CHAPTER 4

ECONOMIC VALUATION OF POLLINATOR GAINS AND LOSSES

EXECUTIVE SUMMARY

Pollinators provide a wide range of benefits to humans, such as securing a reliable and diverse seed and fruit supply, underpinning wider biodiversity and ecosystem function, producing honey and other outputs from beekeeping, and supporting cultural values. **These benefits can be expressed in economic terms to quantify the consequences of gains and losses in pollinator abundance and diversity to human wellbeing (*well established*) (4.1, 4.2, 4.9).**

Current markets and economic indicators (e.g., Gross Domestic Product) fail to capture the full range of benefits from pollinator abundance and diversity (*well established*) (4.1.1.), and the full costs of supporting managed pollinators *(unresolved)* (4.1.1). Given that many decisions about land use are based on markets and economic indicators, such failures can result in the loss of pollinator-mediated benefits and sub-optimal land management decisions from a social perspective (*well established*). Indeed, declines in pollinator abundance and diversity have altered the benefits they provide to humans (*established but incomplete)* (4.1, 4.2).

Economic valuation of such pollinator-derived benefits provides information to undertake corrective actions on these market and economic indicator failures (*unresolved*). Each time we make a decision affecting natural or semi-natural habitats there is an implicit (i.e. not informed) valuation of them, involving trade-offs with other land-use decisions. Therefore, humans are always valuing nature's benefits, either directly or implicitly. Economic valuation is a process in which these values are made explicit by using well-informed methodologies and justified criteria. Explicit values provide information to land managers (e.g., farmers), related industrial sectors (e.g., pesticides, supply providers), consumers, general public, and policy makers to modify land use choices or other public policies with greater consideration of pollinator biodiversity and sustainability (4.1.1, 4.2, 4.6).

The economic consequences of pollinator gains and losses are multidimensional, affecting the production and distribution of scarce goods and services, including production factors (e.g., human, financial and natural assets) (*unresolved*). According to the IPBES conceptual framework, value is defined as: *"In keeping with the general anthropocentric notion of "nature's benefits to people", one might consider a benefit to be ecosystems' contribution to some aspect of people's good quality of life, where a benefit is a perceived thing or experience of value"*. The impacts of pollinator gains and losses can be valued in both non-monetary and monetary terms. Non-monetary indices, such as crop production and nutritional quality enhanced by pollination services, can be of great interest (4.2.6). Within monetary terms, economic methods can measure both market values, when goods or services traded in economic markets (e.g., crop production) (4.2.2, 4.2.3, 4.2.4, 4.2.5), and non-market values, when relating to benefits not directly traded on markets (e.g., supporting aesthetic wild flower diversity) (4.2.6).

Economic valuation can measure use values, such as crop production from insect pollination, and non-use values, such as the values people place on the existence of pollinators. Valuation can be aggregate, examining the combined value of all pollinators within a region, or marginal, examining the change in value given a certain (non-total) gain or loss of pollinators. Marginal values are relevant for decision making because partial increases and decreases in pollinator abundance and diversity are more likely than complete loss, and because decisions concern marginal changes (4.1).

The annual market value of additional crop production directly linked with pollination services is estimated at $235bn-$577bn (in 2015 US$) worldwide (Table 4.8, Section 4.4.3) (*established but incomplete*). In addition, in the absence of animal pollination, changes in global crop supplies could increase prices to consumers and reduce profits to producers, resulting in a potential annual net loss of economic welfare of $160 billion-$191 billion globally to crop consumers and producers and a further $207 billion-$497 billion to producers and consumers in other, non-crop markets (e.g., non-crop agriculture, forestry and food processing) (4.7.4, **Table 4.10**, Section 7).

In addition to crop production, pollinators provide a full range of non-monetary benefits to the economy, particularly to the assets that form the basis of rural economies (*established but incomplete*). For example, human (e.g., employments in beekeeping), social (e.g., beekeepers associations), physical (e.g., honey bee

colonies), financial (e.g., honey sales) and natural assets (e.g., wider biodiversity resulting from pollinator-friendly practices). The sum and balance of these assets are the foundation for future development and sustainable rural livelihoods (FAQ section, 4.2, 4.5). Therefore, evaluating how pollinator-friendly *versus* unfriendly practices (or landscapes) change these assets would be a robust approach to valuing pollinator changes in both monetary and non-monetary terms. This approach allows quantification of the synergies and trade-offs (for example, between financial and natural assets) associated with pollinator enhancement (4.2.6).

Most studies of the economic impacts of pollinator gains and losses only estimate the monetary benefits in existing markets rather than the actual impact they have on peoples' wellbeing (*well established*). These estimates are dependent upon the methods utilized, and can change dynamically across spatial and temporal scales (*well established*) (4.3). For example, the benefits of pollination services to apple production was found to vary between $791 and $25,201 per hectare (2015 US$) for different agroecological systems using different methods (4.7.4, **Table 4.10**, Section 7).

Estimation accuracy of the economic value of pollinator gains and losses are limited by existing biological and economic data, as well as the need for methodological development (*established but incomplete*). For example, although there is broad understanding of the relative extent to which yields of most crops benefit from pollination, there are a number of uncertainties surrounding these such as the shape of relations between crop yield and pollination, how they vary for different cultivars of the same crop, and the interaction between pollination and agricultural inputs (4.5).

Unstable pollinator assemblages can result in substantial economic risks while highly diverse, resilient assemblages can provide stable long-term services (*established but incomplete*). To date, although a number of methods exist, no studies have quantified the economic value of this stability and few have considered the potential economic risks and uncertainties affected (4.4).

The spatial and temporal scales of ecological processes that affect the health of pollinator assemblages and their benefits, and the scales of social, economic, and administrative processes (involved in land-use decisions, market regulations, etc.) are seldom well aligned (*established but incomplete*). An important challenge is to match the ecological scale with the institutional scale of the problem to be solved (*unresolved*). For example, socio-economic value at larger scales may be of interest for policy makers, whereas profit analyses at smaller scales may be of interest for farmers. The temporal scale is also important, because ascribed values are endogenous to changes in the number and diversity of pollinators and other system (e.g., network) properties. Therefore, static values provide only limited, and perhaps misleading information for decision makers. Furthermore, within any given time period, the use of constant (e.g., average) values is also potentially misleading as it disguises the spatial variation in services and hence values (4.2.6, 4.3, 4.6).

Impacts of pollinator loss will be different among regional economies, being higher for economies based on pollinator-dependent crops (whether grown nationally or imported) (*established but incomplete*). For example, many of the world's most important cash crops are pollinator-dependent. These constitute leading export products in developing countries (e.g. coffee and cocoa) and developed countries (e.g. almonds), providing income and employment for millions of people. In general, the importance of animal pollination services varies between 5-15% of total regional crop market output depending on the area, market price, and pollinator dependence of the affected crops, with the greatest contributions in East Asia (4.7).

Although the economic consequences of pollinator gains and losses can be significant across the world, most evidence is based on global market data or case studies in the developed world with very few detailed studies in the developing world (*well established*). This regional bias may therefore fail to capture the impacts of pollinator shifts on the people whose livelihoods and diets are most vulnerable to pollinator losses (4.7.3).

The joint use of monetary and non-monetary valuations (integrated valuation) of pollinator gains and losses can be used to better inform decision making on land use (*unresolved*). Valuation of pollinator shifts can help in the decision making process through cost-benefit analyses, risk analyses, socioeconomic studies, etc. This information can be used in certifications, environmental schemes, green GDP, and regulatory frameworks (4.6.3).

INTRODUCTION AND OUTLINE

Pollinators are a key component of global biodiversity, providing vital ecosystem services to crops and wild plants (Klein *et al.*, 2007; Potts *et al.*, 2010; for more details, see Chapters 2 and 3). However, there is evidence of recent decline in both wild and managed pollinators and parallel decline in the plants that rely upon them (Potts *et al.*, 2010; Biesmeijer *et al.*, 2006). Declining pollinators can result in the loss of pollination services, which can have important negative ecological and economic impact that could significantly affect the maintenance of wild plant diversity, wider ecosystem stability, crop production, food security and human welfare (Potts *et al.*, 2010).

The importance of animal pollinators in the functioning of most terrestrial ecosystems has been extensively described and analysed in a broad range of scientific literature (see Chapter 3). The importance of pollinators and pollination services can often be evaluated in economic terms in order to link decisions made with economic consequences (Daily *et al.*, 1997; Daily *et al.*, 2000). The economic assessment of pollinators and pollination services is measured by their total economic value (TEV; summarized in **Figure 4.1**). Economically, the total value of an ecosystem service is the sum of the utilitarian reasons a society has to maintain it. This is typically divided into (i) use values, the values of the benefits that people gain from the functioning of the ecosystem (e.g., the pollination of crops); and (ii) non-use values, the values that people attribute to the existence of an ecosystem service, regardless of its actual use (existence value, e.g., the existence of pollinators) or the value they place on the potential to use the ecosystem service in the future (bequest value e.g., species that could pollinate crops in the future). Pollinators and pollination have a use value because the final product of their service can be used directly by humans, such as with crops or honey (a consumptive use), as well as the leisure and aesthetics created by the presence of pollinated wild plants within the landscape (a non-consumptive use value). Pollination can also provide indirect use values through supporting the reproduction and genetic diversity of wild and cultivated plants that benefit humans. Finally, the use value of pollinators and pollination also contains an option value (the value given to preserve a choice option of pollinators and pollination-dependent products in the future) and the insurance value (the capacity of pollinator communities to reduce the current and future risks associated with using pollination services; Baumgärtner and Strunz, 2014).

However, not all these values are directly related to markets (only the consumptive uses that are marketed). Consequently, the impacts of management on pollination services could be under-estimated when making decisions, potentially resulting in inefficient or unsustainable use of resources. Economic valuation provides two forms of essential information to stakeholders. Firstly, it highlights the economic contribution of pollinators to the various benefits provided to the agricultural sector and society. Thus, it tells the decision maker how much net benefit arises from different interventions, which in turn allows for the optimal design of such interventions. Secondly, economic valuation can assess the impact of variations in pollinator population on the economic welfare of different groups of people, such as farmers or consumers. By considering this information, decision makers, from both the public and private sectors, are able to make better-informed decisions about the impacts of proposed investments, public spending or management changes. This chapter aims to review the conceptual framework and the various methods of economic valuation of pollinators and the effective use of these valuations. There are also other value systems, including spiritual, cultural and indigenous and local knowledge values, which can inform decision-making, these are reviewed in Chapter 5.

In this chapter, pollination services are considered an ecosystem service, i.e., "the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfil human life" (Daily, 1997). The evidence is clear for wild pollinators that are provided by natural ecosystem as forests or soils, but some ambiguity remains when considering managed pollinators as they can be considered as livestock, far from nature. However, they are used to provide services in agricultural systems that, while heavily managed, remain a functioning ecosystem (or agro-ecosystem, see Swinton *et al.*, 2006; Swinton *et al.*, 2007; Zhang *et al.*, 2007). Thus described, pollination services from managed pollinators are ecosystem services offered by the agro-ecosystem. Unlike many well-quantified ecosystem services, pollination services are provided by mobile organisms that can move in uneven patterns across their foraging range, making them more difficult to assess accurately (Kremen *et al.*, 2007). Furthermore, pollination services are an intermediate service, a service that is not beneficial in itself but instead underpins other benefits, such as crop production and landscape aesthetics, by helping produce pollinator-dependent crops for human food and nutrition security, along with the reproduction of certain plants (Fisher *et al.*, 2009; Mace *et al.*, 2012). The value of intermediate services is assessed not by looking at their direct consequence (pollination) but by their impacts on the final goods that are produced (food, honey, etc.). These final goods have a market price which gives some reasonable indication of their use value (note that prices may under-estimate values). However, pollinators are also final ecosystem services in themselves because of the value associated with their existence. Although this complicates the challenge of accurately valuing pollination services more substantial, these abstract benefits can still be valued economically. Consequently, the methods of valuing the impact of pollinator and pollination gains and losses can range from very simple to very complex at several levels.

The chapter starts with an outline of some frequently asked questions on economic valuation of nature and ecosystem services, with emphasis on pollinator gains and losses. Section 1 then presents the rationale behind economic valuation of pollinators and pollination. Section 2 critically reviews the range of methodologies that have been applied to quantify the benefits of pollination services. The strengths and weaknesses of each method are also discussed, in terms of their ecological and economic validity as well as the capacity to extrapolate the values to different spatial scales and data requirements are outlined for each one. Valuation may vary relatively according to the ecological or biological functioning of the ecosystems that support pollinators, the spatial and temporal specificity of the pollinating animals, and the value given by the consumers or beneficiaries of the final good obtained by this service (Farber *et al.*, 2002; Fisher *et al.*, 2009). Section 3 focuses on temporal and spatial scale effects on the economic valuation, including tools for integrating these factors into valuation. Economic valuation tends to assume that the consequences of pollination service loss are precisely known. However, decision-making is confronted with stochastic relations between events, giving rise to a number of factors that can significantly affect the economic value of pollinator gains and losses. Section 4 considers the effects of economic risk and uncertainty inherent to pollination services (e.g., fluctuations in service delivery or market prices) and pollinator community resilience, including methods to quantify and value these factors. Section 5 reviews knowledge gaps related to the economic valuation of pollinators, covering agronomic, ecological and economic knowledge that could be used to improve value estimates. Section 6 reviews the applied use of these economic valuations for decision-making, reviewing the stakeholders concerned with these valuations and, for each of them, how they should interpret the values and use them. Finally, Section 7 analyses case studies that used the methodologies presented in this chapter. The chapter ends with a synthesis of all these sections 8.

FREQUENTLY ASKED QUESTIONS

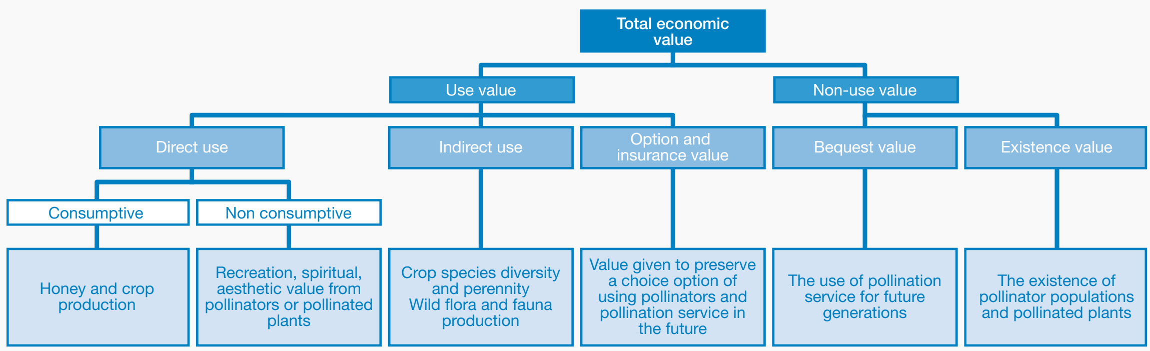
In this section, we briefly outline some common frequently asked questions on economic valuation of nature and ecosystem services, with emphasis on pollinator gains and losses. We briefly explain the approach adopted in this chapter, and direct the reader to specific sections where this is discussed in detail in this chapter. We hope this section clarifies the benefits and the limits of economic valuation.

1. Are economic values the same as prices?

Distinction must be drawn between prices and values. Prices are the monetary exchange rate of a good on a market, or information that institutions (including markets) link with things in order to manage their use. In contrast to this, economic values express the importance people place on things, more precisely, they are a quantitative expression of the impact a service has on the overall economic wellbeing of people. Each time we make a decision affecting natural or semi-natural habitats there is an (implicit and possibly explicit) valuation of the consequences of this choice, involving trade-offs with other land-use decisions. Therefore, humans are, in many circumstances, implicitly valuing ecosystems through the decisions they make. Economic valuation is a process in which these values are made explicit by using well-informed methodologies and justified criteria. The neoclassical economic theory of value can be regarded as a theory of what should be a perfect price system in order to transmit to economic agents the most relevant information on the relative utility

FIGURE **4.1**

Total economic value of pollinators and pollination service (adapted from Pascual *et al.* 2010).



and scarcity of all goods and services. However, in the real world, prices do not usually indicate the values. Ideally, economic valuation studies should estimate values; yet, several methods tend to estimate prices or price variations, which are used as indicators of value (e.g., market price of renting honeybee colonies can be used as a proxy of the economic value of honeybees). See Section 1 for a more detailed explanation.

2. Does economic value mean monetary value?

Though the question is often addressed in these terms, it has to be reformulated because "monetary value" has no clear meaning. If the question is "should the economic values necessarily be expressed in monetary terms?" the answer is "not necessarily", but for practical reasons and communication purpose, it is generally the case. Economic values can be expressed in any currency. Nevertheless, monetary units have practical advantages, for example, as a common unit across highly diverse costs and benefits and it is the same unit that other investments (including in non-environmental policy) are assessed in. Therefore, monetary units are generally used in valuations, although this tends to reinforce the ambiguity between values and prices. In monetary terms, economic valuation methods include market prices, when the benefits relate to existing markets (e.g., crop production), and non-market values, when relating to benefits not directly traded on markets (e.g., supporting aesthetic wild flower diversity). Non-monetary indicators can also be of great importance, for example, given that demands for agricultural products are constantly increasing from a growing and more affluent population, it is important to maintain the regenerative nature of agroecosystems, such that food production and diversity, and livelihood are improved for farmers. These important considerations are indeed difficult to express in monetary terms. See Sections 1 and 2.4 for further discussion.

3. Does the valuation of nature and ecosystem services imply privatization or commodification?

Economic evaluations are usually motivated by goals such as decision support, policies design or raising awareness among public decision makers of the importance of certain issues. The intention is not privatizing or commodifying public assets, which is often considered both impractical and unethical, but to recognise their values and include them explicitly in public or social decision-making. For example, the value of a river as a provider of clean water for a town does not imply a market for buying and selling rivers. Similarly, the value of a meadow as a provider of insect pollination for nearby crops does not imply a market for buying and selling meadows. It recognises a common, natural asset that should be protected for the benefit of the overall welfare of those affected. Valuation allows the importance of such an asset to be compared with the interest for society of alternative actions or policies that degrade it. Therefore, using techniques to estimate the value of a resource to society can help its members to better understand the scope and scale of the benefits received from the resource. Furthermore, economic values and other valuation systems (see Chapter 5) are not mutually exclusive and can be combined using multi-criteria analyses. See Section 1 for further discussion.

4. Does economic value include non-use values?

Non-use values have been progressively introduced in economic valuation of natural assets in order to get more significant indicators of the total importance of the multiples reasons explaining why people value nature's services. Economic valuation thus includes methods to quantify both use values (e.g., crop production due to insect pollination) and non-use values (e.g., the value people place on the existence of pollinators). Indeed, valuation theory places a great emphasis in capturing both of these types of economic value. See Section 1 for further discussion.

5. How much uncertainty is associated with economic values?

The uncertainty is an important limitation affecting the precision of economic valuation methods related to crop production. For example, the underlying empirical data linking pollination to yield are sparse and do not adequately represent variation among crop varieties, years, or places, particularly for the widely grown crops. Unfortunately, valuations have often been widely communicated without explaining this uncertainty (whether or not it is in the discussion text of the scientific papers). The fact that the estimation of values share uncertainty, as is true of most estimates in any scientific field, does not mean that the process and use of valuation is inherently flawed. If the valuation process is not made explicit, the value given to natural assets or ecosystem services may be zero, a value that we can be certain is wrong. It is important that values should be communicated to policy makers and the public with corresponding estimates of uncertainty, for example, by providing ranges of values instead of a unique value. We also identify in this chapter several biological knowledge gaps that directly affect valuation uncertainty. Thus, though variations among valuations may be the effect of technical failure, they may also reflect the fact that the valuation of the same service in different circumstances has no a priori reason to be the same. Moreover, these differences can simply reflect the natural heterogeneity in benefits, which in turn inform these values in decision-making. The underlying 'true' value that we are trying to measure is likely to fluctuate itself quite considerably because of changes in food demand and supply, the development of technology and changes in populations and their socio-economic characteristics, among others. See Sections 3 and 4 for further discussion.

6. Does valuation precludes conservation because the use values of natural systems are usually lower than alternative land uses?

