-off*”) **Google Scholar:** pollination AND policy AND trade-off
Integrated responses	**Web of Science** (“citizen science” AND [TERMS FROM TABLE A1 ROW 1]) **Google** “pollinat* AND research AND (centre OR initiative OR funding)” Search conducted 20 August 2014. First 100 hits examined.

1. This search was carried out without the general search terms in the top right cell of Table A1.
2. Underlined terms used in a search with the Review term from Table A1. Where appropriate, we consulted databases, websites, people and organisations for each section. These sources are listed in Table A3.

TABLE **A3**
List of organisations, websites and people consulted by each section.

ORGANISATIONS

Name	Country	Website/URL	Contacted person	Data/information obtained	Section
ARIES (ARtificial Intelligence for Ecosystem Service) development team	USA	http://www.ariesonline.org		No response	6.5
EcoMetrix Solutions Group	USA	www.ecometrixsolutions.com	Michelle Kenna	Details of underlying pollination model	6.5
AfroMaison Technical Team	South Africa	http://www.afromaison.net/	Fonda Lewis	Details of underlying treatment of pollination in model	6.5

WEBSITES

Name	Website/URL	Data/information obtained	Section
Mapping and Assessment of Ecosystem Services in Europe	http://biodiversity.europa.eu/maes Accessed 2-Sep-14	One document found	6.5
Ecosystem Services Partnership	http://www.es-partnership.org/esp Accessed 2-Sep-14	No new material found	6.5

PEOPLE

Name	Country	Affiliation	Data/Information obtained	Section
Joachim Maes	Belgium	Leader of European Commission MAES (Mapping and Assessment of Ecosystems and their Services) project	Pollination maps have not been used for policy decisions in Europe yet.	6.5
Anne Teller	Belgium	European Commission	None	6.5
Paul Cross	UK	University of Bangor	Clarified interpretation of Pesticide Toxicity papers	6.4
John Bolte	USA	Lead developer of Envision model	Check that a pollination module from InVEST included in the model.	6.5
Tereza Giannini	Brazil	University of Sao Paulo	Findings on climate change and passion fruit pollinators have not been used by industry.	6.5
Mike Harfoot	UK	United Nations Environment Programme-World Conservation Monitoring Centre (UNEP-WCMC)	Asking if progress incorporating pollination into IAMs.	6.5
Per Rydahl	Denmark		Asking about use of Plant Protection Tool	6.5
Bob Bulmer/Jeremy Macklin	UK	InVivo Agricultural Solutions	Details and use of InVivo farm pollinator resource model	6.5
Virginie Boreux	Germany	Universitat Freiburg	Asked about Sacred grove research	6.4.3
Hisatomo Taki	Japan	Forestry and Forest Products Research Institute	Asked for help on regional (Asian) perspectives - got some new references on Japanese bumble bees	6.4.3
Connal Eardley	South Africa	Agricultural Research council, Plant Protection Institute	Asked about Kenyan taxonomy initiative - got a useful reply	6.4.3
Anton Pauw	South Africa	Stellenbosch University	Asked for help on regional (African) perspectives no reply yet	6.4.3
Ariadna Lopes	Brazil	Universidade Federal de Pernambuco	Asked for help on regional (South American) perspectives - got some new references	6.4.3
Blandina Viana	Brazil	Universidade Federal da Bahia	Asked for help on regional (South American) perspectives - got some new references	6.4.3
Gretchen LeBuhn	USA	San Francisco State University	Asked for examples of citizen science, and outcomes of the Great Sunflower Project.	6.4.3 6.4.6
Sam Droege	USA	United States Geological Survey	Told me about a bee monitoring program in northeast US	6.4.3
Laurie Adams	USA	North American Pollinator Protection Campaign www.pollinator.org	Reports of success or other outcomes, and case study	6.4.6

TABLE **A3**
List of organisations, websites and people consulted by each section.