In many instances, a particular use value of natural ecosystems can be lower than alternative land uses. For example, the opportunity cost of replacing more forest area with coffee plantation can be higher than the pollination services provided by the forest habitat to the coffee plantations. In plain language, it may be possible for a farmer to make more profit by expanding coffee area than from the higher yields (tons ha^{-1}) that result from pollination services from forest next to plantation, thus creating incentives to destroy the forest. Although a particular use value of nature can be lower than alternative land uses, the estimation of this value does not inherently promote the destruction of nature. On the contrary, valuation may illustrate that the long-term consequences of pollination services lost may be greater than the value of new coffee production by reducing benefits to other plantation patches. Furthermore, the economic value of pollination services is additive to the values of other ecosystem services that forests provide in greater quantities than plantations, like clean water and fresh air to humanity (i.e., use values beyond crop pollination), and that conserving nature has a value for society even without perspective of use (i.e., non-use value is high). In this way, by estimating the value of pollination among other ecosystem services we add reasons to the conservation of nature in addition to the traditional, long-standing non-use values. As stated before, an advantage of economic valuation is to make the benefits and the decision-making process more explicit in regards to nature. For example, a particular forest may have low private use values (e.g., timber value) but high public use values (e.g., recreation). Social decision makers might therefore protect this forest even if its non-use values were low (e.g., no wildlife species of conservation interest). Therefore, a key issue is; 'valuation for who'? The potential value of a field to the farmer is different to the potential value of that field to society. The market reflects the preferences of private individuals. Economic valuation allows us to look at values in the round, both private and public, and shows that the two are rarely identical. See Sections 3 and 5 for further discussion.

SECTION 1. NATURE AND SIGNIFICANCE OF THE ECONOMIC VALUATION OF POLLINATION

1.1 On the meaning of economic valuation

The concept of **value** is used to describe how **agents** (typically individuals or, more broadly, societies) assign or express their interest in things; the "things" are objects, ideas, persons or anything else. Among multiple frameworks, the economic concept of value aims to measure and capture these values in largely quantitative terms; the current significance that is explained within this section. For an extensive analysis of economic valuation, non-economist readers are referred to microeconomic or environmental economics textbooks such as Just *et al.* (2008), Hanley *et al.* (2013) or Perman *et al.* (2012).

1.1.1 Understanding the meaning of economic value: utility and scarcity

Economics has been defined as "the science, which studies human behaviour as a relationship between ends and scarce means which have alternative uses" (Robbins, 1932). As such, economic value reflects the utility and scarcity of "things".

Utility refers to the satisfaction that agents obtain from the consumption of goods or services (a simple distinction is that services are not depleted by use, while goods can be). It is usually accepted that agents' utility is subjective and depends on their preferences. The social welfare is the sum of the utility gains and losses of each agent in society. The utilitarian perspective advocates choosing options that offer the greatest social utility or welfare. However, consumers do not derive utility directly from pollinators, but they can gain utility from consuming the products of the pollination process, such as fruits or aesthetically valuable flowers (Fisher *et al.*, 2009).

Scarcity is not necessarily a measure of physical amounts, but of the tension resulting from the lack of supply of usable resources relative to the wants of the people (demand). Scarcity is at the core of the allocation issues. The scarcity of pollinators can lead to a decrease of pollination services and therefore a reduction of the utility of consumers of these benefits. Properly informed, economic valuation of pollinators provides relevant indicators of the relative utility and scarcity of the diverse resources offered through the process of pollination that may contribute to human welfare.

1.1.2 Values, costs and prices

Advantages and limitations of bringing the diversity of preferences into a single-dimension analysis. Economic valuations typically measure values in monetary figures. However, this is often criticized as being too simplistic as it brings the diversity of wants and needs into a one-dimension indicator. When related to nature, these wants and needs are difficult to substantiate and do not really help decision makers to understand the actual functioning of human societies in their relation to ecosystems as, because of methodological limitations, economic valuations alone cannot fully capture the richness and diversity of relations between societies and nature. This is a particular issue when the results are poorly reported and do not allow to fully capture or express the variability and diversity of values among individuals. However, the purpose of the valuation is to enlighten decision-makers on the utility/scarcity issues resulting from the choices they can make. Expressing benefits and costs in a way common to standard economic activity allows, aside of other measures, for more informed decision-making than would otherwise be possible. Expressing the intensity of the tensions on ecosystem services with a monetary indicator allows comparing them with the prices that can be observed on the markets.

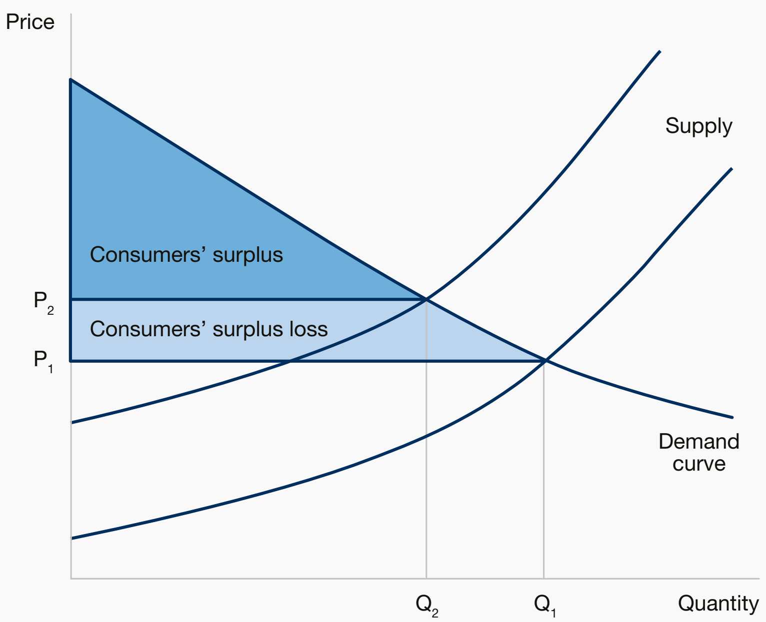
Prices, costs and values: how do they differ? Economists use three complementary but distinct concepts to express the impacts of economic activity in monetary units: prices, costs and values. Prices are the amounts that buyers must pay to sellers when there is a market i.e., the mechanism by which buyers and sellers interact to determine the price and quantity of a good or service. When the market is competitive, prices may vary in order to balance supply and demand. **Costs** express what agents must give up to get (or produce) the items they want, i.e., the efforts they would bear in terms of monetary cost, but also of time, inconvenience or income foregone (often referred to as opportunity costs). The use of ecosystem services could lead to a situation with no cost if there are no private cost (the cost incurred by the suppliers or the price paid by the consumers if any), or negative "externalities" (see Section 1.1.3.). **Values** reflect the interest of agents for goods and services, knowing that their preferences for these objects are influenced by both their needs and culture, and the information they have. Although they are often used interchangeably with values, the **benefits** are, in reality, the positive impacts produced by pollinators and pollination services. Economic valuation of pollination and other ecosystem services aspires to quantify the welfare gains from benefits[1].

Marginal values. Economic value is often derived from the maximum amount a consumer is willing to pay for a good or service in a market economy. For goods and services for which there is no market, these welfare values must be estimated by appropriate methods (see Section 2). The values useful to inform public policy choices are the values of goods and services units gained or lost resulting from the different choice options. These are what economists call marginal values. In the context of ecosystem services,

1. In the "cascade model" of the CICES (Haines-Young and Potschin, 2010), benefits are defined as the share actually used of the entire ecosystem services potential.

FIGURE **4.2**

A simple scheme of the consumers' surplus.



marginal values are even more relevant to informing decision making when complete collapse of services is unlikely (Costanza *et al.*, 2014).

Net economic value and consumer surplus. Most economic valuations refer to "willingness to pay" (WTP) as a measure of the value of goods and services, regardless of whether WTP are obtained from direct statements or derived from any observable information. WTP is used as a measure of utility because it represents an individual's subjective view of what a thing is worth to them, given their budget constrains (as are market prices). In this way, it differs from utility, which may be much greater than an agent's budget. As it is not possible to ask every individual what they are willing to pay for a benefit, WTP is instead estimated from surveyed sample or observed behaviours using economic statistics (Econometrics). From this, it is possible to derive consumer surplus (CS) – the difference between what consumer would be willing to pay (WTP) to get a good or service and the cost they actually bear (market price or opportunity cost). Symmetrically, producer surplus (PS) is the difference between the market price and the production costs, representing the welfare gains to the producers of the good or service.

In **Figure 4.2**, the demand curve is built by ranking the WTP for each unit of the service from the highest to the lowest and the supply curve ranks units by increasing production costs. The intersection (Q*, P*) indicates the hypothetical market equilibrium (if there is a market), the equilibrium being where market prices are determined. The blue area covers the difference between the WTP and the market price for all the units that will be effectively produced and consumed. It represents the CS or net value of the service for the final consumers.

When there is no cost, CS is directly equal to the sum of WTP. Such cases are extremely rare in the real world, except where there are no alternative uses of that resource. This would be the case for ecosystem services if they were available at no cost, including no opportunity cost resulting either from legal constraint imposed to agents interacting with processes behind the ecosystem service or either from no alternative uses of these services.

1.1.3 The externalities issue

An externality is a cost (negative externality) or a benefit (positive externality) that affects a party who did not choose to incur that cost or benefit, and does not get or pay compensation for it. A positive externality may be pollination when as a by-product of honey production. A negative externality could be the loss of crop pollination resulting from declining insect pollinators due to pesticide use.

The existence of externalities is directly dependent on the structure of the property rights (there is no externality if the managed pollinators belong to the farmers that grow the crops) and on the legal or economic status of pollinators or pollination services (*private goods, public goods, common goods, club goods*, see **Table 4.1***,* Fisher *et al.*, 2009). The criteria of classification are two-fold: whether the consumption of a good by one person precludes its consumption by another person (rivalness) and whether or not one must pay for a good in order to use it (excludability). Honeybees can be considered as a private good or service when they are exchanged in a pollination market. Indeed, their services are privately owned (rival) and marketable (excludable). However, this classification assumes that the honeybees have no possibility to pollinate other crops in another field or wild plants. In this case, their services would become a common good because they are non-excludable (once they are provided everybody use them) but rival. Wild pollinators are considered as a public good because their services are non-rival (the fact that an agent uses them does not prevent other agents to use them) and non-excludable.

The economic status of pollination service is not quite clear because it may vary according to several circumstances and institutional context (see Cheung, 1973). When wild pollinators provide the service, it can be considered a public good. When honeybees that have not been rented provide services, they can be seen as a positive externality of honey production or as a reciprocal externality between beekeepers and farmers (Meade, 1952). When there is a market for hives rental (e.g. in the United States), pollination becomes a marketed service whose economic efficiency can be discussed (Cheung, 1973; Rucker *et al.*, 2012). The difference between a market and non-market situation may

TABLE **4.1**
Characteristics of good and services from pollinators adapted from Fisher *et al.* (2009)

	Excludable	Non excludable
Rival	**Private good**. Pollinators are private good when they are managed by beekeepers; pollination may be a private good when it can be controlled or when there is a market for pollination service.	**Common good**. The pollination is provided by pollinators to all crops and wild flora in an area that depend only on the pollinator species (say honeybees). If the abundance or diversity is limited, there is rivalry among crops or between crops and wild flora.
Non rival	**Club good**. Pollinators could be a club if a group of farmers and beekeepers were organized to manage them, but scientific literature does not provide an example of such an organization.	**Public good**. Wild pollinators and in many cases managed pollinators are a public good when the pollination service is provided freely on the sole criterion of spatial proximity either to crops or to wild flora that create social amenities.

have significant implications for the long-term management of the service. As long as there is no price signal from the market, or other signals from e.g., public policies, the agents (those whose choices and behaviours influence the dynamics or conservation of pollinators) will not be affected by the consequences of their choices and behaviours. This may potentially result in unstable or unsustainable long-term management practices.

1.1.4 Monetary contribution versus economic value of the impact (or consequences) of an ecosystem service

A distinction should be made between the monetary value of the contribution to society of an ecosystem service and the economic impact of the loss of this service on the society. Taking the example of **Figure 4.2**, we could assume that the contribution of the ecosystem service to society is the gain in production between Q_1 and Q_2. In this way, the monetary value of the contribution would be the price, P_1, multiply by the net production due to the ecosystem service. The economic impact or consequence of the ecosystem service loss measures the impact on the price and quantities at the equilibrium of such a decline. The economic value of the decline would be measured by consumer and producer surplus losses. A more detailed discussion of the distinction between monetary contribution and economic valuation of pollination services can be found in Gallai *et al.* (2009a).

1.1.5 The cost-benefit analysis framework

Economic valuations are usually part of a larger process of economic analysis. There are in fact two main frameworks: cost-benefit analysis and cost-efficiency analysis. Both framework use many of the same principals and data but have substantially different scope and objectives, making them useful in different situations.

Cost-benefit vs. cost-effectiveness analysis. Economic valuations refer primarily to the idea of calculating and comparing the costs and benefits, typically for policy-makers who have to make a decision among several choice options. Cost-benefit analysis aims at identifying the option with the highest net present value (NPV). NPV measures the balance of economic gains and losses linked to each option. In order to allow the comparison of cost and benefits that occur at different time, future gains and losses are down weighted using a **discount rate** (see Section 3.2.2.3.) according to the expected change in the value of money over time in order to obtain their present value. When calculated in a social context (as opposite to individual or private), and provided you have included and accurately valued all major benefits and costs and applied the appropriate discount rate, the highest NPV maximizes the social welfare. Cost-Benefit Analysis (CBA) is often used to identify this maximum: what are the levels of benefits gained from investing certain costs in an action. For example, Blaauw and Isaacs (2014) explicitly measured the benefits of pollination services from field margins sown with flowering plants to nearby blueberries relative to the costs of managing and maintaining these margins, finding that the total benefits outweighed the total costs after 3 years. It is therefore quite different from the cost-effectiveness analysis (CEA), which aims at identifying the most efficient way (lowest cost) to reach a particular goal: e.g., considering which mitigation measure would provide a minimum level of insect pollinators needed at the lowest relative cost.

CBA and distributive justice. A well-designed CBA should be able to recommend choice options that maximize social welfare. This optimal situation is sometimes called **allocative efficiency** because it is a situation where all goods are allocated to their most beneficial use. Nevertheless, this result may not be considered fair. The CBA may lead to solutions that are theoretically optimal but less preferable in terms of social justice since the positive and negative effects are distributed unevenly among agents. A policy with positive aggregated impact (say a ban of some pesticides that degrade the diversity of pollinators) may have a negative impact on certain agents that do not receive much or any of the benefits (e.g., farmers that grow wind pollinated crops that depend on this pesticide) (for overviews of these issues see Martinez-Allier, 2003; Pearce *et al.*, 2006). Following seminal critics such as Rawls (2001), Sen (1999a, 1999b) or Fehr and Schmidts (1999), innovative analyses have introduced justice considerations. CBA can be carried out with different social decision making rules and taking into account issues such as the diminishing marginal utility of income (as required in the UK Treasury Green Book guidelines) so as to incorporate issues of social distribution. The same comment may apply to CEA.

The sustainability criterion. Maximizing NPV is an efficiency-based criterion (the *most efficient alternative is the one that maximizes NPV*). As such the NPV can be positive for a project that is not sustainable (i.e., consistent with sustainability goals). Indeed, a development project can be sustainable, while its NPV is negative. The measure of sustainability is still an ongoing debate, however the classical sustainability criterion (Pezzey, 1989; Solow, 1993) assumes that consumption or welfare must be non-decreasing over time (the consumption of tomorrow should not be lower than the one of today). Since the consumption path is not necessarily representative of the welfare (Ascheim, 1994), classical conceptions of sustainability tend to focus on non-decreasing social welfare (Arrow *et al.*, 2004). Following the concept of development as freedom (Sen, 1999a), recent perspectives tend to consider that a better sustainability criterion should be to maintain life opportunities (Howarth, 2007). The sustainability of pollination services should be evaluated regarding, not only its impact on consumption path or the welfare of a typical individual, but in order to maintain these life opportunities.

1.2 Linking economic values with pollination

The economic literature systematically links valuation with decision, public awareness and policy-making. Indeed, the conceptual framework of economic valuation is designed for collecting and organizing information toward hierarchizing and selecting choice options (for instance, agriculture policy or biodiversity strategy; Costanza *et al.*, 2014). However, there apparently are broader motives behind economic valuations, and some authors have suggested that the link between valuations and decision-making was more related to general advocacy than to providing technical information (Laurans *et al.*, 2013; Laurans and Mermet, 2014).

1.2.1 Understanding the importance of what is at stake

There is growing evidence of insect pollinator decline in many regions and its consequences (e.g., fruit and vegetable production decline in quantity and/or quality) are occurring, but building indicators of these changes is difficult and the result can be controversial or of limited social impact if expressed in a metric understood only by scientist and experts. The first interest of estimating the value of pollination service or the cost of pollinator decline is certainly to raise awareness on their importance for our societies, and to offer a clear and simple argument to help policy-makers to make choice about the opportunity to design and implement appropriate measures. Estimating the cost of pollinators' decline in economic terms allows the comparison of the result to other issues and, more importantly, to the cost of the remedies that can be proposed to this problem. In many cases, a precise study of the local variations in value indicators will be more helpful for decision making than global information.

1.2.2 Defining hierarchies, priorities and choices

Comparing the cost of declining pollinators to the cost of implementing alternative options in behaviours and solutions is clearly a difficult task. The main difficulty is usually to assess the cost of moving away from the current policies and behaviours. However, drawing a clear picture of alternative practice and organization can be a challenge as well. There is in fact little literature that directly offers estimates of such change (for an analysis based on cost of replacement, see Allsopp *et al.*, 2008) and the few published results appear quite sensitive to the valuation method.

The design and assessment of cost-effective policies and action can be of real importance, but enlighten only a framework for a least-cost approach for some policy target (cost-efficiency) without demonstrating that it is the best social choice (the gain are not necessary larger than the costs). For example, the market for colony rental for almond orchards in California (Klein *et al.*, 2012) might be the simplest way to meet the needs of large-scale monocropping landscapes. However, the pollinator shortage might also be solved if agricultural landscapes were to become more heterogeneous (Hussain and Miller, 2014), if producers switched to crops less dependent on pollinators or even developing artificial pollination techniques, but this is in most cases highly speculative. Economic valuation can assist in this process by identifying not only the most cost-effective solution but the fairest and most sustainable ones as well.

SECTION 2. METHODS FOR ASSESSING THE ECONOMIC CONSEQUENCES OF POLLINATOR GAINS AND LOSSES

A number of methods have been used throughout the published literature to quantify the economic consequences of pollinator gains and (most often) losses. The following section reviews the principle details of each of these methods, focusing on **what it measures** (price or value and of what specifically), an overview of the **methodology** involved, it's **strengths** and **weaknesses**, under what situations it is **suitable to use** and what **data is required**. Key examples of each method (some of which are reviewed in detail in Section 7) are provided for interested readers. **Table 4.2** summarises these methods for ease of reference.

2.1 Price Aggregation

2.1.1 Aggregate crop price

What it Measures: The total market price of animal pollinated crop production.

Methodology: This method assumes that production of all animal pollinated crops would cease in the absence of pollination services and therefore equates the total sale price of all crops that benefit from animal pollination, with the value of pollination services themselves.

Strengths: As it assumes that crops are either uneffaced or completely lost, this method has very simple data requirements and is equally applicable at all spatial scales providing sufficient data is available. Assuming the complete loss of insect pollinated crop production may be realistic for some highly pollinator-dependent crops with high management costs.

Weaknesses: By assuming that crops are either entirely dependent upon pollination or not dependent at all, this method significantly overestimates the overall benefits of pollination services and does not estimate the marginal impacts of pollination services. Although production of some crops would probably cease, in many crops, these benefits are not large enough (Klein *et al.*, 2007) that they could not potentially be produced profitably without animal pollination. Finally, the method does not consider producer's ability to substitute between crops or sources of pollination and the effect such losses may have on prices and consumer or producer welfare.

Data Required: Data on the price per unit and number of units sold for crops known to benefit from animal pollination.

Examples: Matheson and Schrader (1987); Costanza *et al.* (1997).

Suitable to use: As it greatly overestimates the impacts of pollination services and does capture economic value, this method is not suitable for use as an economic appraisal of pollinator gains or losses and is included only for historic reference.

2.1.2 Managed pollinator prices

What it Measures: The market price of managed pollination services.

Methodology: The sum market price for the use of these pollinators in crop production is taken as the total value of the pollination service they provide, which is assumed to have arrived at an accurate price via traditional market forces (Rucker *et al.*, 2012). This can be based on a) recorded numbers of hives actually hired (Sandhu *et al.*, 2008) or b) the total stock of managed pollinators. To date, this method has only been applied to honey bees, although it is equally applicable to any managed species bought or rented for use as a crop pollinator.

Strengths: This method reflects the market price for pollination services as an input and is thus compatible with standard economic theory and accounting. Differences in rental price for honeybees can capture variations in the relative value the market places on pollination services to crops, theoretically linked to the market price of the crop and the relative benefits of the service. Providing that regional variations in prices are captured, this method is equally applicable at any scale. Economic modelling can also be used to predict future values based on changes in factors affecting services (Rucker *et al.*, 2012).

Weaknesses: While some larger markets such as the United States have well-developed markets for managed honeybees (Rucker *et al.*, 2012), in many counties, markets for honey bee pollination services are very small resulting in little commercial beekeeping for pollination (e.g., Pocol *et al.*, 2012; Carreck *et al.*, 1997). Where markets do exist, existing evidence suggests that prices are largely independent of the benefits to the crop, influenced instead by factors such as management costs, limited honey yield (or none suitable for human consumption) from some crops, the availability of commercial honey bees and the sale prices of the crop (Rucker *et al.*, 2012; Sumner and Boriss, 2006). Other managed pollinators are bought at fixed prices per unit, which are, similar to other agricultural inputs, uninfluenced by the benefit to the crop. As such, price fluctuations will not reflect changes in the benefits of the service but the market forces affecting the price of producing and supplying these pollinators. Most significantly, this method completely discounts the benefits of wild pollinators, which are often a more significant contributor of pollination services than e.g., managed honey bees (Garibaldi *et al.*, 2013), services provided for free by local beekeepers (Carreck *et al.*, 1997) or pollinators managed directly by producers. Finally, managed pollinator prices alone will not reflect the benefits of varying interactions between wild and managed species that often have different, complimentary foraging habits (Brittain *et al.*, 2013; Greenleaf and Kremen, 2006 but see Garibaldi *et al.*, 2013).

Data required: Rental prices of managed honeybees and/or purchase price of other managed pollinators; estimates of the number of pollinators per hectare required for optimal pollination.

Examples: Burgett *et al.* (2004); Sandhu *et al.* (2008).

Suitable to use: This method should only be employed where a market for managed pollination services exists at a large enough level to form a substantial proportion of pollination service provision. Due to the inability to capture wild pollination services, this method is primarily suitable in systems where all pollination is provided by managed insects – for example glasshouses. Spending on managed pollinators is however likely to be important to local decision-making (Section 6).

2.2 Production functions

Production functions are analytical or statistical models that represent the impact of a quantity of an input on the quantity of an output produced in relation to all other inputs used. Two forms of simplified production function have been widely used to estimate the economic consequences of pollination services: Yield Analysis and Dependence Ratios. These methods are only partial production functions, as they do not account for the impacts of other inputs on production. Full production functions (covered in Section 2.2.3) have not been applied to pollination services to date, however a growing number of studies have advocated their use. Ultimately, none of the methods detailed below capture the true value of pollination services, only the market price of production these services underpin. In particular, as they do not capture changes in prices resulting from changing production they are mostly suitable at smaller spatial scales where yield change is unlikely to affect market price. Therefore, all production function approaches have to be combined with surplus estimation in order to assess the welfare value of benefits, particularly at wider scales.

2.2.1 Yield analysis

What it Measures: The market price of additional crop production resulting from pollination services.

Methodology: Using agronomic experiments, this method compares the average output of sub-samples where pollinators have been excluded to other sub-samples left open to pollination with the difference acting as a measure of pollination service benefits. More recent studies have expanded this approach by considering the impacts of the observed change in output on producer costs (e.g., Winfree *et al.*, 2011) and the potential market price of production lost from deficits in pollinations services (e.g., Garratt *et al.*, 2014). In these studies, changes in producer output or profit resulting from pollination are used as a measure of value. If data on pollinator visitation rates and efficiency are available, it is possible to divide the market price of output per hectare among particular pollinator taxa to estimate their relative importance within the system (Winfree *et al.*, 2011). The marginal benefits of different levels of managed pollination services on yield can be captured by varying the number used within the landscape (Delaplane *et al.*, 2013) or by assessing the suitability of local habitat to provide pollination services (Ricketts and Lonsdorf, 2013).

Strengths: Comparing open-pollinated and pollinator-excluded sub-samples, allows for an accurate assessment of the benefits from pollination to particular crops under field conditions if all other factors are equal. These studies can also capture the variation in pollination services benefits to different cultivars of the same crop and the impacts that pollinator driven changes in production will have on marginal costs (e.g., the costs of labour for fruit picking) allowing for more detailed and accurate estimates of service benefits (see Garratt *et al.*, 2014).

Weaknesses: Despite numerous studies using this method, yield analysis is not a standardized methodology within economic valuation literature. Although most studies are use relatively consistent methods for determining pollination service benefits, variations in methodology (e.g. Ricketts *et al.*, 2004) may affect the accuracy of estimates even in the same crop (Garratt *et al.*, 2014; but see Vaissière *et al.*, 2011 and Delaplane *et al.*, 2013 for standardized methods). For example, few studies account for the impacts of pollination services on crop quality, which may result in an underestimation of benefits of pollination (Garratt *et al.*, 2014; Klatt *et al.*, 2014). By contrast, as this method does not account for the marginal effects of other inputs or ecosystem services on crop productivity (e.g., pest regulation; Melathopoulos *et al.*, 2014; Lundin *et al.*, 2013) the benefits of pollination services may be overestimated. This is particularly significant in very highly dependent crops where as much as 100% of crop market output can be attributed to pollination using this method, effectively estimating that all other inputs having no benefit. In reality, other inputs will still influence yields, even in very highly dependent crops, by affecting e.g., the size and number of fruits produced.

Data required:

- **Minimum:** Agronomic estimations of crop yield in both a pollinator-excluded and open-pollinated system (following e.g., Vaissière *et al.*, 2011; Delaplane *et al.*, 2013), crop market price per unit.
- **Optimal:** As above plus agronomic estimations of crop specific quality and market parameters in both a pollinator-excluded and open-pollination system. Estimates of changing management and harvest costs arising from lower yields without pollinators.

Examples: Garratt *et al.* (2014); Klatt *et al.* (2014).

Suitable to use: As they capture pollination service benefits at a very precise scale, yield analyses are most useful illustrating the benefits of pollination services at local levels. Regional scale benefits can be estimated with this method if a number of sites, covering a diverse range of environmental conditions, are sampled. At larger scales, assessment at a very large number of sites to cover variations in environmental conditions would be required.

2.2.2 Dependence ratios

What it Measures: The market price of additional crop production resulting from pollination services.

Methodology: These studies use dependence ratios, theoretical metrics of the proportion of crop yield lost in the absence of pollination, to estimate the current contribution of pollination to crop production within a region. This proportion of crop production is multiplied by the producer price per tonne (or other unit of production) to estimate the total benefits of pollination services. The expected proportion of yield lost can also be multiplied by yield dependent producer costs (such as labour costs) to estimate producer benefits. Unlike yield analyses, which utilize primary data collected from the field, dependence ratios are based on secondary data such as personal communications with agronomists (e.g., Morse and Calderone, 2000) or from literature on agronomic experiments comparing yields with and without pollination services (e.g., Allsopp *et al.*, 2008), often using the same methods as employed in yield analyses.

Strengths: By estimating the proportion of yield lost, dependence ratio studies theoretically capture the link between pollination services and yield, without the need for further primary data collection (Melathopoulos *et al.*, 2015). Because of the large body of literature available (e.g., Klein *et al.*, 2007), dependence ratio studies are relatively simple to undertake and can be readily applied across a range of crops at any regional, national or international scale (e.g., Lautenbach *et al.*, 2012).

Weaknesses: As with yield analyses (above) dependence ratio studies neglect the impacts of other inputs on crop production potentially biasing estimates upwards. Most dependence ratio studies are based on subjective personal communications which lack an empirical backing (e.g., Morse and Calderone, 2000) or from reviews, particularly Klein *et al.* (2007) and Gallai *et al.* (2009a) which, although a synthesis of available knowledge, bases many of its estimates on a small number of often older studies (see Section 4.5.2.2). Consequently, the metrics are generalized for a whole crop, regardless of variations in benefits between cultivars or the effects that variations in environmental factors or inputs have on the level of benefits (Section 4.5). When applied over large areas where multiple cultivars and environmental conditions are present, this can result in substantial inaccuracies (Melathopoulos *et al.*, 2015). As the dependence ratio metrics typically represent a complete loss of pollination services, they inherently assume either that pollination services within the region are presently at maximum and that the studies they are drawn from compare no pollination to maximum levels, neither of which may be accurate (e.g., Garratt *et al.*, 2014). In most cases, no assessment is made of the marginal benefits of different pollinator populations or consumers and producer's capacity to switch between crops (Hein, 2009).

Data required: Crop yield per hectare, crop market price per unit, measure of insect pollinator dependence ratio (e.g., Klein *et al.*, 2007).

Examples: Leonhardt *et al.* (2013); Lautenbach *et al.* (2012); Brading *et al.* (2009).

Suitable to use: As the dependence ratios used are often rough approximation of pollinator dependence, this method is mostly suited to illustrate the benefits of pollination services to crops larger scales. Due to their inability to distinguish differences in benefits between locations, cultivars and management and their implicit assumption that services are at a maximum level the method is less suitable for making more informed management decisions but can act as an initial estimate.

2.2.3 Production function models

What it Measures: The market price of additional crop production resulting from marginal changes in pollination services in relation to other factors influencing crop production.

Methodology: Production functions measure the role of pollination as part of a broader suite of inputs (e.g., fertilizers, pesticides and labour) and environmental factors (e.g., water) allowing for an estimation benefits relative to other factors (Bateman *et al.*, 2011; Hanley *et al.*, 2015). Production functions can take a number of forms depending on the relationships between the variables involved: e.g., additive functions assume that inputs can perfectly substitute for one another, Cobb-Douglas function assumes that inputs cannot be substituted at all. All of these forms assume that inputs have diminishing marginal returns – i.e., after a certain point and all things being the same, the benefits of additional units of input gets progressively smaller and may eventually become negative. By incorporating the costs of inputs (e.g., the costs of hiring managed pollinators or the opportunity costs of sustaining wild pollinators), it is possible to determine economically optimal combinations of inputs that maximize output relative to cost.

By incorporating the costs of each input, these crop **production functions** can accurately relate pollinator gains and losses to benefits under different management strategies. The resultant effects on output can be incorporated into partial or general equilibrium models (see Section 2.4) of surplus loss. Separate **pollination production functions** can also be developed to estimate the levels of pollination services provided by a pollinator community, depending on the efficiency of the species within the community and any additive, multiplicative or negative effects arising from their activities (e.g., Brittain *et al.*, 2013) and interactions (Greenleaf and Kremen, 2006). The sum of these relationships and the crop and variety specific thresholds of pollen grains required will determine the overall service delivery of the community (Winfree *et al.*, 2011). By focusing on functional groups of pollinators, rather than individual species, these results can also be readily transferred across regions to account for community variation. Finally, **pollinator production functions** can link the production of an output or a pollinator community to resources surrounding the crop (e.g., forest fragments around fields), allowing for accurate estimation of potential service delivery (Ricketts and Lonsdorf, 2013).

To date, only Lonsdorf *et al.* (2009) have developed a production function for pollinators, using expert opinion on habitat suitability for different pollinator groups to estimate the availability of pollinators within the landscape. However, this model does not translate the effects into economic benefits. Ricketts and Lonsdorf (2013) further develop this by linking aspects of surrounding land use with the benefits of pollination services to crops, which, although not explicitly pollinator production functions, can inform the basis of such analysis in the future. Jonsson *et al.* (2014) demonstrate the full applicability of the method by using field data to develop a production function analysis of the benefits of aphid pest control via natural enemies in Swedish barley fields.

Strengths: Production functions for crop yields allow the benefits of pollination services to be accurately estimated from any region with respect to local environmental and agricultural systems, assuming similar levels of pollination service. This avoids issues of over-attributing benefits to pollination services common to yield analysis and dependence ratio studies and captures substitution patterns between inputs (Hanley *et al.*, 2015). In combination, crop and pollination service production functions allow for the most accurate estimation of the marginal benefits of pollination services across most regions where the crop is grown, providing sufficient data on local pollinator communities and agri-environmental conditions are available. Pollinator production functions linking the landscape to pollinator populations also allow estimation of the monetary value of pollinator natural capital (Section 2.6) within a landscape or even at larger scales. By directly linking pollinator populations to services and outputs, multiple production functions can be used to model the marginal effects of pressures (e.g., habitat loss) and mitigations (e.g., habitat recreation) on the economic productivity of a crop and thresholds at which shifts in pollinator communities result in collapses of service provision.

Weaknesses: Production function models are complex to estimate, requiring extensive agronomic and ecological research in order to quantify the impacts of each parameter on a given crop. A wide range of communities have to be assessed to account for the varied impacts of community composition and interactions if the effects estimated are to be transferred beyond the study sites or economic production functions are to be used to identify efficient combinations of pollination and other inputs. Although substitution patterns among inputs and ecosystem services can be modelled, further experimental data would need to be added to identify pollination service thresholds in case minimum levels of services are required for viable output.

Data Requirements: Ecological data on the impact of pollination services on crop quality and quantity relative to other inputs. Data on producer input costs and crop sale prices. Ecological data on the pollination service efficiency of different pollinators (pollen deposited and rate of visitation) relative to landscape parameters and community composition. For extrapolation: local data on pollinator community composition, environmental conditions and agricultural inputs.

Suitable to use: As they draw a strong focus on local pollinator communities, production function models are most suitable when assessing the local scale impacts of pollination services and changes in management but can be generalized for wider use if sufficient ecological data is available.

Examples: None to date but see Ricketts and Lonsdorf (2013).

2.3 Replacement costs

What it Measures: The estimated market price of artificial or supplemental pollination services.

Methodology: Typically, this is the cost of mechanical pollination via a human applicator (Allsopp *et al.*, 2008) but can also be the costs of hiring managed pollinators to replace a known proportion of total services provided by wild pollination services (Winfree *et al.*, 2011). Artificial pollination is often undertaken via hand pollination, using small paintbrushes to apply pollen to flowers, although a variety of mechanical methods have been developed, such as vibration wands to pollinate tomatoes (Pinillos and Cuevas, 2008). This method requires that the replacement method is i) the lowest cost replacement available ii) at least as effective as animal pollination and iii) that producers would be willing to pay these costs rather than simply switching crop (Söderqvist and Soutukorva, 2009).

Strengths: Unlike other methods, the replacement costs method does not overestimate the impacts of pollination services, as the cost estimate is independent of yield benefits (Allsopp *et al.*, 2008). As long as appropriate labour and material capital required is known, the estimated costs per hectare can be transferred to other regions by adjusting the input costs used. Managed pollinators can also foreseeably provide pollination services to many wild plants either deliberately or as an additional side effect of pollinating crops and as such, the price of these insects can be an effective replacement cost for non-market benefits.

Weaknesses: Different replacement techniques may be ineffective for certain crops. For instance, hand pollination is not effective at replacing insect pollination in raspberries (Kempler *et al.*, 2002) and managed pollinators are differently effective on certain crops (Delaplane and Mayer, 2000). Even where methods are effective, their viability may depend heavily upon the local availability and costs of labour. For example, hand pollination, was used on some insect pollinated fruit crops in areas of the Sichuan Province, China, affected by severe pollinator loss until rising wages made this increasingly unviable for producers, resulting in pollinated crops being widely replaced with wind-pollinated species (Partap and Ya, 2012). Therefore, it is doubtful that producers in countries with high wages would adopt these practices at all. While technological advances could produce lower cost alternatives (e.g., Sakomoto *et al.*, 2009), limited information regarding pollination service management makes the market viability of such alternatives difficult to assess. Finally, replacement costs do not reflect the economic value of pollination services, only the market price of the replacement method. Surplus valuation models (Section 2.4.) can estimate the impact of these changing costs on producer and consumer welfare if the replacement is likely to be adopted by most affected growers.

Data required:

- **Minimum:** estimates of material costs and labour requirements, minimum/typical wages.
- **Optimal:** estimates of replacement efficiency relative to original services, indication of levels of producer willingness to pay for replacement.

Examples: Allsopp *et al.* (2008); Winfree *et al.* (2011).

Suitable to use: This method is only suitable for decision-making where the replacement method is both demonstrably effective and likely to be adopted by affected growers (e.g., they have expressed a willingness to pay to adopt it). In the case of pollination services, this is only likely to be replacement of wild pollinators by managed pollinators (e.g., Winfree *et al.*, 2011). Otherwise, as it does not quantify the either benefits or economic value of pollination services, only the potential costs to replace it, this method alone is not suitable for public decision-making.

2.4 Surplus valuation models

While the methods reviewed previously have measured the price of various pollination service benefits to markets, economic welfare valuation methods use statistical models to estimate the impacts of changes in production on the economic welfare of producers and consumers. Welfare valuation methods can be complex and a variety of different econometric models can be used; however, for this assessment, only the methodologies as a whole are discussed. These models can take two forms: partial or general equilibrium. Partial equilibrium models only consider what the impacts of changing supply and demand of a product will have on the market for that product. General equilibrium models however capture the impacts on other markets by considering producers' ability to substitute between inputs and consumers' ability to substitute between products.

What it measures: The economic value of pollination services to a single market (partial equilibrium models) or several interlinked markets (general equilibrium models).

Methodology: Surplus valuation models begin with the estimation of supply and demand curves for a given product using standard economic models. From these, further economic models (e.g., Gordon and Davis, 2003; Gallai *et al.*, 2009a) are used to estimate the effects a shift in supply resulting from a change in pollination services will have on prices and the subsequent impacts upon economic welfare via consumer and producer surplus (see Section 1). As pollination service loss causes crop supply to fall relative to demands, crop prices will rise, reducing consumer welfare and making the remaining produce less competitive, relative to other produce, when sold on wider markets. This price change is quantified by the multiplying proportion of crop production lost by the price elasticity of supply (if supply changes) or demand (if demand changes): a metric of the percentage changes in price in relation to a 1% change in supply or demand, assuming all other factors influencing price remain constant. These elasticity parameters can be approximated based on past studies (Gallai *et al.*, 2009a), estimated using time series statistical analyses (Southwick and Southwick, 1992) or by estimating arc elasticity, an average of the change in production divided by the change in price over a large number of time periods (Winfree *et al.*, 2011).

General Equilibrium models expand this by using more complex models (e.g., Bauer and Wing, 2014) that incorporate additional elasticity parameters that capture (a) producers' ability to substitute between pollination and other marginal inputs (e.g., Marini *et al.*, 2015) and (b) consumers' ability to substitute between different crops and different sources of the same crop (Kevan and Phillips, 2001). Consequently, general equilibrium models capture the impacts of pollinator service losses on both the affected crop market and other related markets. Bauer and Wing (2014) propose a model that includes eight substitution elasticities, including substitution between different inputs and between domestic and imported varieties of each crop. However due to limited data availability, most of these are broad estimates included for exploratory purposes.

Strengths: Unlike the methods reviewed previously, surplus valuation models estimate the true welfare value of pollination services by quantifying how much available income consumers and producers would lose or gain following a drop in pollinated crop availability. If both consumer and producer surplus metrics are modelled, these models allow for relatively accurate estimation of both marginal and total welfare changes in response to total pollinator changes in the crop market (Gallai *et al.*, 2009a). By using multiple elasticity parameters to simultaneously model a broad range of market reactions, General equilibrium models can produce more conservative and realistic estimates of pollination service value within a single crop market, with producers potentially profiting from price rises caused by service losses in other region while consumers always suffer a welfare loss (Bauer and Wing, 2014). By modelling these values in other markets, General equilibrium models can also highlight the wider impacts of service losses and identify vulnerable secondary sectors. If applied to different locations, these models can highlight areas where losses of pollinators would cause the most significant impacts on prices and, by extension, welfare.

Weaknesses: Accurate estimation of crop price elasticity relies on significant volumes of long-term data, which may not be available in a consistent form (Southwick and Southwick, 1992). As the scale of yield losses drives surplus changes, inaccuracies in these estimates (see Section 2.2.) can result in inaccurate estimations of value. While producer surplus estimates are applicable at all scales, consumer surplus is generally more appropriate at larger scales as, imports will often compensate for small scale losses, resulting in little or no price change unless the region is a major global producer of the crop (Kevan and Phillips, 2001).

By not accounting for producer and consumer substitutions, partial equilibrium models may overestimate the impacts of pollination services on a single crop market. To date, due to the complexity of estimating both supply and demand curves simultaneously, most studies using partial equilibrium models have only estimated consumer surplus (but see Gordon and Davis, 2003). This assumes that supply has an infinite elasticity, i.e., that producers can switch freely between crops and make no profit from their productive activities regardless of price (Southwick and Southwick, 1992; Gallai *et al.*, 2009a). In reality, most producers trading in a national or globalized market will try to generate profit (Hein, 2009) and it may be difficult or impossible for producers to switch between high-price perennial crops.