PEOPLE				
Name	**Country**	**Affiliation**	**Data/Information obtained**	**Section**
Celine Geneau		Syngenta	Reports of success or other outcomes, and case study from Operation Pollinator	6.4.6
Gemma Light	UK	Welsh Government	Reports of success or other outcomes, and requested case study from Welsh Pollinator Action Plan	6.4.6
Una Fitzpatrick	Ireland		Reports of success or other outcomes, and requested case study from Irish Pollinators Initiative	6.4.6
Debbie Harding	UK	Biotechnology and Biological Sciences Research Council	Reports on the amount of investment, success or other outcomes of UK Insect Pollinators Initiative	6.4.6
Margaret Heath	Australia	Rural Industries Research and Development Corporation	Reports on the amount of investment, success or other outcomes of Pollination Programme	6.4.6
Christina Grozinger	USA	Penn State University	Reports on the amount of investment, success or other outcomes of the Center for Pollinator Research	6.4.6
Amina Harris	USA	University of California, Davies	Reports on the amount of investment, success or other outcomes of the Honey and Pollination Centre	6.4.6
Parthib Basu	India	University of Calcutta	Reports on the amount of investment, success or other outcomes of the Centre for Pollination Studies	6.4.6
Norman Carreck	UK	University of Sussex	Reports on the amount of investment, success or other outcomes of the International Bee Research Association	6.4.6
Norman Carreck	UK	University of Sussex	Reports on the amount of investment, success or other outcomes of the International Bee Research Association	6.4.6
Nicolas Deguines	France		Outcomes of SPIPOLL citizen science project	6.4.6
Gretchen LeBuhn	USA		Outcomes of Great Sunflower citizen science project	6.4.6
Emma Krafft	USA	Xerces Society	Evidence of outcomes from pollinator training events	6.4.6
Lynn Dicks	UK	University of Cambridge	Evidence of trade-offs and synergies (Bennett et al 2009; Dicks *et al* 2013)	6.7
Tom Breeze	UK	University of Reading	Evidence of trade-offs and synergies (Carvalheiro et al 2011; Holzschuh *et al* 2011; Rucker *et al* 2012)	6.7
Carol Poole	South Africa	South African National Biodiversity Institute	Case study on eucalyptus and honeybees in South Africa	6.7
Mike Allsopp	South Africa	Agricultural Research Council	Case study on eucalyptus and honeybees in South Africa	6.7
Brin Hughes	UK	Conservation Grade/Fair to nature	Asking for evidence of effects of Conservation Grade on pollinators. Two MSc thesis and an PhD thesis under development were provided.	6.4.1
ILK (Indigenous and Local Knowledge) Task Force Global Dialogue Workshop	Panama		Workshop attended by Maria del Coro Arizmendi to gather ILK stories for chapter 6.	6.4
Phil Lyver	New Zealand	The Intergovernmental Platform on Biodiversity and Ecosystem Services - Indigenous and Local Knowledge (ILK) Task Force	Validating text on the experience of using video to pass on biocultural tradition	6.4.6
Harold van der Valk		Independent	For information on relevant policies and actions to avoid or reduce impacts of pesticides and pollutants on pollination and pollinators	6.4.2

TABLE **A3**
List of organisations, websites and people consulted by each section.

PEOPLE

Name	Country	Affiliation	Data/information obtained	Section
Harold van der Valk		Independent	For information on relevant policies and actions to avoid or reduce impacts of pesticides and pollutants on pollination and pollinators	6.4.2
Barbara Ekbom	Sweden	Swedish University of Agricultural Sciences	For information on relevant policies and actions to avoid or reduce impacts of pesticides and pollutants on pollination and pollinators	6.4.2
Daniel Ward	New Zealand	Nature Watch	Checking verification process for Nature Watch	6.4.6
Karen Oberhauser	USA	Monarch Larva project	To check details of scheme for Table 6.4.6.3	6.4.6
PP Dhyani	India	Govind Ballabh Pant Institute of Himalayan Environment and Development-EarthWatch Project	To check details of scheme for Table 6.4.6.3	6.4.6
Richard Fox	UK	National Moths Recording Scheme	To check details of scheme for Table 6.4.6.3	6.4.6
Stuart Roberts	UK	Bees Wasps and Ants Recording Scheme	To check details of scheme for Table 6.4.6.3	6.4.6
Geoffroy Williams	Switzerland	Institute of Bee Health, University of Bern	Checking text on COLOSS and asking for additional information on outputs. Replied with edits, 26 September 2014.	6.4.6