General equilibrium models require extensive ecological analyses and economic analysis from a range of different markets, in order to determine the full range of substitutions involved. This may be very difficult for minor crop markets where degrees of substitutions are unclear or for crops where global production has recently expanded significantly due to expanded market opportunities (such as biodiesel feed crops; Banse *et al.*, 2011). The effects of multiple markets on the modelled elasticities can also make it difficult to identify which variables in the model have a strong effect on the resultant estimates of welfare change (Bauer and Wing, 2014).

Data Required:

- **Minimum:** Crop yield per hectare, crop market price per unit, measures of insect pollinator dependence, estimates of crop price elasticity of demand or elasticity of supply (these can be estimated with long-term data on the total market consumption of the crop and the price per unit of crop over the same time period).
- **Optimal:** Estimates of both crop price elasticity of demand and of supply, estimates of the proportion of total consumption arising from national production (as opposed to imports), final consumer price per unit, price elasticity of demand for end consumers.
- **For GEM only:** Estimates of elasticity of substitution: between local and imported supply of a crop, between the production of crops grown in the same system, between the consumption of crops consumed within the same market and between crop inputs.

Suitable to use: Surplus valuation models are suitable for measuring the benefits of pollination services to consumers only where a sizable portion of a national or international crop market is likely to be affected by a change in regional or national production unless the crop is part of a specialty market with few suitable growing sites. They are suitable to estimate the value of pollination services to producers at all scales. Partial equilibrium models of producer surplus are more widely applicable for highly pollinator-dependent crops with high capital investments and few viable substitutes for the crop itself. Due to their comprehensive assessment of markets, General Equilibrium Models are more suitable for evaluating the impacts of national or international scale policy and scenarios but may be limited by their high data requirements.

Examples: Gordon and Davis (2003); Gallai *et al.* (2009a); Bauer and Wing (2014).

2.5 Stated preferences

Previous methods for assessing the economic benefits of pollination services focus on the benefits of pollination services to markets, a number of methods exist for estimating the value of non-market benefits from ecosystem services (see Section 1). These methods fall into two broad categories: **revealed preferences**, which use existing market data to extrapolate the value of benefits derived from the ecosystem service, and **stated preferences**, which use surveys to elicit respondent willingness to pay for ecosystem goods and services within a hypothetical market. No revealed preference methods are considered suitable for use in valuing pollination services (de Groot *et al.*, 2002). Stated preference techniques however are potentially useful for valuing the existence of pollinators themselves and the non-market benefits that they have marginal influence on. Unlike previous methods however, this does not capture the effect of pollinators on production.

What it Measures: The marginal existence value(s) of pollinator populations and/or non-market benefits of pollination services (e.g., the diversity of pollinator-dependent wildflowers).

Methodology: Stated preference methods are particular survey or experimental based methods that typically use questionnaires to create a hypothetical market for bundles of ecosystem goods or services, which are not traded on existing markets. Respondent preferences for different bundles within these hypothetical markets can then be estimated using discrete choice models (Bateman *et al.*, 2011). Prices are attached to each variable to enable researchers to estimate the economic value of each bundle to different respondents. These prices framed to capture either respondent willingness to pay (WTP) to either gain an increase or avoid a loss in the goods or services or respondent willingness to accept (WTA) payments to allow that a degradation or forego a gain in the good or services.

There are several forms of stated preference methods with the two most widely used being: contingent valuation and choice experiments. Contingent valuation methods offer respondents a complete bundle of goods with an attached price and a zero cost alternative representing a degraded or current state. Choice Experiments follow similar principles, except respondents are given multiple alternatives to the zero cost option. Each alternative has different amounts of the various goods within the bundle. Through repeated observations of such choices, typically across many respondents and using different attached prices, discreet choice modelling methods can estimate the probability of respondents within the sample selecting a given bundle, depending on its price, and a typical respondent WTP or WTA value.

Stated preference techniques can be applied to estimate the existence value of pollinators by eliciting respondent WTP for the maintenance of pollinator populations (e.g., Mwebaze *et al.*, 2010) or marginal changes in wider pollinator abundance or species diversity. Estimates of the impacts of marginal changes in of pollination services to various non-market benefits (e.g., the diversity of aesthetic wildflowers) require a further analytical step, such as dependence ratios (Breeze *et al.*, 2015) or production functions, to estimate the contribution of pollination to these benefits.

Strengths: Stated preference methods can be used to assess the economic value of potentially any non-market benefits arising from pollination services, regardless of the existence of markets for these services. Stated preference surveys can also estimate the WTP/WTA of different groups of respondents based on their demographics (e.g., age, income, proximity to the site of proposed change etc.), allowing a more accurate extrapolation of the values estimated beyond the survey area.

Weaknesses: Like many questionnaire-based methods, stated preference surveys are often particularly costly to undertake due to the substantial pretesting required to present the scenario in an easily understood manner and the large, representative samples required for statistically robust analysis. Responses to stated preference questionnaires can also be affected by number of factors, which may cause respondents to, deliberately or unintentionally, misreport their preferences, biasing estimations of their WTP/WTA. For instance, respondents may ignore the cost of options because the payment is a hypothetical situation, expressing a greater WTP than they actually hold (e.g., Henscher *et al.*, 2010). Respondents may also have difficulty forming preferences for unfamiliar goods such as ecosystem services, resulting in them expressing inconsistent, often extreme preferences (Christie and Gibbons, 2011). Statistical analyses (e.g., Henscher *et al.*, 2010; Christie and Gibbons, 2011) can reduce the impacts of these and numerous other biases but extremely careful question and scenario formulation is required to identify the occurrence of these biases.

Data required: Estimates of respondent willingness to pay for preventing a loss/maintaining existing levels of pollinators/pollination services or estimates of willingness to accept a loss in pollinators/pollination service benefits, ecological estimates of the impact of pollination services on these benefits. Empirical information on the impacts of proposed scenario on pollinator populations or other non-market benefits affected by pollinators is necessary to allow respondents to make informed choices.

Examples: Mwebaze *et al.* (2010), Diffendorfer *et al.* (2014), Breeze *et al.* (2015).

Suitable to use: This method is suitable for assessing the marginal values of either changing pollinator populations or other, non-market ecosystem service benefits. However due to the numerous biases and uncertainties that can occur in respondent preference expression, they should only be undertaken following rigorous testing to ensure that the questionnaire can be answered accurately by respondents and require a large, representative sample of the population affected by proposed changes.

2.6 Measuring Pollinator Natural Capital

2.6.1 Overview

Although monetary valuation methods can provide a useful tool in facilitating decision-making (see Section 6), they are primarily focused on capturing the impacts of change on ecosystem service flows. Another key factor of economic systems are the **capital assets** that underpin economic activity which are generally considered separately from the flows they generate. There are five widely recognised forms of capital: **human capital** (the skills and labour within the market), **social capital** (institutions such as businesses or schools), **manufactured capital** (physical items such as tools, buildings etc.), **financial capital** (credit, equity, etc.) and **natural capital** (natural resources and ecosystem

TABLE **4.2**
Summary of Methods to assess the economic consequences of pollinator gains and losses

	Method	Strengths	Weaknesses
Crop price	Sum market price of insect pollinated crops	- Minimal data requirements	- Does not reflect the benefits of pollination services.
Managed pollinator prices	Sum market price of managed pollinators hired or purchased for pollination services	- Reflects the benefits of pollination in a manner comparable to other inputs - Differences in prices can reflect varying benefits	- Ignores wild pollination services - Many countries have small or no pollination markets - Prices are influenced by market forces more than benefits
Yield analysis	Market price of output of pollinated crops vs. crop without access to pollination services based on field studies	- Directly captures benefits of pollination services - Captures more precise variations in benefit between cultivars - Can capture marginal benefits	- Only appropriate for very local scales - Requires extensive planning to capture all benefits and any pollination deficit. - Does not account for the relative effects of other inputs or ecosystem services - Only estimates producer benefits
Dependence ratios	Total market price of crop output multiplied by a crop-specific dependence ratio (metric of the proportion of yield lost without pollination)	- Captures the varied benefits of pollination across crops - Equally applicable at all scales - Minimal data requirements	- Only estimates producer benefits - Dependence ratios may over generalize between cultivars - Does not account for the relative effects of other inputs or ecosystem services - Assumes services are currently at maximum levels
Production functions	Models of the effects of pollinators and pollination services on total crop output	- Highly accurate estimates of benefits - Can be used to model the effects of pressures on services - Captures the benefits of pollination relative to other inputs and ecosystem services - Can be accurately extrapolated to other locations and scales	- Requires extensive ecological data - Models can be complex - Only estimates producer benefits
Replacement costs	The cost of replacing pollination services technologically or with managed pollinators	- Not linked to crop prices - Applies at all scales - Does not over-attribute benefits to pollination services	- Replacements may not be effective - Assumes producer willingness and ability to pay - Not linked to benefits - Tied to input and labor prices
Partial equilibrium models	Estimates the welfare value of price change on available income to producers and consumers of a single crop market	- Can assess consumer and producer benefits - Captures marginal benefits - Can be used to assess impacts of service loss beyond the focal region	- Very complex to estimate, especially across regions - Does not account for substitution between crops or crop inputs - Subject to the quality of data on pollination benefits - Does not account for the relative effects of other inputs - Assumes services are currently at maximum levels
Generalized equilibrium models	Estimates the welfare value of price changes on producers and consumer both within the crop market and across other, linked markets	- Values benefits to producers and consumers - Captures effects across and within markets - Can be applied at any scale	- Extremely complex - Many substitution effects are not yet defined - Subject to the quality of data on pollination benefits - Assumes services are currently at maximum levels
Stated preferences	Economic survey instruments designed to estimate respondent's welfare from the maintenance or improvement of non-market benefits such as the existence of pollinators.	- Values non-market benefits - Not tied to market prices or factors - Can be used to analyze public opinion	- Difficult to develop in a manner easily understood by respondents, especially if they are unfamiliar with the ecosystem service being valued. - Need to ensure a representative sample and accurate responses - Requires complex modeling to analyze - Expensive to test and implement - Monetary valuation is not always applicable

services) (Nelson *et al.*, 2010), each of which comprises a number of assets. Capital assets represent measurable, quantifiable stocks that can produce various flows of goods and services. Pollinators are generally considered natural (wild pollinators) or manufactured (managed pollinators) capital asset that produce pollination services, a flow. Changes in capital assets fundamentally affect what flows of goods and services are available to an economy and therefore the economic activities available. This subsection reviews the links between pollinators and various capital assets that produce and sustain the economic benefits of pollination services.

2.6.2 Measuring capital

In neoclassical economics, capital assets are often components of accounting frameworks, such as Gross Domestic Product. In recent years, other frameworks have been developed to integrate natural capital assets into these frameworks using "Green GDP" measures (See Chapter 6). The main international standard for Green GDP is the UN's System of National Accounts and its associated System of Environmental Economic Accounts (SEEA) (UN, 2012). These are expressed as the monetary price of all flows arising from each stock of capital assets, including future flows via discounting (see Section 3), using market prices where available but otherwise estimating value through non-market measures (e.g., replacement costs – Edens and Hein, 2013). Typically, neoclassical economics assumes a high degree of substitution between capital assets and aims to preserve and increase the net balance of all capital collectively (van den Bergh, 2001).

Within the SEEA there are a number of challenges affecting the asset valuation of pollination services – foremost, it is important to disambiguate the benefits of pollination relative to other ecosystem service flows produced from the same assets to avoid double counting (Boyd and Banzhaf, 2007). This is particularly important when considering honeybees, which can be used as both a source of honey production and pollination within the same year but will often not because of the low nectar yields of many crops (Rucker *et al.*, 2012). Secondly, the SEEA framework assumes that assets are controlled by an institute and are marketable. Although managed pollinators are an owned asset and patches of habitat can be owned, pollination services are almost always a public asset as access to the animals cannot be restricted (aside from enclosed crops) and their foraging habits are very difficult to control (e.g., Stern *et al.*, 2001). Finally, the SEEA framework also assumes that assets are marketable, which is not true for wild pollination services. These issues can be partially overcome by considering ecosystems not directly controlled by private actors as a separate productive sector within the market that produces its own outputs (Edens and Hein, 2013), although care should still be taken to avoid double counting.

Monetary valuation of assets can be complimented with non-monetary quantifications of the biophysical stocks that underpin ecosystem services to provide a more holistic assessment of the impacts of capital management and support planning for sustainable, long-term management (Dickie *et al.*, 2014). This approach is particularly advantageous because it is not tied, directly or indirectly to market prices and can be used to monitor the status and trends of those assets that are economically valuable to production. Stocks of a multiple assets of a particular capital can also be measured as an index; assessing stocks of assets in a single period relative to the same assets in a reference period (with a default value of one) (Dong *et al.*, 2012; Nelson *et al.*, 2010). To date, no study has expressly included pollinators as an asset in these indexes.

2.6.3 Pollinator assets

A variable number of capital assets are often required to produce pollination services and hive products. For wild pollinators, this can be as simple as having sufficient suitable habitat to support viable populations and available land, inputs and labour to produce pollinator-dependent crops. For managed pollinators, there are additional requirements in terms of human capital to breed and manage the pollinators, manufactured capital to house and transport the pollinators, social capital to maintain the knowledge necessary to breed and use them effectively and natural capital in terms of wild pollinators that form the basis of breeding stock and genetic diversity.

Quantities of available managed pollinator assets are simply the number of available managed pollinators available to a region (e.g., Breeze *et al.*, 2014). Estimating wild pollinator assets can be more complex as their numbers are almost impossible to measure without dedicated, systematic monitoring data (e.g., Lebuhn *et al.*, 2013). Such monitoring is presently only undertaken in an ad hoc manner in a few countries and remains focused on species presence-absence (Carvalheiro *et al.*, 2013). Larger scale analyses models such as InVEST (Lonsdorf *et al.*, 2009) can be used to estimate pollinator populations and pollination service potential based on habitat suitability and proximity to pollinated crops (e.g., Polce *et al.*, 2013; Schulp *et al.*, 2014). Although rigorous, InVEST is only capable of estimating habitat suitability, not populations of pollinators, and assumes that there is a linear relationship between habitat quality and pollinator abundance in fields. A more expansive production function approach (see 2.2.3) linking quantitative metrics of habitat quality from primary ecological research with observed abundances of different pollinators could substantially improve estimates.

Because these assets will only supply services to relatively small areas, methods to assess economic value (Section 2.4) are not generally appropriate, as the impacts on crop price from any individual asset are likely to be small resulting in little to no welfare loss. At a basic level, yield analysis can be used in conjunction with regression analysis to estimate the benefits of pollinator capital from habitats at different distances to the crop (e.g., Olschewski *et al.*, 2006). However, detailed production function models (Section 2.2.3) are ideal as they can produce estimates that more accurately represent the quality of services produced from particular habitat patches (e.g., Ricketts and Lonsdorf, 2013). Furthermore, they can also examine the substitution patterns between pollination and other capital inputs. However, the highly specific nature of these models makes it unlikely that they can be widely employed at present, necessitating a focus on using biophysical units of pollinator capital.

Unlike other measures of pollination value, quantifications of pollinator stocks should account for potential as well as realized pollination services as assets may not always be able to provide services. For example, if arable farmers within the landscape around a source of pollinator capital **(Figure 4.3)** regularly rotate their production between pollinated and non-pollinated crops, the assets will still have value as stocks of pollination even in years where no pollinated crops are grown as they still have the potential to contribute to crop production.

2.6.4 Pollinators influence on other assets

In addition to the flow of pollination service benefits, pollinators can also contribute to the production and maintenance of other capital assets **(Table 4.3)**. Foremost by contributing to the propagation of plants that provide other ecosystem services (Isbell *et al.*, 2011; Ollerton *et al.*, 2011), pollination has a direct influence on the quantity and integrity of a range of other natural capital assets. These plants can in turn affect wider biodiversity (e.g., insect pollinated hawthorn berries which are inedible to humans but which provide winter feed for many birds; Jacobs *et al.*, 2009). By influencing crop productivity, pollination services can also influence the flow of available nutrients within the human diets. This can have an impact on the asset of human health (Nelson *et al.*, 2010) by causing additional disability and death (Smith *et al.*, 2015), which in turn affects the availability of labour within the market. The link between pollinators and human health capital is discussed in terms of disability-adjusted life years below. In many local communities, unique beekeeping knowledge is a form of social capital, helping to support diversified farming incomes and providing a source of honey and other hive products (e.g., Park and Youn, 2012; see Chapter 5 for several case studies of applied indigenous and local beekeeping knowledge). Finally, by affecting profits from the sale of pollinator-dependent crops, pollinators can potentially affect financial assets such as debt or equity among producers

TABLE **4.3**
Summary of methods to assess the economic consequences of pollinator gains and losses

Capital	Asset	Measure	Potential impacts of pollinator gains and losses
Crop price	Managed pollinator stocks	Number of honeybee colonies, bumblebee colonies or absolute numbers of other managed pollinators	Reduced availability of economically valuable pollination services, particularly if wild pollination services are also unavailable (Breeze *et al*., 2014; Southwick and Southwick. 1992)
Managed pollinator prices	Equity and debt	Monetary measures of equity and debt associated with beekeepers and producers of insect pollinated crops.	Impacts on profits can affect available financial capital for future investment and expansion, influencing their welfare over the long term (not yet observed for pollination services but see e.g. Lawes and Kingwell, 2012)
Yield analysis	Wild Pollinators	Estimates of wild pollinator population or likely populations based on suitability using e.g. InVEST models (Lonsdorf *et al*., 2009)	Reduced availability of economically valuable pollination services, particularly if managed pollination services are also unavailable (Garibaldi *et al*., 2013)
	Biodiversity	Area and population of plants affected by pollination.	Reduced levels of pollination can potentially affect plant species diversity (Ollerton *et al*., 2011) and wider biodiversity which relies on pollinated plants (e.g. Jacobs *et al*, 2009)
Dependence ratios	Labor (for providing services)	Available number of beekeepers and other professionals able to provide managed pollination services.	Increasing losses of managed honeybees may push beekeepers out of business if expenses from replacing lost colonies become too severe. This in turn may affect the number of beekeepers available to supply pollination services and produce hive products, even if those that do remain have a large number of colonies each (Potts *et al*., 2010).
	Labor (benefitting from services)	Available labor within the workforce lost through malnutrition associated with a lack of pollinator dependent crops.	Losses of pollination services may cause a decline in the availability of nutrients in the food chain, increasing disease and mortality (Smith *et al*., 2015); in turn potentially affecting the availability of labor within the work force.
Stated preferences	Beekeeping knowledge	Number of local beekeepers with indigenous and local beekeeping knowledge	Pollinator losses may cause a decrease in the number of beekeepers and with this the knowledge and skills required to effectively manage honeybees to provide pollination services and produce hive products (e.g. Park and Yuon, 2012).

(which will always be measured in monetary terms). This effect has not been observed directly due to pollination services but factors such as drought that affect crop yield have been linked with substantial losses of farmer equity (Lawes and Kingwell, 2012).

2.7 Pollinators contribution to nutritional security

As reviewed in Chapter 1, animal pollinated crops are often significant sources of key nutrients in the human diet, such as vitamins A and C, calcium, fluoride and lycopene (Eilers *et al.*, 2011). Globally, a total loss of insect pollinators would potentially cause sharp increases in the number of people suffering from vitamin A (41M-262M) and Folate (134M-225M) deficiency, particularly in Africa and the Eastern Mediterranean (Smith *et al.*, 2015). This could potentially result in up to 1.38M-1.48M deaths from malnutrition and communicable diseases and a further 25.8M-29.1M lost disability adjusted life years (a metric measuring years of healthy, non-disabled life lost) from factors such as heart disease and strokes due to limited dietary intake of fruits and vegetables (Smith *et al.*, 2015). Although trade and supplements could compensate for these losses at a national level, many low-income regions of the developing world with high levels of vitamin A deficiency, such as southern Africa and Southeast Asia, are strongly reliant upon animal pollinated crops to provide these nutrients (Chaplin-Kramer *et al.*, 2014). For example, based on information from food diaries, loss of pollination services in Uganda would cause an estimated 54% increase in the rate of vitamin A deficiency in rural parts of the country (Ellis *et al.*, 2015).

2.8 Valuing pollination services in barter economies

In many less-developed countries, portions of the population do not trade goods for money but for other goods and services, limiting the relevance of monetary valuation (Christie *et al.*, 2012). This can be overcome by using the various production function (2.2.2) or stated preference (2.2.5) methods described above, but expressing the benefits in terms of equivalent goods or time allocation within the market rather than monetary terms (e.g., Rowcroft *et al.*, 2006). To date, no study has examined the value of pollination services to these barter economies, despite some studies valuing pollination services in many areas where such markets exist (Partap *et al.*, 2012; Kasina *et al.*, 2009).

SECTION 3. VALUATION ACROSS TEMPORAL AND SPATIAL SCALES

3.1 The importance of scale for pollination valuation

Ecosystem services, such as those resulting from pollination, are essentially the consequences of ecological processes that depend on a combination of small structures (e.g., a flower or a leaf that can live from hours to months; Kremen *et al.*, 2007) and large arrangements (e.g., community assemblage and landscape complexity emerging along decades or centuries; Liss *et al.*, 2013). Indeed, there are hierarchical scales in Ecology that remain independent of human decisions, despite ecologists' efforts to define and delimit scale categories (**Table 4.4**; spatial scale). Institutional scales, on the other hand, are products of human social organization. For this reason, the scales of ecological processes that affect pollination effectiveness (and thus fruit set and crop yield; see Chapter 3) and those of social and economic processes (involved in decisions and management) are seldom compatible (MEA, 2005; Vermaat *et al.*, 2005; Hein *et al.*, 2006; Satake *et al.*, 2008; Abildtrup *et al.*, 2013). Studies into pollination valuation should incorporate elements from both ecological and institutional processes (e.g., the geographic distribution of pollinator species and national subsidies for crops), with proper scale categories that allow the collection and analysis of the data necessary to quantify the economic benefits of pollination services.

The Millennium Ecosystem Assessment (MEA, 2005) recommends that assessments of ecosystem services should be conducted at multiple temporal and spatial scales. However, delimiting scale categories to value pollination (as for any other ecosystem service) is complicated because some terms are often vague and used arbitrarily and in a relative way (i.e., linguistic uncertainty, see **Table 6.6.1** of the Chapter 6). Studies on pollination should define what constitutes their specific spatial or temporal scale of interest (Kremen *et al.*, 2007; Hein, 2009; Genersch *et al.*, 2010; Bartomeus *et al.*, 2011; Kennedy *et al.*, 2013), for example, it is likely that a regional economic process in Costa Rica does not have the same geographic extension as in Brazil. In addition, the definition of scale is frequently influenced by political issues, such as municipal, provincial or national boundaries, or transitory policies from successive governments with contrasting ideological positions. As such, multi- and cross-scale approaches are necessary to account for all the factors involved in pollination valuation.

Here, we adopt the MEA's definition of scale: the extent or duration of observation, analysis, or process. According to Limburg *et al.* (2002) and to the MEA (2005), the scales of economic systems are determined by the area and time horizon over which goods and services are traded, extracted, transported or disposed of. The temporal and spatial scales (the scale "domain") of analyses can affect valuation of ecosystem services, including pollination (MEA, 2005), because the nature of the economic value generated by pollinators (see Section 2.4) varies with the physical dimensions (space and time). For example, according to Hein (2009), in a small spatial scale (i.e., local) pollination supports farmer income, whereas in a large spatial scale (i.e., national) it is fundamental to ensure food supply. Thus, the institutions involved in decision-making that affect land management and markets change across scales; at a local scale, decisions such as type of crop and pesticide use can be made by an association of farmers, whereas national scale decisions (e.g., pesticide regulations) are usually taken by government agencies and financial organizations.

Scale mismatches in pollination valuation can occur in three basic ways: Firstly, the scales of ecological, social and economic processes that affect crop yield and production costs often differ. Secondly, the scale of the provision of the pollination service (i.e., local, see definition in **Table 4.4**) is different from the scale of decision-making by farmers (i.e., farm) and agencies involved in land and economic policies

TABLE **4.4**
The matches and mismatches between ecological and institutional (economic) spatial scales (Modified from Hein *et al.* 2006, originally adapted from Leemans 2000). We adopted a particular scale for pollination valuation, and its compatibility with ecological and institutional scales varies across categories.

Ecological scale (km²)	Institutional scale	Match	Pollination valuation scale	Compatibility
Global (> 50,000,000)	International	Yes	Global	Both
Biogeographic region (1,000,000-50,000,000)	Continental/ International	No. Lack of consensus on boundaries of biogeographic regions[1] and continents. A given continent can contain more than one region and vice-versa.	Continental	Institutional
Biome (10,000 – 1,000.000)	National	No. Biomes frequently are much bigger or smaller than the country's area	National	Institutional
Landscape (10,000 – 1,000.000)	State/Provincial	No. Lack of consensus on landscape boundaries. Catchment area is frequently used[2] and is sometimes much smaller than state/ province area	Regional	None
Ecosystem (1 – 10,000)	County/Municipal	No. Lack of consensus on terrestrial ecosystem boundaries. Usually smaller than county/municipality area	Farm/local	None
Plot (< 1)	Family	Yes	Field	Both
Plant	Individual	Yes	Not used	---

[1]See Udvardy 1975, Cox 2001, Holt *et al*. (2013).
[2]See Vermaat *et al*. (2006).

TABLE **4.5**
Definition of temporal and spatial scales proposed for pollination service valuation

Temporal scales:	
Seasonal:	changes observed within one year, from periods of weeks to months, according to climate changes, pollinator phenology, the specific timing of crop production, fiscal calendar and economic events;
Annual:	changes along consecutive years, analyzed with classical economic indicators that are obtained every year via institutional census and databases;
Decadal:	changes compared every ten years, using classical economic indicators, reflecting recent past and future trends that are influenced by biodiversity decline, climatic variations and economic and political crises;
Century:	changes observed or projected for more than 100 years, reflecting long-term, slow processes such as climate change and massive biodiversity loss via local or global extinctions.
Spatial scales:	
Field:	a sub-division of a farm for which data on pollinator dependency (plant's pollinator threshold, fraction of flowers pollinated by each pollinator species) are compiled;
Farm:	one productive unit composed of several fields for which data on yield and production costs are compiled;
Regional:	aggregation of farms within a well-defined region;
National:	area defined by a country's boundaries for political reasons, where the government collects data from farms in regular basis;
Continental:	area defined by continents (large land masses) that contain several countries, delimited by convention or political reasons;
Global:	the geographic realm includes many countries from different continents worldwide.

management (i.e., national; Satake *et al.*, 2008). Finally, the chosen scale for valuation is different from the characteristic scale of the processes that affect pollination effectiveness and product prices (a methodological problem; MEA, 2005). Scale mismatches can affect the accuracy of valuation estimates and, more crucially, the distribution of benefits from management actions.

Thus, it is crucial to delimit clear scale categories for pollination valuation. Many approaches were proposed for ecological processes and ecosystem services in general (Turner, 1988; MEA, 2005; Vermaat *et al.*, 2005; Hein *et al.*, 2006; Feld *et al.*, 2009; Díaz *et al.*, 2011; Serna-Chavez *et al.*, 2014), but no standard categorization of scales has been proposed for pollination valuation so far. It makes sense to work with scale categories that represent the extension (spatial scale) and duration (temporal scale) of processes for which the necessary data for valuation can be collected or compiled. Variables such as crop yield and price are frequently aggregated in government censuses by farm, county, politically defined sub-state or sub-national regions, provinces/states and countries, and conducted monthly or annually. The proposed scale categories for the present assessment are defined in **Table 4.5**.

3.2 Pollinator valuation across the temporal scale

3.2.1 Rationale

The temporal scale has important strategic implications that can vary between stakeholders. For example, farmers are often more interested in longer term average yields (over several years) than short-term (1 year) maximization of yield, thus considering longer time scales is essential when linking valuation to decision-making. Another example is related to the farmer decision-making in crop choice: farmers can easily switch between different annual species; however, due to the time lag between planting and productivity, switching from annual to perennial species or between perennial crops involves a major long-term commitment. Farmers' ability to switch between crops depends also on the level of investments needed by the managing choices (e.g., irrigation costs limit the ability to switch to another crop). Thus, the temporal scale is important to consider because the meaning of the economic valuation is fundamentally scale-dependent as well as the political implications of management decisions. In indigenous beekeeping, while the majority of beekeepers take a short-term view to exploiting their seemingly abundant resources, some innovative groups and networks of local entrepreneurs have secure long-term products, processes and market sustainability laying the foundations for sustainable livelihoods and conservation (Ingram *et al.*, 2011). In the next sub-section, we present the factors that need to be taken into account when considering the different temporal scales.

3.2.2 Temporal factors affecting pollination valuation

3.2.2.1 Price dynamics

Many economic valuation studies estimate pollinators' contribution to crop production (see Section 7). In several methods used for evaluating pollination benefits, two main variables are used: the crop price (Section 2.2 and 2.4.) and the price of beehives (Section 2.1.2 and 2.3.).

The variability of the crop price across time is driven by variation in both demand and supply of the crop. However, these two components of the agricultural market are prone to change at different intervals, some crops will change every few years while others will change several times a year, due to many factors (Drummond and Goodwin, 2014). Factors influencing demands include the price of substitute goods of pollinated crops, price of complementary goods, the consumers' income, the consumer's tastes and preferences for different crop (dependent or not on pollinators), the expectations of a pollinator decline and the demography of consumer population. Factors influencing the supply include the price of inputs, the price at a preceding period, the substitutes and their characteristics (e.g., their prices), the technology, the taxes and subsidies, the expectation about future events and the number of businesses. The complexity arising from the interaction of all these factors highlights the difficulties of predicting future crop market prices, affecting longer-term valuation estimates.

The price of hiring beehives for pollination is similarly determined through equilibrium between supply of beehive from beekeepers and the demand from farmers. Professional beekeeper[2] will also aim to maximize their benefits. However, this benefit depends on the two main goods or services that this activity contributes to produce: pollination service and honey. Thus, Rucker *et al.* (2012) and Muth *et al.* (2003) demonstrated the competition between pollination service and honey market; when the price of honey was high, beekeepers preferred to produce more honey and abandoned the pollination service. The consequences for the crops market are measurable, because the decrease of the supply of pollination service has a negative impact on the yield of crops and, consequently, the price of crops will increase. Therefore, the evolution of the beehive price is also highly dependent on other markets, making predictions similarly difficult.

2. Hobby beekeepers are not considered in detail here because of the limited available literature on the subject.

It is noteworthy, that the pollination service market by bees or bumblebees seems very well developed in North America (Bond *et al.* 2014, Rucker *et al.* 2012, Burgett 2011, Sumner and Boriss 2006). However, there are very few studies analyzing this market all over the world. Breeze *et al.* (2011, 2014) and Aizen and Harder (2009) analyse the potential availability of honeybees in the UK, Europe and across the world respectively, in comparing the supply and the demand for beehives. These studies demonstrate the potential for expanded pollination service markets around the world but there is no proof of the existence of such well-developed market as in North America.

Because the markets are mutually influenced, policy interventions on one market will have consequences on the other. This is highlighted by Muth *et al.* (2003) who demonstrate that subsidies paid by the US government to beekeepers to protect them from competition with cheaper Chinese honey resulted in increased crop prices and decreased social welfare due to a loss of consumer surplus from US crop consumers.

3.2.2.2 Production effect

Economic valuation should consider the time period over which the effects of an action occur because variations in pollinator availability will change over different temporal scales as populations become more or less resilient (see Section 4). For example, when considering the seasonal scale, valuation focuses on the impact of pollinators' gain or loss on the price of the pollinator service before and after the pollination period for the beekeepers (Rucker *et al.* 2012). The annual scale would take into account of i) the adaptation cost of beekeepers, (e.g., buying new beehives or losses in honey production – Muth *et al.* 2003); ii) the farmer gains or losses due to pollination in agricultural production (Winfree *et al.* 2011); and iii) national indicators of annual contribution of pollinators to crop production (e.g. Gallai *et al.* 2009). The decadal scale is a way to incorporate the impact of the preceding year on the result of actual year, for example how the previous year's prices affect the production of annual crops in the focal year. Economic valuation should measure not only the impact of yearly pollinator variation but also the evolution of this impact (see examples in Lautenbach *et al.*, 2012; Breeze *et al.*, 2014 and Leonhardt *et al.*, 2013). At a longer scale (i.e., century), economic valuation can be used to measure the sustainability of the relation between pollinators and our society. This involves both the role of bees in agricultural production and their importance on the wild nature. Within this scale, there are likely to be immense long-term fluxes in policy and agricultural technology, for example the massive shift to high intensity agriculture in post-WW2 Europe into the common agricultural policy.

3.2.2.3 Discount rate

The temporal scale has some implications on the approach used for the valuation in the case of a cost-benefit analysis (CBA). As expressed in Sections 1 and 6, CBA compared the flows of future private benefits to future social costs of doing a project. The rule of decision is that when the net present value (NPV) is positive, the action is more likely to be implemented. The procedure used for the actualization of future values to present time and conditions is called discounting.

A long debate exists around the value of the discount rate and, more precisely, on the discount of future "utility" or "welfare". It is defined by Nordhaus (2007) as: *(the) measures (of) the relative importance in societal decisions of the welfare of future generations relative to that of the current generation.* It includes also the valuation of the present generation for the benefits she will receive in their future. A discount rate of zero would mean that the value gives to future benefit of using pollination service are identical than the present one. A positive discount rate means that people give more value to consumption by their own generation compared to the future one while a negative discount rate indicates a focus more on the value for future generations.

The value of this rate has a significant importance to the interpretation of the NPV because, in the rare instances when it is negative, the weight attached to the welfare of individuals increases with time. However, discount rates are more commonly positive (Nordhaus, 2007, Chapter 7 of the TEEB, 2010). However, as mentioned by Neumayer (2007), the focus on discounting rates misses the whole issue that future degradation may result in the permanent loss of natural capital. Indeed, Nordhaus (2007) suggests that human welfare still expands under positive discount rates but does not expand optimally and may be unfair or unsustainable. With respect to pollinators, this may suggest that lower discount rate that reflect the importance of pollinator conservation for future generations may have negative impacts if they result in high levels of extinction or if pollinator abundance and diversity losses would happen in a long time. Consequently, the value given to this loss and the consequences of such loss to the future generation may be too low to affect the behaviour of the present generation. According to Neumayer (2007), in such cases it may be better to argue on the grounds of preserving natural capital before irreversible loss takes place. This argument was adapted to the specific case of pollination by Olschewski and Klein (2011). Another solution would be to use a discount rate that falls with time (Weitzman, 1993). However, evidence to argue that present generations have a strong or weak interest in preserving the future benefits of pollination service is needed to develop such revised or scaling discount rates.

3.2.2.4 Availability of long-term data sets

Good estimates of pollination value to consumer and producer welfare depend on the availability of several biological and economic data (see Section 2.4.). These databases are seldom consistent for long periods. There is also a strong interaction between temporal and spatial scales at this case, with better temporal resolution (i.e., data collected at shorter time intervals) at medium scales (national). Geographic bias is strong, with great variation in the availability of long-term national and sub-national data between countries (Lautenbach *et al.*, 2012). At the global and national scales, most estimates used crop production, cultivated area, prices and beehive number, among others, provided by the Food and Agriculture Organization (FAO) of the United Nations over the last five decades (e.g., FAOSTAT, 2007; http://www.fao.org). For some variables, data is not available for all consecutive years for all countries, demanding statistical procedures to estimate values for specific periods (Leonhardt *et al.*, 2013) or assuming that introduced biases are consistent in time and space (Lautenbach *et al.*, 2012). At the sub-national level (i.e., within-country variations), the level of detail on data collection and availability in FAO databases differs substantially among countries. For example, the USA provides spatially structured data on yield whereas Germany reports yield data in highly aggregated formats (Lautenbach *et al.*, 2012). In addition, FAO data on production prices are subdivided in two datasets, from 1966 to 1990 and from 1991-2009, which are not directly comparable (Leonhardt *et al.*, 2013).

Long-term biological data is also difficult to obtain, since it involves many different species of pollinators and variables that are prone to temporal and spatial variations. Usually, variables such as the amount of pollen deposited by each pollinator species and the fraction of flowers each of them fully pollinate are quantified without temporal replicates. In a recent review, Melathopoulos *et al.* (2015) indicated the high level of uncertainty about the pollination dependency coefficients for the 10 crops with the highest aggregate benefits of pollination services. Such biological data are not available in public databases aggregating multiple countries or regions but are usually scattered on published documents regarding each specific crop at local scale (see Bommarco *et al.*, 2012). In a recent review, Vanbergen *et al.* (2012) presented a list of major gaps in knowledge and research priorities to demonstrate how pollination functions differ across species and crops. Many of their recommendations include obtaining temporally replicated biological data that are important for valuation, with systematic monitoring of pollinator diversity, abundance and efficiency. This is especially necessary for those crop types with very limited knowledge and high economic importance. A summary of the most important data limitations and needs for valuing pollination services at different scales is given in **Table 4.6** (see also: Sections 2 and 5.3).

3.2.3 Tools

3.2.3.1 Time series analysis

The term "time series" is generally used to refer to a non-random temporal sequence of values of a variable, ordered at successive and regular time intervals (Tsay, 2002; Montgomery *et al.*, 2008). Time series analysis implies that

TABLE **4.6**
Main data needs for more precise economic valuation of pollination services across scales

	Excludable	Non excludable
Local/national	Non-market or non-monetary food consumption	- Production for own consumption or direct trade for goods and services; - Harvesting of wild fruits and honey
Local/national	Production and consumption in the secondary market	- Quantity and sale prices on the secondary markets
Local/national	Price responses to changes in supply of particular crops	- Information on consumer preferences; - Crop substitution elasticities.
Local/national	Management of pollinators	- Number of beekeepers and beehives for own production and rental; - Type and extension of crops that use managed pollinators
Local/national	Seasonal variations in production and prices	- Intra-annual data on production and prices
National/global	Standardized databases (National- among regions/ states/provinces; Global – among countries)	- Standard procedures for data collection (i.e., minimum crop area considered for inclusion, area/volume units, cultivars)
National/global	Distortion in market prices due to taxes or subsidies	- Official information on subsidies and taxes
Local/national/global	Precise estimation of pollinator dependency is not available for several crops	- Pollination biology for different crops and cultivars replicated through time and space
Local/national/global	Decrease in agricultural value in the case of pollination failure	- Frequency of different types of decisions of farmers and consumers responding to changes in supply
Local/national/global	Pollination impacts on fruit quality	- Quantification pollination effects on fruit visual appearance, palatability or nutritional composition

data points taken over time may have an internal structure (such as seasonal variation) that should be considered (Montgomery *et al.*, 2008). Thus, this approach is well suited for valuing pollination services across temporal scales, because several factors influencing pollination benefits can be addressed and forecasted. This would include ecological aspects, such as plant and pollinator phenological patterns and future trends, pollinator abundance and diversity changes, and economic variable, such as yield, production costs and prices.

There are several different types of time series analyses and models (see Tsay, 2002; Montgomery *et al.*, 2008 for a full compendium), but most studies regarding pollination services usually adopt regression methods **(Table 4.7)**. More complex time series analyses, such as stochastic simulations and complex forecasting models constitute a powerful tool to determine the impacts of pollinator loss under different land use scenarios (Keitt, 2009) but no studies have yet applied these techniques to pollination services (Section 7). Forecasting methods are frequently used in econometrics, finance and meteorology, but their use in ecological analyses is increasing (Clark *et al.*, 2001). Availability of new data sets and the development of sophisticated computation and statistical methods, such as hierarchical models (Clark *et al.*, 2001), offer new venues to work together with decision-makers to use forecasting techniques in pollination service assessments.

3.2.3.2 Scenarios

A way of understanding the future is to create scenarios of possible futures. The aim of scenarios is not to predict the future evolution of our society but to discuss the impact of pollinators under different possible futures of our society (MEA, 2005). More precisely, a scenario is a storyline that describes the evolution of the world from now to a possible situation (Garry *et al.*, 2003). Scenarios are constructed to provide insight into drivers of change, reveal the implications of current trajectories, and illuminate options for action. They should compare at least two possible futures. Scenario analysis typically takes two forms: quantitative modelling (mathematical simulation models or dynamic program models) and qualitative narrating (deliberative approaches used to explore possible futures and describe how society could be situated in these futures – MEA, 2005). Qualitative deliberation can be undertaken between experts, consultants, researchers and stakeholders.

More recent scenarios often combine the qualitative and quantitative approaches; e.g., the SRES scenarios (Special Report: Emissions Scenarios; Nakicenovic *et al.* 2000), MEA scenarios (MEA, 2005) or ALARM scenarios (Assessing Large scale risks for biodiversity with tested methods; Spangenberg *et al.* 2012, Settele *et al.* 2012) at the global scale. Similarly, the UK NEA scenarios (Haines-Young *et al.* 2014) use this approach at the national scale. The SRES scenarios project the future evolution of greenhouse gases following the evolution of several driving forces, such as demographic change, social and economic development, and the rate and direction of technological change. However, these scenarios do not take into account the interaction between ecosystem services and our human society. These issues were introduced by the MEA and ALARM project.

The MEA defines four scenarios: Global Orchestration, Order from Strength, Adapting Mosaic and Techno garden (MEA, 2005). In the Techno garden and Adapting Mosaic scenarios, ecosystem services are recognized as important for society and need to be maintain and developed, whereas in the Global Orchestration and Order from Strength scenarios, they are replaced when it is possible or made robust enough to be self-maintained. Pollination services were explicitly addressed within these scenarios: Global Orchestration, Order from Strength and Techno garden projected a loss of pollination services because of species losses, use of biocides, climate change, pollinator diseases and landscape fragmentation. In the Adapting Mosaic scenario, pollination services remain stable due to regional ecosystem management programs.

However, these scenario options do not consider the economic value of these changes. By contrast, Gallai *et al.* (2009b) utilised existing estimates to project these values in the ALARM scenarios. Three scenarios are defined by the ALARM project (a Europe wide project on biodiversity): BAMBU, GRAS and SEDG. BAMBU (Business As Might Be Usual) refers to the expected continuation of the current land use practices. The GRAS (GRowth Applied Strategy) scenario is a kind of liberal scenario where the borders between countries are considered open to free market and the weight of restrictive policies is lower than BAMBU scenario. The SEDG (Sustainable European Development Goal) scenario focuses on the reduction of greenhouse gases and, more generally, on climate change. Using the land use change within each scenario, Gallai *et al.* (2009b) evaluated the changes in the economic value of insect pollinators to the Spanish and German agricultural sectors in 2020. They demonstrated that the economic contribution of insect pollinators would increase in Germany within GRAS and BAMBU scenarios, while it would remain the same within the SEDG scenario. On the other hand, the economic value would decrease in all scenarios in Spain.

The scenarios presented above are general (national or global scales) and difficult to apply to a specific region. Another study (Priess *et al.*, 2007) used basic regression models combined with metrics derived from field data to analyse the impact of deforestation on pollination services (in terms of revenue per hectare of coffee) in north-eastern border of the Lore Lindu National Park (Indonesia). This study used four scenarios of twenty years each (from 2001 to 2021): business as might be usual (BaU), agricultural progress (AgPro), high migration (HiMig) and forest encroachment (ForEnc). Their analysis indicated that producers in the region would experience losses of between 0.3% (AgPro) and 13.8% (ForEnc) of their total revenue over a 20-year period.

These general scenarios have difficulties in quantifying the changes in both wild and managed bees across a range of possible futures and evaluating the economic consequences. The InVEST model is an interesting tool that could be integrated to the scenarios (Sharp *et al.* 2014). The model is based on a land use and land cover (LULC) map of natural and managed lands. Crossing different ecological and agronomic variables and land management strategies, the model predicts the evolution of wild and managed bees from a local to national level.

In brief, scenarios are a tool that aim to help guide the stakeholders for decision making in giving them the possible future state of the abundance and diversity of pollinators and the benefits of their services. However, they do not provide information on the actions to take, the instrument to use or other that stakeholder should entertain in order to undergo in one specific scenario that seems better than the others do.

3.3 Pollination valuation across spatial scales

3.3.1 Rationale

Economic analysis proposes three frameworks of analysis: **macroeconomics**, **microeconomics** and **mesoeconomics**. Macroeconomics is the study of the entire economy including employment, inflation, international trade, and monetary issues. It may be used to value pollinators at the national and global scales. Microeconomics deals with the economic behaviour of individuals, either producers or consumers. It may be used to value pollinators at the field, farm, and regional scales. Mesoeconomics is an intermediary point of view between micro and macro level – defined as the sum of utility of agents and firms at a local and regional level.

The distinction between microeconomics, mesoeconomics and macroeconomics is important to clarify because the analysis would change radically. Indeed, the valuation at the field, farm or even regional scale would consider two types of impacts from pollination services on crop supply: the marginal impact of these pollinators into crop production (ideally using a production function model – Section 2.2.3.) and the consequences for the marginal cost of the farmer (e.g. Winfree *et al.*, 2011). The effect of a marginal change in pollinator populations can be directly observed in the crop market, however unless a region is a major producer of a crop, the impact is likely to be small (Section 2.4.). These analyses are limited to the crop market, whereas sometimes the stakeholder would need a more complex analysis, which considers national or global scale analyses, (i.e., macroeconomics).

At a national scale, economic analysis can consider the interaction of different markets through a multimarket analysis or a general equilibrium model (e.g., Bauer and Wing, 2014 – see Section 2.4.). These allow modelling of the impacts of pollinator loss on other sectors that do not depend on pollinators in the analysis, i.e., the ability to substitute pollinators (Bauer and Wing, 2010). Thus, the spatial scale is important to consider because the type of economic approach fundamentally depends on it. In the next subsections, we present the factors that need to be taken into account when considering the different spatial scales.

3.3.2 Spatial factors affecting pollination valuation

3.3.2.1 Loss of data quality at large scales

A frequent shortcoming of spatial analyses is that the resolution (i.e., the interval between observations) (MEA 2005) of the data decreases as the scale increases (Turner *et al.*, 1989). One of the causes of such loss is the fractal nature of spatial information (Vermaat *et al.*, 2005), which increases the length of borderlines when they are mapped at finer scales (Costanza and Maxwell, 1994). The same occurs for the area of a given valuable natural habitat (Vermaat *et al.*, 2005). For example, Konurska *et al.* (2002) used satellite data with different spatial resolutions (NOAA-1 km and Landsat-30m), finding that the aggregated value of ecosystem services for the entire USA increased approximately three times with increasing resolution. Thus, the same problem may occur for valuation of pollination across scales using Geographic Information System (GIS) procedures.

GIS use involves obtaining and processing satellite imagery, which can be expensive and time-consuming at large scales, although these limitations are decreasing as Earth Observation data becomes more widely available. Frequently, it is impossible to distinguish very similar land cover categories using GIS, for example while most satellite images can be detecting cropland areas, they are not suited to determine crop type (Monfreda *et al.*, 2008; see Schulp and Alkemade, 2011 for a review on the limitations of global land cover maps to assess pollination services). In this case, ground-truth validation is necessary, involving fieldwork to determine land cover, which can be logistically impeditive at national and global scales. Finally, the spatially explicit information available for valuation is usually obtained from censuses and aggregated at municipality, state or national levels by national bureaus of statistics, a procedure that *per se* causes some loss of information (Vermaat *et al.*, 2005). Furthermore, increasing the spatial scale means using data collected by different researchers or agencies using distinct protocols, which frequently are not directly comparable (Lautenbach *et al.*, 2012, Leonhardt *et al.*, 2013). By contrast, GIS data are gathered by pixel or cell. Inserting such reported administrative data (crop type, production area, yields) into mapped units frequently involves several calculation steps and many assumptions (Monfreda *et al.*, 2008) that may decrease estimate accuracy at large scales.

Some studies used GIS to calculate pollination service value at the local (including landscape) scale (Lonsdorf *et al.*, 2009, Ricketts and Lonsdorf, 2013), but the most comprehensive attempt to map pollination benefits at the global scale was conducted by Lautenbach *et al.* (2012). These authors used the geographic distribution of crop areas and crop yields made by Monfreda *et al.* (2008) with latitude-longitude grid cells of 5 minutes x 5 minutes made possible by the use of the use of satellite. Despite the fine resolution (approximately 10 km x 10 km at the equator), this approach has some limitations, because the distribution of yield statistics into raster cells (i.e., a grid containing values that represent information) eliminates some crops for such cells (Lautenbach *et al.*, 2012). Thus, accurate estimates of pollination benefits at national and global scales can be strongly influenced by evolving low-cost satellite technology to distinguish different crop types, and countries' adoption of standardized frameworks to collect crop data (e.g., Vaissière *et al.*, 2011; Ne'eman *et al.*, 2010).

An alternative to the lack of detailed data for pollination valuation at larger scales is the use of benefit or value transfer-based mapping (Troy and Wilson, 2006; Eigenbrod *et al.*, 2010). This procedure consists of determining the value of the pollination service for a given crop type at a local scale, and using this as a proxy to estimate the value of the same crop type at other locations or at the regional or national scale. However, this procedure has several limitations related to the lack of correspondence between locations (Troy and Wilson, 2006; Plummer, 2009; Eigenbrod *et al.*, 2010), leading to generalization errors that can only be overcome with improved spatial data and increasing the number of local replicates used for calculating the value of pollination services. A review of spatially explicit tools for pollination service valuation is available in Chapter 6 (see also a summary in **Table 4.7**), and details on geographic differences on pollinator availability, efficiency and dependency are given in Chapter 3.

3.3.2.2 Landscape design

The general effects of landscape design (spatial heterogeneity, connectivity, isolation, and proportion of natural habitats) on pollination by managed and wild species are addressed in Chapters 2, 3 and 6. Several studies have demonstrated positive effects of the pollinator habitats maintenance on agricultural yield (Ricketts *et al.*, 2008; Garibaldi *et al.*, 2011; Ferreira *et al.*, 2013; Kennedy *et al.*, 2013). However, sparing natural vegetation in a given farm incurs an opportunity cost from not using that area for crop production or other

TABLE **4.7**
Summary of factors that affect valuation methods across scales and the tools to apprehend such effects.

	Factors affecting valuation across scales	Tools to apprehend scale effects	Examples
Temporal scale Rationale: different demands across institutional levels (e.g., farmers x government)	- Price dynamics - Production effect - Discount rate - Availability of long term data sets	- Time series analysis	- Regression methods[1] - Stochastic simulations[2] - Forecasting models[3]
		- Scenarios	- SRES[4] - MEA[5] - ALARM[6] - UK NEA[7]
Spatial scale Rationale: micro vs. macroeconomics valuation	- Loss of data quality at large scales - Landscape design	- GIS techniques	- Maps[8] - Landscape metrics (fragmentation, connectivity)[9] - Polyscape[10]
		- Spatially-explicit frameworks	- InVEST[11] - ARIES[12] - Envision[13] - Markovian models[14] - Niche modeling[15]

References

[1] Gordo and Sanz, 2006; Aizen *et al.*, 2008; 2009; Aizen and Harder, 2009; Lautenbach *et al.*, 2012; Bartomeus *et al.*, 2013; Leonhardt *et al.*, 2013; **[2]** Keitt, 2009; **[3]** Clark *et al.*, 2001; **[4]** Nakicenovic *et al.*, 2000; **[5]** MEA, 2005; **[6]** Spangenberg, 2007 ; Gallai *et al.*, 2009b; Spangenberg *et al.*, 2012; Settele *et al.*, 2012; **[7]** Haines-Young *et al.*, 2014; **[8]** Schulp and Alkemade, 2011; Lonsdorf *et al.*, 2009; Lautenbach *et al.*, 2012; Kennedy *et al.*, 2013; Ricketts and Lonsdorf, 2013; **[9]** Ricketts *et al.*, 2004; Garibaldi *et al.*, 2011; Ferreira *et al.*, 2013; Kennedy *et al.*, 2013; **[10]** Jackson *et al.*, 2013; **[11]** Lonsdorf *et al.*, 2009; Nelson *et al.*, 2009; Tallis *et al.*, 2011; Ricketts and Lonsdorf, 2013; Zulian *et al.*, 2013; **[12]** Bagstad *et al.*, 2011; Jackson *et al.*, 2013; **[13]** Bolte *et al.*, 2007; Hulse *et al.*, 2008; **[14]** Satake *et al.*, 2008; **[15]** Settele *et al.*, 2008; Giannini *et al.*, 2013; Polce *et al.*, 2014.

economic activities. Thus, management decisions regarding land use can be greatly improved by cost-benefit analyses of trade-offs between different ecosystem services (Farber *et al.*, 2006; Nelson *et al.*, 2009; de Groot *et al.*, 2010). Most information on trade-offs between economic gains from forest conversion and pollination services comes from case studies on coffee production, usually at the local and regional scale (Priess *et al.*, 2007; Ricketts *et al.*, 2008; Olschewski *et al.*, 2006; Olschewski and Klein, 2011). For example, Olschewski *et al.* (2006) compared the net welfare of increased coffee production by maintaining nearby forests versus converting such forests to alternative crops in Ecuador and Indonesia. In both regions, crop revenues exceeded coffee pollination values, generating incentives to convert forests, even if owners would be compensated for pollination services. However, it is important to highlight that i) pollination is only one of the many ecosystem services provided by natural vegetation; and ii) that less impacting management systems (e.g., agroforestry, rustic practices) are good candidates to reconcile ecological, economic and cultural values (Priess *et al.*, 2007; Olschewski and Klein, 2011; Vergara and Badano, 2008; see also Chapter 5).

Environment friendly production systems (shaded coffee and cacao and other agroecological practices; Mas and Dietsch, 2004; Priess *et al.*, 2007; Kremen *et al.*, 2012) can be economically viable at the producer level if "green certificates" (e.g., organic and fair-trade) enhance landowners net revenues (Gobbi, 2000; Perfecto *et al.*, 2005). However, cost-benefit analyses for coffee and other production indicated that only an elevated consumer's willingness to pay high prices for green products could generate the necessary economic incentives for forest preservation (Benítez *et al.*, 2006; Olschewski *et al.*, 2006; Bateman *et al.*, 2015). Thus, direct payments for ecosystem services, accounting not only for pollination but also for carbon sequestration, soil conservation, water quality and biological control, among others, are probably necessary to sustain biodiversity-friendly production systems. This seems to be true for a high-price commodity with a global market such as coffee, but studies on other crop types are still lacking.

The implementation of payments for ecosystem services generated by biodiversity-friendly landscape planning has been controversial and difficult for many reasons (Landell-Mills and Porras, 2002; de Groot *et al.*, 2010, Kinzig *et al.*, 2011; Lockie 2013). The economic impacts of wild pollination are still not fully incorporated into market schemes (especially the stock market), and natural vegetation is usually evaluated only it's benefits to for carbon storage and timber production (De Konig *et al.*, 2005; Satake *et al.*, 2008; Phelps *et al.*, 2010). Thus, mechanisms for income generation are still lacking (Olschewski and Klein, 2011). Another problem is the mismatches between the scale at which the pollination service is provided (e.g., regional) and the scale of landowner management decision (i.e., farm); and between the scale of pollination provision and the global scale of carbon storage, which can create inequalities among landowners with and without forest areas (Satake *et al.*, 2008). Payments for ecosystems services are often criticized on the ground that they commodify nature (Liverman 2004; McAfee and Shapiro, 2010; Gómez-Baggethum and Perez, 2011; Adams, 2014). Several authors have expressed concerns that this could have severe social-environmental consequences particularly, reducing protection efforts for species/habitats with little to no economic importance, eliminating of not-for-profit conservation values and abandoning traditional management practices (Wunder, 2006; Kleijn *et al.*, 2015; Wilcove and Ghazoul, 2015). Some alternatives to direct payments for ecosystem services that promote a non-utilitarian view of nature, such as land use planning, environmental education and community-based approaches are presented in details in Chapter 6.

SECTION 4. VALUING POLLINATION SERVICE STABILITY

4.1 Overview

Economic analysis and valuation aim at comparing options to develop quantitative indicators of the impacts of decisions and policy-making. Typically, economic valuation tends to assume that the consequences of pollination service loss are precisely known. In reality, things are usually more complicated and decision-making is confronted with stochastic relations between events. This gives rise to the concepts of uncertainty, risk, vulnerability and resilience (collectively referred to, for the sake of brevity, in this assessment as Stability), all of which can significantly affect the economic value of pollinator gains and losses in decision-making.

- **Uncertainty** is defined by the UN approved ISO 31000 framework as "the state, even partial, of deficiency of information related to, understanding or knowledge of, an event, its consequence, or likelihood." (ISO, 2009). Numerous forms of uncertainty (see Chapter 6) affect pollinators and pollination services but within economic valuation, uncertainty usually arises from stochastic factors, those that derive from the natural variability within a system. For example, increasing distance from habitat has been linked with increasing variation in the level of pollination services provided to crops (Garibaldi *et al.*, 2011).

- **Risk** is defined as the "effect of uncertainty on objectives", typically measured as a composite of the magnitude of impacts and the probability of them occurring (ISO, 2009). Economic theory usually assumes that people are either risk-averse (avoid risks), risk-neutral (indifferent to risk) or risk-loving (seeking risk) in different situations. Economic analyses often assume that agents are risk-averse and will therefore typically make decisions that have lower risks than other decisions (i.e., are either less likely to occur and are less likely to be negative) than other decisions. Changes to pollinator populations can increase the risk of inadequate pollination service delivery if key species decline. Managed pollinators can reduce these risks but over-reliance can impose other risks to growers should production costs rise (Rucker *et al.*, 2012). By increasing the flow of genetic materials within plant populations, pollination can also increase resistance to disease, reducing the risks of yield loss from disease outbreaks. For example, Mexican production of bat pollinated Agave cacti, farmed as the basis for tequila production, has suffered substantial losses from outbreaks of vascular wilt *(Fusarium oxysporum)* due to a reliance upon cloned varieties with little resistance to the fungus (Ávila-Miranda *et al.*, 2010).

- **Vulnerability** measures the degree to which a system is susceptible to and is unable to cope with adverse effects (McCarthy *et al.*, 2001). Vulnerability is a function of three elements: exposure, sensitivity and adaptive capacity (Turner *et al.*, 2003). In the case of pollination, the exposure can be represented by the dependency of a plant upon pollination to reproduce or, for crops, the change in crop yields or economic outputs affected by changes in pollinator populations. The sensitivity is indicated by the shape of the relationship between pollination and benefit (linear, concave or convex yield loss). The adaptive capacity of the cropping system can be approximated by the capacity of alternative techniques to substitute animal pollinators (e.g., substituting managed pollinators for wild species or increasing other inputs).

- **Resilience** (in the context of social-ecological systems[3]) refers to the capacity of a system to return to its original state after being disturbed and the magnitude of change it can sustain before it changes to a radically different state (e.g., Berkes *et al.*, 2003; Folke, 2006). In the case of pollinator communities, resilient communities are those that can continue to provide a reliable level or services even in the case of temporary or permanent loss of major pollinators. Communities that are more resilient will recover from temporary declines in key species (e.g., temporary population declines due to extreme weather) than less resilient communities (which may permanently cease to provide any services).

3. The concept of resilience has also been used for many decades in material sciences or in psychology.

4.2 Incorporating stability into standard valuation methods

Although variation in pollination services can result in uncertain benefits (e.g., Bauer and Wing, 2014), to date, most valuation studies have not considered issues of service variability within the benefits of pollination services (Melathopoulos *et al.*, 2015), often only providing a single estimate of benefits rather than a range of possible values (see Section 7). Uncertainty has been incorporated into some existing dependence ratio and surplus analysis studies by assessing the impacts that variations in certain factors, such as dependence ratios (Lautenbach *et al.*, 2012), price elasticities (Gallai *et al.*, 2009a) or substitution parameters (Bauer and Wing, 2014) can have on estimates of value. In yield analysis, uncertainty can be incorporated by estimating value subject to inter-site or inter-annual variance in the benefits observed. The production function method can directly capture the effects of variation in several aspects of pollinator communities on service delivery, identifying how community variations may cause the output to vary.

Risks from potential honeybee losses have been incorporated into some dependence ratio (Section 2.2.) and surplus analysis (Section 2.4) studies (e.g., Cook *et al.*, 2007; Southwick and Southwick, 1992) using hypothetical or expert derived weights that reflect the capacity of wild pollinators to replace honeybee losses. In these studies, the risk value of honeybee loss is the value of production that cannot be compensated for by other pollinators. However, these weights are subject to many of the assumptions of dependence ratios themselves and often stem from the assumption that honeybees are presently the majority pollinator, which may not be the case (Garibaldi *et al.*, 2013). Within stated preference studies, risk can be applied to non-market benefits by including an attribute representing the probability that the benefits will not be delivered as described. Vulnerability of producer benefits can be quantified by estimating the proportion of the total economic value of the agricultural sector (Gallai *et al.*, 2009a) or agricultural GDP lost in the event of pollinator community collapse (e.g., Lautenbach *et al.*, 2012).

4.3 Additional methods for assessing the economic value of stability

A number of methods from the wider ecological economics literature are also suitable to specifically assess the economic value of stability and resilience in benefits from pollinators, the most relevant of which are reviewed below. These values are generally considered distinct from the direct use value of service benefits themselves but can draw upon methods to estimate use values, becoming an additive factor in assessing TEV by quantifying the uncertainty in management decisions that will affect pollinators and services (Armsworth and Roughgarden, 2003). For each method this subsection reviews: what it measures (uncertainty, risk resilience or vulnerability), an overview of the methodology, including its strengths and weaknesses, links with the main methods for valuing the impacts of changes in pollinator populations (Section 2) and the data required. **Table 4.8** summarises the methods and their strengths and weaknesses.

4.3.1 Portfolio models

What it Measures: Uncertainty (the degree of uncertainty of service provision) and Risk (the costs of maintaining communities that provide different levels of service stability).

Methodology: Portfolio models use various econometric models to estimate an economically optimal collection of assets, including their associated costs, which minimize the variability of the output and with it the risks to producers (Admiraal *et al.*, 2013). This method has not yet been applied to pollinator populations but has been adapted to assess the effects of soil natural capital on crop production (Cong *et al.*, 2014a). This methodology could be used develop optimal portfolios of pollination service assets, such as managed pollinators or specific habitat types to support particularly effective wild pollinators, that have low risk of service collapse. Alternatively, this method can be used to determine portfolios of the suitable foraging resources for honey production within a year. Portfolios may vary depending on the risk aversion of the agent expected to make the change (Cong *et al.*, 2014a) and costs (e.g., the opportunity costs of habitat management) should factor into portfolio analysis as portfolios based on benefits alone may differ strongly compared to cost-benefit portfolios (Ando and Mallory, 2012).

Strengths: Portfolio models can be projected across longer time scales in order to minimize long-term risks (Cong *et al.*, 2014a). Portfolio models also allow for varying degrees of producer risk aversion to be incorporated (Cong *et al.*, 2014a), allowing research to present a range of options for management to producers (see Chapter 6). These can in turn be incorporated into map based optimization models as constraints (e.g., Cong *et al.*, 2014b) to determine the optimal distribution of assets within a landscape e.g., where management measures should be placed on a farm). Model constraints may also be applied to prevent a portfolio over-emphasizing wild or managed pollinators, as the large-scale population collapses of one could be difficult to compensate with the other (Garibaldi *et al.*, 2013). More hypothetically, portfolio models can build on production function methodologies to better optimize spatial placement of pollinator assets relative to other assets.

Weaknesses: Pollinator populations can vary strongly between years and landscapes, causing fluctuations in risk on an annual basis. Capturing these fluctuations, and the associated risk to producers, requires complex modelling that should account for other inputs (e.g., Production function models). Furthermore, no portfolio analysis model has actively considered how producer risk-aversion may change over years, making it difficult to estimate optimal portfolios over longer time periods. Portfolio models typically assume that assets do not interact with one another (Koellner and Schmitz, 2006) however, this is rarely true for pollination services where different assets (pollinators) can interact to affect service provision (e.g., Greenleaf and Kremen, 2006) and long-term risks via pathogen spill over from managed to wild pollinators (e.g., Meeus *et al.*, 2011). Although costs can be determined for managed pollinators, it can be more difficult or even impossible to estimate the costs of wild pollinators at a group or species level. Finally, as land use, land management and producer risk aversion can vary strongly; portfolio models are rarely appropriate for larger scale analyses.

Links to primary valuation methods: Portfolio models would be most effectively used an extension of the production function method (Section 2.2.3). By identifying links between assets (e.g., pollinators within a community, pollination as one of a number of inputs into crop production) and outputs (the economic value of pollination services), it is possible to determine the combination of assets that produces the lowest variation in outputs (Koellner and Schmitz, 2006). As service spill over will be affected by habitat configuration, this method should be combined with ecological models (e.g., Cong *et al.*, 2014b) to determine how the configuration of interventions could affect variance in service delivery. Where links between the pollinator community and pollination services are not explicitly established, yield analysis (Section 2.2.1) or dependence ratios (Section 2.2.2) will be required to quantify the economic benefits and variance of each portfolio. At a minimum, yield analyses can be used to infer the benefits of individual habitat patches, but this will be subject to greater uncertainty. Portfolio models could also use information from plant-pollinator network analysis and stated preference surveys (Section 2.5.) to identify possible co-benefits from the portfolio. For example, stated preference surveys into the value of aesthetic wildflowers could be sued to weight the selection of flowers and the placement of flower rich habitats within a landscape to optimize both pollination services to crops and the aesthetic value of the habitat.

Data required:

- **Essential:** Production function data on the effects of different habitats on pollinator communities and/or the impacts of individual pollinators within a community on pollination services. Information on the costs beneficiaries incur when using an asset.

- **Desirable:** Measures of producer risk-aversion, projected availability of assets (e.g., habitats or managed pollinators).

4.3.2 Sustainable livelihood framework analysis

What it Measures: Vulnerability (local capacity to adapt to significant losses of pollinators).

Methodology: Sustainable livelihood framework analysis uses biophysical measures of various capital assets (Section 2.6.) to determine how vulnerable a region is to a particular change (e.g., a marginal loss of pollinators) by evaluating whether the available capital within the region would be able to fully substitute for any capital affected by that change (Tang *et al.*, 2013). This method has not yet been applied to pollination service losses but has been used to assess the impacts of climate change on rural communities (Hahn *et al.*, 2009; Nelson *et al.*, 2010). Alternatively, biophysical metrics of pollination service stocks could be built into an assessment of regional vulnerability to global pressures including climate change. The assets studied are selected based on how likely they are to be affected by the change in question and their effectiveness as substitutes for other capital assets in providing a service (Nelson *et al.*, 2010). Biophysical measures are often derived from existing data sources such as the national statistics or from primary survey data (e.g., Hahn *et al.*, 2009). As capital assets will often have substantially different units of measure (e.g., number of pollinators, area of forest etc.), an index is created for each asset, which is then usually compiled with other assets of the same capital type (e.g., natural capital). All capital indexes are then combined into a composite index that captures the total access to capital, the capacity of capitals to substitute for each other and the relative access to each capital; for instance, an area with high financial capital but little access to other capital would score lower on the index. The lowest-scoring regions are therefore the most vulnerable to the change (Nelson *et al.*, 2010). Indexes typically weight all capitals equally (e.g., Hahn *et al.*, 2009; Bryan *et al.*, 2015) but some can use more specific weights based on statistical modelling (Nelson *et al.*, 2010) or assigned directly by participants (e.g., Below *et al.*, 2012).

Strengths: By incorporating non-monetary measures of capital, this method is particularly suitable for use in areas where monetary markets for pollination service benefits are minor, incomplete or absent (e.g., communities that do not trade crops for money). This also allows for the identification of key aspects of vulnerability to a region, such as the relative availability of particular capital that could become important under an alternative scenario. It can also be readily applied at any scale from households (e.g., Below *et al.*, 2012) to regions (e.g., Hahn *et al.*, 2009) and under a variety scenarios as long as the effects (positive and negative) on different capitals and the trade-offs between them can be accurately estimated (Nelson *et al.*, 2010). It may also be appropriate to justify action where benefits are unknown but policy actions (and therefore preferences) are.

Weaknesses: This method does not inherently capture the benefits provided the focal capital, only the level of stocks that generate it and therefore does not fit into the typical cost-benefit paradigm (Section 1). As such, it should be coupled with assessments of the local benefits that are provided by the asset in its present state (e.g., Section 2) in order to determine appropriate responses. This method primarily functions by compiling different assets into one or several other indexes which may mask relationships and trade-offs between different capitals; improving an index of natural capital by planting large areas of forest on uncultivated land may improve overall natural capital at the expense of wider biodiversity. The methods used to weight the index used in sustainable livelihoods analysis often introduce assumptions about the relative substitution between capitals with e.g., equal weighting assuming that all capitals are perfectly substitutable (Hinkel, 2011). Often the link between the capitals and the adaptive capacity of the affected region is abstract, taking little account of how the capital is actually used (Below *et al.*, 2012). Furthermore, sustainable livelihoods analysis inherently assumes that all capital can reduce vulnerability to a change and is substitutable. However, in certain highly pollinator-dependent crops, fruit set cannot be initiated without animal pollination (Klein *et al.*, 2007) and labour costs may prohibit the use of artificial pollination. Although substitutions between different forms of pollination service assets are possible, these are often imperfect (Garibaldi *et al.*, 2013) and may not be effective in the case of technological replacements (e.g., Kempler *et al.*, 2002). Although technological innovation may increase the capacity for capital to substitute for other capitals, the occurrence and adoption of this innovation is almost impossible to predict. Even where substitution is viable, estimating the quality of substitution between forms of capital is extremely complex and impossible to accurately quantify without strong data (Nelson *et al.*, 2010).

Links to primary valuation methods: Quantitative biophysical measures of managed or wild pollinator assets (see Section 2.6) can be included in framework without any modification as part of natural and manufactured capital indices. However, care should be taken to separate hives managed by professional and amateur beekeepers as changes in pollinator capital have different trade-offs to wider capitals. For example, price shifts for managed pollinators for instance may affect the financial capital of professional beekeepers (Sumner and Boriss, 2006) but not amateurs that do not typically receive payment for pollination services.

Data Required: Measures of all relevant assets and their distribution within a region at a spatially explicit scale.

4.3.3 Resilience stock

What it Measures: The monetary value of resilience (the capacity of the pollinator community to withstand and recover from pressures that affect its capacity to provide benefits).

Methodology: This method assesses the long-term trade-offs and benefits from different managements on service availability by considering resilience (Section 4.1.) as a separate asset that can be affected by pressures and mitigations (Maler *et al.*, 2009). The impacts of a pressure or mitigation on resilience can be measured as a change in the marginal shadow values of the service (Bateman *et al.*, 2011). Shadow values represent the long-term benefits of ecosystem services from natural capital to society, including their potential future values. The shadow value of an ecosystem service can be estimated by applying a discount rate (see Section 3.2.2.3) to estimates of the future value of the ecosystem services generated by the capital asset; e.g., the value of pollination services now and in the future assuming similar land use. The resilience of pollination services to crops and wildflowers will be influenced by the abundance and diversity of key functional pollinators (Winfree and Kremen, 2009). Higher abundances of key species and a higher diversity of potential service providers will increase resilience by increasing the community's capacity to adapt to change (e.g., Brittain *et al.*, 2013). Thresholds for resilience, the point at which an asset would be unable to return to its original state if a pressure were to degrade its functioning, will therefore be the point at which a pollinator community is unable provide services following a reduction in a key species or group. These thresholds are presently unknown, although ecological network analyses may provide a starting point for future evaluation.

Strengths: The economic value of resilience as a stock inherently captures the value of insurance; the mitigating effect of resilience upon producer wellbeing, which can be estimated separately utilizing specialized models (Baumgartner and Strunz, 2014). As a capital asset it can be readily incorporated where monetary markets for crops are absent, with the shadow value simply becoming the projected stock of the resilience asset.

Weaknesses: This method is highly influenced by the discount rate applied to create the shadow value. In the case of pollination services, this will depend on both the projected future benefits and, for crop pollination, the discounted price of the crop in future periods. These prices are likely to be very difficult to project and discount rates can be very difficult to estimate (Section 3.2.2.3). By applying this method to a single ecosystem service, this method may over-state the impacts of pollinator gains and losses in isolation. In reality, ecosystem services and inputs may compensate for one another (e.g., pollination services increasing yield in certain oilseed rape, *Brassica napus*, varieties in the absence of fertilizer – Marini *et al.*, 2015), necessitating a complex, whole systems approach that considers multiple services in a single resilience stock. Insurance values are inherently linked to user preferences for risk aversion, such as the maximum amount of pollinator-dependent yield loss a producer is willing to accept before switching crops (e.g., Gordon and Davis, 2003), which should be estimated separately to extrapolate insurance value (Baumgartner and Strunz, 2014). Most critically,

TABLE **4.8**
Summary of methods and their strengths and weaknesses for assessing the economic value of uncertainty, risk, vulnerability and resilience

	Method	Strengths	Weaknesses
Portfolio methods	Statistical models are used to construct an optimal portfolio of assets (pollinators or habitats) that minimize variance in expected benefits	- Account for varying degrees of producer risk aversion - Readily incorporated into long term management and spatial planning	- Often highly complex to estimate - Requires substantial and in depth ecological and economic data, ideally from production function analyses to capture changing risks - Assumes that assets do not interact with one another
Sustainable livelihoods framework analysis	A range of complementary capital assets are quantified and summed into an index to identify regional vulnerability to a proposed change.	- Does not require the presence of monetary markets valuation studies - Applies at all spatial and temporal scales - Can be used without adaptation for any policy scenario	- Pollination cannot always be substituted for and many substitutes are imperfect - Weighting of the index can be difficult and introduce assumptions. - Many indicators are only abstract representations of adaptability
Resilience stock	Resilience is quantified as a stock that can be quantitatively degraded like other capital assets	- Does not require the presence of monetary markets - Captures the value of service insurance	- Monetization is highly dependent upon discount rates which are difficult to estimate accurately - Does not account for service substitution - Difficult to extrapolate from source site

the threshold levels of pollinator diversity and abundance needed to provide economically viable levels of pollination services remain unknown due to a lack of large-scale community monitoring of pollinators or pollination services.

Links to primary valuation methods: The shadow value of pollination services will have to be derived from either a production function (Section 2.2.) or, ideally, surplus valuation methods (Section 2.4.). Production functions can inform the marginal effects of changes in the pollination service community, including the relative contribution of different species, identifying thresholds for the system studied and the value of benefits potentially lost by a composition change. Finally, stated preference methods will be required to assess the non-use value of pollinator resilience stocks.

Data required: Threshold levels of pollinator abundance and diversity required to provide pollination services to a particular plant, estimates of the present value of pollination services, projections of future benefits and a suitable discount rate.

SECTION 5. KNOWLEDGE GAPS

5.1 Overview

There is a consensus that biological knowledge gaps are an important limitation to economic analyses of the benefits of pollinations services (TEEB, 2009; Vanbergen *et al.*, 2012; Dicks *et al.*, 2013). The absence of biological information directly affects each of the methodologies and frameworks used or proposed to evaluate the impact of pollinators' declines (see Section 2). For example, there is only limited information about the effect of habitat fragmentation in pollination dynamics (Hadley and Betts, 2011) or landscape effects (Viana *et al.*, 2012) and variability in the concept of pollination deficit (Liss *et al.*, 2013). There are also biases in global sampling towards large-scale farming in temperate regions (Steward *et al.*, 2014), bias in sampling examples (Archer *et al.*, 2013) or the interface with climatic change (Prather *et al.*, 2013). An urgent priority and research challenge will be to establish how multiple pressures affect pollinators and pollination under continuing environmental change and their subsequent economic impacts (Vanbergen *et al.*, 2013). The relationship between crop management practices and the response of crop yield to pollination is complex and, in the vast majority of cases, completely unknown and for most regions of the world. For most wild pollinator taxa, we have no data as to whether there have actually been declines (Goulson *et al.*, 2015). While the contribution of wild bees to crop production is significant, service delivery is restricted to a limited subset of all known bee species and conserving the biological diversity of bees therefore requires more than just ecosystem-service-based arguments (Kleijn *et al.*, 2015).

Although biological knowledge gaps remain the primary factor limiting accurate valuation of pollination services, a number economic knowledge gaps fundamentally also limit the current scope of valuation studies. As such, the current knowledge base is likely to neglect certain beneficiaries and may over- or under-estimate the impacts of pollinator gains and losses. This section critically reviews a number of the key knowledge gaps affecting accurate estimation of the economic impacts of pollinator gains and losses, highlighting which methods are primarily affected (Section 2 and 4) and what the impacts of this incomplete information are likely to be.

5.2 Agronomic/ ecological knowledge gaps

5.2.1 How do we measure pollination services?

In a review regarding how pollination is measured in published works, Liss *et al.* (2013) found that pollination was most often defined by crop yield (41%), followed by pollinator abundance/diversity (31%), pollen transfer (21%), pollinator visitation (13%), and plant fitness (9%). Lack of robust, reliable and consistent indicators for pollination services could produce contradictory or inaccurate results by lack of understanding of the relationship between pollinator identity, abundance and diversity and service level (Liss *et al.*, 2013).

Different ecosystem service definition and metric selections could hypothetically alter study conclusions about pollination service provision and confound comparisons among studies. Pollination services are estimated to be high in Landscape A when using a crop yield definition but low based on pollinator abundance and diversity, while the opposite is true in Landscape B. Production function models in these landscapes would over- or under-estimate pollination service benefits and may in turn drive sub-optimal decision making if farmers were to add or not add mitigation measures respectively (modified from Liss *et al.*, 2013).

Methods affected: Production Functions (Section 2.2.3), Yield analysis (Section 2.2.1), Stated preferences (Section 2.5.).

Impacts: A robust metric of pollination services is essential to accurately estimate the pollination service provided by pollinator communities. Inaccurate measures can potentially cause over- or under-estimation of benefits. In crops, this is particularly important in production function analyses, which should capture the effectiveness of different pollinators within a community in providing pollination services. An ideal measure would be to estimate the pollen deposition by each species up to a threshold required for fruit or seed set (Winfree *et al.*, 2011). However, although standardized frameworks exist to measure this in the field, it is a very labour intensive process (Vaissiere *et al.*, 2011; Delaplane *et al.*, 2013). Assessments of how well pollination service metrics correlate with one another could therefore allow for simplification of fieldwork and greater comparability between studies. Different metrics may also be required for valuing different benefits; for crops the level of pollen deposition is key to ensuring optimal economic output (Winfree *et al.*, 2011), however for aesthetic wildflowers, the rate of legitimate visits to aesthetically valuable species rather than other species may be more important.

5.2.2 What are the benefits of pollination service on the final crop output?

Much of the current understanding of pollination service benefits is based on studies that solely focus on changes in initial fruit/pod set rather than final producer profit (including costs) and are often assumed to be representative of all cultivars of a crop (Bos *et al.*, 2007; Garratt *et al.*, 2014). In reality, crop quality can be a significant component on the markets for a particular crop increasing the sale price (e.g., apples – Garratt *et al.*, 2014) or the quantity of extractable materials (e.g., oilseed rape – Bommarco *et al.*, 2012). In some crops a minimum quality threshold is often required for a crop to enter a specific market, for example, in the European Union strawberries must be of a particular shape and size to enter the primary produce market (Klatt *et al.*, 2014), with others entering a lower quality secondary market for processing. Similarly, recent studies have demonstrated

FIGURE **4.3**

Comparison of different methods for evaluating pollination services.(Liss *et al.*, 2013)

Landscapes of equal sizes

Landscape A

- Large pollinator-dependent cropland with a small forest patch
- Pollinator-nesting habitat of moderate quality, but some cropland is beyond the pollinator foraging range
- Pollinator dependent crop is under- and unevenly pollinated

Landscape B

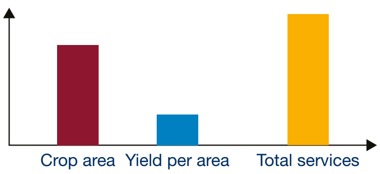
- A smaller pollinator-dependent cropland bordered by a large forest patch, hedgerows, and a meadow
- The entire cropland within pollinator foraging range

Method 1

Pollination service:
The production of the pollinator-dependent crop from the entire landscape

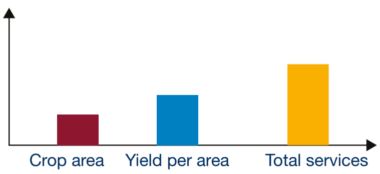
Two metrics used:
- Area of cropland
- Crop biomass produced per unit area of cropland

Landscape A:



A lower level of production per unit area but higher total crop production

Landscape B:



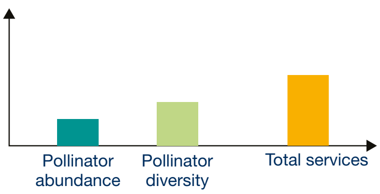
Limited high-performing crop area

Method 2

Pollination service:
Pollinator abundance and diversity

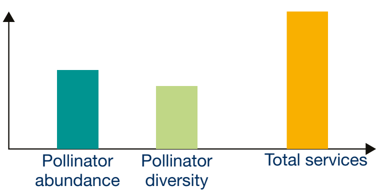
Two metrics used:
- Total number of pollinators observed at the study site
- Species diversity of the pollinators

Landscape A:



Sparse pollinators with low diversity
Pollinators do not regularly reach the entire field

Landscape B:



A large pollinator populations with higher diversity substantial variations in the benefits of pollination services to different cultivars of the same crop (e.g., Hudewenz *et al.*, 2013; Garratt *et al.*, 2014); however, for many crops the variations in these benefits remain unknown. As such, estimates of value extrapolated from a single cultivar may be misleading, particularly in crops with a high cultivar turnover (e.g., oilseed rape – Hudewenz *et al.*, 2013) or where cultivars sell for different prices (e.g., Garratt *et al.*, 2014). Many studies do not account for increases in costs resulting from additional pollination, such as greater picking or input costs (Winfree *et al.*, 2011).

Methods Affected: Yield Analysis (Section 2.2.1.), Dependence Ratios (Section 2.2.2.), Surplus Models (Section 2.4.).

Impacts: Failure to capture the full extent and variation of benefits for a crop can result in under- or over-estimation of benefits, particularly if extrapolated over a range of cultivars (see Garratt *et al.*, 2014). This will in turn affect the estimates of changes in crop production on prices, an important component of welfare analysis – for instance if crop quality decreases more than quantity then overall prices may fall even in cases of lower available supply.

5.2.3 Interactions between pollination services and land management or other ecosystem services

5.2.3.1 How do management practices affect the benefits of pollination services?

Although pollination services can have a strong influence on yields, yields will be strongly driven by local management of the crop, such as input, planting regimes etc. In most economic studies, the benefits of pollination are overestimated because the influence of other anthropogenic inputs (insecticides, fertilizers, etc.) are not accounted for (see Section 2). For instance, Marini *et al.* (2015) demonstrate that in certain oilseed rape cultivars, yields are enhanced to different extents by the amount of nitrogen applied to the soil but benefits to crop yield from insect pollination seemed to increase with decreased nitrogen levels.

Furthermore, local management can affect the delivery of pollination services. Recent reviews and meta-analyses suggest that the impacts of human land use on pollinators are generally negative (Kennedy *et al.*, 2013). Kremen *et al.* (2012) concluded that agricultural intensification reduced the diversity and abundance of native bees such that pollination services they provided are below the necessary threshold to produce marketable products. To date there have been very few studies that have looked at the impacts of changing management on the economic benefits of pollination services (but see Blaauw and Isaacs, 2014).

Methods Affected: Dependence Ratios (Section 2.2.2.), Production Functions (Section 2.2.3.), Surplus Models (Section 2.4.).

Impacts: Failure to account for the impacts that management and inputs can have on the scale of benefits to crops (including additional costs) can result in over- or under-estimation of the benefits of pollination services to a crop. This is particularly significant when extrapolated across larger spatial scales that encompass areas with natural variations in productivity (e.g., through soil quality, climate etc.). Furthermore, the capacity to trade-off between pollination and other inputs is an important consideration in surplus modelling, particularly general equilibrium models (which consider how such substitutions could affect benefits) and production function analyses (which consider the benefits of pollination relative to other factors affecting yield) and could limit the accuracy of both approaches.

5.2.3.2 How do different ecosystem services affect the benefits of pollination services?

Most research implicitly uses as a simplifying assumption the notion that ecosystem services (in this case pollination) do not have significant and variable relationships with one another (Bennett *et al.*, 2009). Decreasing level and stability of yield in insect-pollinated crops has so far solely been attributed to pollinator declines, without considering how other ecosystem services have changed in tandem (Lundin *et al.*, 2013). Different factors, including pollution, can change these ecological relations; therefore, there is a need to alleviate humans' impact on nature by a holistic approach that includes and prioritizes the loss of pollinators. To ensure continued ecosystem services, it will be important to maintain not only an abundance of key species but also species interactions and the diverse, healthy ecosystems that sustain them.

Furthermore, despite their apparent importance, interactions among ecosystem services, particularly those involving regulating services have generally been underappreciated; ecological management and monitoring have focused on provisioning or cultural services. While there has been substantial ecological research on some regulating services such as pollination and carbon sequestration, these services' role in ensuring the reliability of other ecosystem services has not been systematically assessed (Bennet *et al.*, 2009). For example, Knight *et al.* (2005) demonstrate the impact water quality can have on pollinators via trophic cascades. Fish that require good water quality to maintain stable populations in turn predate upon dragonflies, the principal predators of pollinators within the system **(Figure 4.4)**. Loss of water quality can therefore affect pollination services by reducing the fish population, reducing the predation on dragonflies and indirectly increasing predation on pollinators.

Methods Affected: Yield Analysis (Section 2.2.1.), Dependence Ratios (Section 2.2.2.), Production Functions (Section 2.2.3.), Surplus Models (Section 2.4.).

Impacts: Coordinated management for multiple ecosystem services can have positive synergistic effects, which can outweigh the summed benefits of managing ecosystem services that are spatially or temporally separate (Lundin *et al.*, 2013). Failure to adequately capture these trade-offs will lead to an over-/under-attribute yield gains to pollination services. Research that quantifies the provision of multiple services, the trade-offs and synergies among them and also examines the ecosystem processes that link services will lead to a better understanding of how the relationships among ecosystem services can change over time and space (e.g., Marini *et al.*, 2015). Such understanding may enable manipulation of systems to decrease trade-offs, enhance synergisms, and promote resilience and sustainable use of ecosystem services (Volk, 2013).

5.2.3.3 How do pollination services affect the benefits of other ecosystem services?

Although pollination is a service that results from direct interactions between plants and animals, because of its reproductive value to plants it also has an important, indirect role in other vegetation-based services, such as water filtration, erosion control, carbon storage and sequestration (Montoya *et al.*, 2012) and landscape aesthetics (Breeze *et al.*, 2015). The total value of insect pollinators to crop production would be even higher if indirect benefits, such as enhanced soil fertility and soil conservation through the pollination of various nitrogen-fixing legumes and replenishing soil nutrients, were taken into account (Partap *et al.*, 2014).

For example, the total value of insect pollinators to agriculture would be even higher if economic risks of both direct crop sectors and indirect non-crop sectors in the economy were taken into account (Bauer and Wing, 2014). Perhaps the most drastic effects would be in uncultivated areas where a large share of the soil-holding and soil-enriching plants would die out (Bohart, 1952).

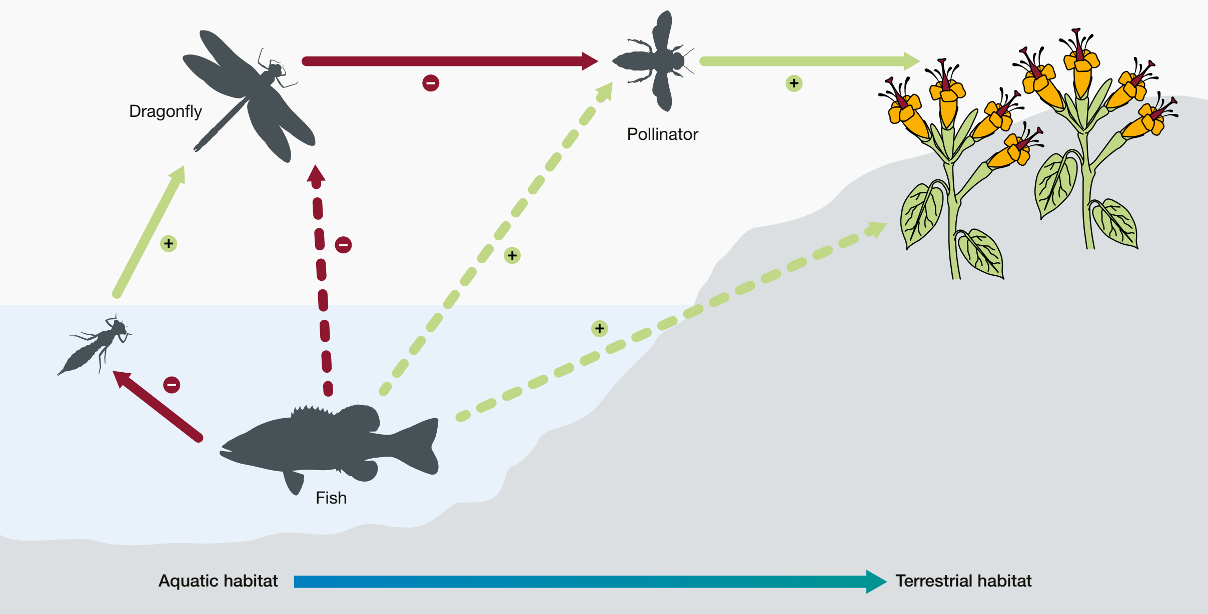
Methods Affected: Yield Analysis (Section 2.2.1.), Dependence Ratios (Section 2.2.2.), Production Functions (Section 2.2.3.), Surplus Models (Section 2.4.), Stated Preferences (Section 2.5.)

Impacts: Like farm management practices, failure to account for the interaction between pollination and other ecosystem services can result in under- or over-estimation of the benefits of pollination services, especially for crops that are highly self-incompatible. In order to assess total economic value, it is important to quantify the various non-market benefits of pollination services. In order to do so, the contribution of pollination services to various benefits provided by other, intangible ecosystem services must be quantified to accurately extrapolate the value of pollination to these final services via stated preferences or production

FIGURE **4.4**

Interaction web showing the pathway by which fish facilitate plant reproduction.

Solid arrows indicate direct interactions; dashed arrows denote indirect interactions. The sign refers to the expected direction of the direct or indirect effect (modified from Knight *et al.*, 2005).



functions that capture appropriate feedbacks. Failure to do so will result in some benefits being ignored in valuation and trade-off decisions informed by them.

5.2.4 How do variations in wild pollinator communities affect service delivery?

Only recently have ecologists specifically addressed daily, seasonal, and annual temporal patterns in network structure of plant-pollinator interaction networks (Burkle and Alarcon, 2011). For example, Price *et al.* (2005) studied pollination by insects and humming birds to a montane herb (*Ipomopsis aggregate*) for 7 years, finding that pollination services are variable within and between years by several orders of magnitude even at the same sites. Whereas studies of short duration may detect covariance of floral variation and pollination success, additional sources of variation across sites and years may weaken, strengthen, or even reverse this effect (Burkle and Alarcon, 2011). Although plant–pollinator systems are highly dynamic, measures of their interaction networks are structurally stable across all time scales studied. This suggests that the mechanisms governing the assembly of pollination networks are likely independent of species composition, thereby preserving ecosystem function, across seasons, years or decades (Burkle and Alarcon, 2011). A better understanding of the links between pollination and population dynamics is needed to know when limits to seed input and seedling establishment affect population size and structure (Wilcock and Neiland, 2002).

Several case studies have noted that wild pollinators may positively enhance the effects of managed honeybees on crop yields through by increasing movement across flowers (Greenleaf and Kremen, 2006) or movement between different individuals of self-incompatible crops (Brittain *et al.*, 2013). These studies demonstrate the economic importance of interspecific interactions for pollination services in some crops (but this may not be widespread; see Garibaldi *et al.*, 2013) and suggest that protecting wild bee populations can help buffer the human food supply from honey bee shortages.

Both abundance and behavioural-mediated mechanisms can enhance the stability of pollination services in some crops (Greenleaf and Kremen, 2006; Brittain *et al.*, 2013). Assemblages that contain a wide range of species with different ecological requirements could maintain pollination services as environmental conditions change over time because i) declines in abundance of some taxa can be offset by increases in others and ii) interspecific interactions can enhance net pollination services. This is the basis of the biological insurance hypothesis with respect to pollination as an ecosystem service (Rader *et al.*, 2012). Lever *et al.* (2014) describes the capacity of pollinator populations to persist under harsh conditions. However, once a system's threshold is reached, pollinator populations may collapse simultaneously, raising questions about the resilience of pollination networks across different temporal and spatial scales (Petanidou *et al.*, 2008).

Several studies (Javorek *et al.*, 2002; Artz and Nault, 2011; Rader *et al.*, 2012) have compared the pollination service effectiveness of honeybees and various wild pollinators (wild bees, flies), using not only the frequent visitors but also different measures of pollen transfer efficiency (amount of pollen deposited on stigmas per single visit and stigmatic contact). Rader *et al.* 2012 found that pollinator importance changed little irrespective of the spatial and temporal variations among taxa.

Methods Affected: Production Functions (Section 2.2.3.), Natural Capital quantification (Section 2.6.), Resilience stocks (Section 4.3.3).

Impacts: Understanding the contributions of different pollinators within a community and the effectiveness of their interactions (Greenleaf and Kremen, 2006) is essential to understanding the total economic benefits of a community, identifying areas with possible pollination deficits and planning management accordingly. The management requirements for e.g., ground-nesting bees may be very different to those of hummingbirds, moths etc. This can result in over- or under-estimating the value and resilience of wild pollinator natural capital within the landscape by incorrectly assuming that all pollinators provide equal benefits to a particular crop.

5.2.5 How effective are artificial pollination methods

While numerous technological replacements and supplements for insect pollination services have been developed (Pinillos and Cuevas, 2008) their effectiveness in providing pollination services compared to animals remains unknown for a large number of crops. Different technologies are likely to be differently effective for different crops; for example, hand pollination is effective in Cherimoya (Gonzalez *et al.*, 2006) but not Raspberry (Kempler *et al.*, 2002) and some have been developed in response to specific needs (e.g., vibration wands in tomatoes – Pinillos and Cuevas, 2008).

Methods affected: Replacement Costs (Section 2.3.).

Impacts: Replacement cost studies must assume that methods are equally effective to animal pollination, which may not be the case, over- or under-estimating the total costs involved. Furthermore, effectiveness may affect producers' willingness to uptake the replacement. If this is not known, it will not be possible to accurately estimate how realistic the replacement scenario is.

5.3 Economic knowledge gaps

5.3.1 Limited information regarding non-market or non-monetary food consumption

Studies into the economic benefits of pollination services have thus far exclusively focused on crops produced and traded on monetary markets. In reality, producers in many countries will consume a certain amount of their own produce in lieu of selling it on an open market or will exchange their produce directly for other goods and services. For example, in India though most of the crops and their value are covered, fruit and vegetable production statistics are inadequate. About 40% of the geographical area under agriculture is without the benefit of reliable statistics on crop acreage by crop season (Sengupta, 2007). Similarly, people across the world have access to wild fruits and many will grow a small amount of their own food in gardens or allotments. While it is possible to estimate the economic benefits of this produce by determining the equivalent value of the produce on the market and applying standard valuation methods, there are no large-scale estimates of the amount of produce used in this way.

Methods affected: Dependence Ratio (Section 2.2.2), Surplus Models (Section 2.4.).

Impacts: This knowledge gap limits understanding of the full extent of pollination service benefits to crop production by underestimating the total amount produced. In many developing countries, crops consumed at home or traded in non-monetary exchanges are likely to be a significant part of local consumption. The welfare benefits of non-market crops consumed by producers are likely to be very significant to local producers as the crops are consumed at effectively no cost.

5.3.2 Limited information regarding seasonal trade in produce

Most studies on the value of pollination services have only considered inter-annual variations in crop production. In reality, production and, by extension prices will fluctuate within the year as well (intra annual variation) for some crops. Although modern refrigeration can extend a crops storage life, making it available longer throughout the year (Klatt *et al.*, 2014), spikes in availability are likely to occur for many crops. This will affect both short-term prices and total international trade within the year, with imports increasing to meet demands where supplies are lower and subsequently lowering the overall price (Kevan and Phillips, 2001). Although some seasonal price data is available (e.g., UK – Defra, 2014) the extent of seasonal variation in international production and trade of insect pollinated crops remains largely unknown.

Methods affected: Surplus Models.

Impacts: Lacking seasonal data, the effects of international trade on national prices over time are impossible to estimate. As such, estimates of the impact of pollination services on consumer or producer welfare remain incomplete. This is particularly significant when estimating the impacts on secondary consumers as supplies may be strongly linked to certain regions at particular times of the year, increasing the negative consequences of service losses in those regions.

5.3.3 Limited information regarding production and consumption on the secondary market

Presently, all estimates of the market value of pollination services have used data on the sale prices paid to producers. As such, any estimates of value derived from them only reflect the welfare benefits to primary consumers only. In many countries, these buyers will be wholesalers (e.g., supermarkets) who will in turn sell the produce at a higher price elsewhere; for instance, in the UK, sales at farm gate only reflect 42% of the final sale price (Defra, 2014). Thus, the welfare of these end consumers has not yet been assessed and may potentially be additive to the value to initial buyers, should price shocks be passed further down the supply chain. Furthermore, the preferences of end consumers will drive primary consumption and production of particular crops in order to meet demands. As long-term sales and prices set by these suppliers are considered commercially sensitive, it is very difficult for research to establish the structure of these secondary markets.

Methods affected: Surplus Models (Section 2.4.).

Impacts: The lack of sufficient information on the quantity and price of produce on the secondary market limits the capacity of existing methods to assess the impacts on end consumers, under-estimating the total benefits of pollination services by neglecting a large proportion of beneficiaries. Furthermore, information on consumer preferences is important to establishing crop substitution elasticities, limiting the capacity of research to estimate how prices respond to changes in the supply of a particular crop and the resultant impacts on producer and consumer welfare.

SECTION 6. HOW ECONOMIC GAINS AND LOSSES IN POLLINATION CAN BE USED TO INFORM DECISION-MAKING?

6.1 Overview

Institutions, governance systems and other indirect drivers are the ways in which people and societies organize themselves and their interactions with nature at different scales (Díaz *et al.*, 2015). The decision process of protecting or not protecting pollinators is driven by the organization of the society. These benefits can be private (increased farmer profit due to pollination), or public as the amenities created by pollination on a landscape. **Figure 4.5** illustrates how economic valuation (red arrows) can be used directly or indirectly for decision-making (green arrows) at different scales within the framework of IPBES. Economic valuation can be used by private and public institutions to estimate the importance of pollination services. By measuring the economic impact of changes on private or public benefits', valuation can feed directly into the decision making process.

6.2 Tools and methods for using economic valuation in decision-making

Economic valuation of pollination services can be used at scales ranging from individual farmers and cooperatives to national governments. Important tools and methods to inform decision-making that rely on economic valuation are, mainly, cost-benefit (and cost-effectiveness) analysis (Chapter 4, Section 1.1.4 and Chapter 6, Section 6.5.1.5), environmental accounting (Chapter 6, Section 5.8) and modelling pollination services (Chapter 6, Section 5.10). Some other tools integrate or incorporate economic valuation as vulnerability assessment (Chapter 6, Section 5.7), decision support tools (Chapter 6, Section 5.12), and Multi-Criteria Analysis (Chapter 6). Multi-Criteria Analyses (MCA) are a family of methods which combine multiple metrics into a series of criteria to simultaneously consider a range of impacts arising from activities and decisions (Sijtsma *et al.*, 2013). MCA often include economic considerations (e.g., the rate of employment and profit) alongside environmental (e.g., habitat and air quality), political (e.g., political stability and participation) and socio-cultural (e.g., education and cultural identity) aspects (Estevez *et al.*, 2013; Scriedu *et al.*, 2014). Although MCA have been applied to management scenarios concerning the management of ecosystem services, including those important to food production (e.g., Fornata *et al.* 2014, Volchko *et al.*, 2014), to date no study has directly assessed pollination services within this framework. MCA are particularly advantageous as they are capable of considering the full suite of values that the affected stakeholders possess, rather than solely focusing on an economics worldview, which may not always be appropriate (Scriedu *et al.*, 2014). Both monetary and non-monetary assessments of the benefits of pollination services can be incorporated into MCA depending on the criteria identified by the affected stakeholders. For instance, if agricultural productivity were identified as an important economic criterion for stakeholders, then both the monetary value of pollination services to crops and the available stocks of pollinator assets to ensure current and future production would be ranked highly. However, in regions where agriculture is primarily subsistence based, it may be more appropriate to consider the non-monetary benefits of pollination to capital (Section 2.6, 2.8.).

In Chapter 6, Section 6.5 **(Table 6.5.2)**, the experience, strengths and weaknesses of these tools and methods for informing decisions about pollinators and pollination are reviewed, alongside other tools and methods less reliant on valuation.

Economic valuation of pollination is a crucial element in designing payment for ecosystem services schemes (FAO, 2007; Chapter 6, Section 4.3.3), because the value of the service provided could constitute one basis for justifying the payment amounts. Another basis could be the opportunity cost to the producer.

6.3 Use of economic valuation of pollination at different stakeholder levels

Once the use and non-use values for both, private and/or public benefits of pollination services (including economic consequences of pollinator decline) are known, appropriate responses can be developed at multiple levels. In agriculture, the main levels of governance are typically: farmer, producer/cooperative, industry and government (Daily *et al.*, 2009; Kleijn *et al.*, 2015). In Chapter 6, **Table 5.3** describes the utility of different tools and methods for decision-making on pollinators at these different levels.

6.3.1 Use of valuation at farmer level

If farmers know the potential economic consequences of pollinator decline in their private benefits, they can choose alternative crops or varieties that do not result in either loss of income to them as private actors or to society as a whole. For example, hybrid varieties of oilseed crop have both higher values per unit produce and requirements for insect pollinators than the open-pollinated varieties. If there are declining trends on the availability of managed honeybee colonies in the area, then the farmer will be able to estimate loss of production from hybrid crop versus open-pollinated crop and make appropriate decision at farm level (Hudewenz *et al.*, 2013; Marini *et al.*, 2015). Economic valuation will be helpful in understanding or estimating tangible losses from any change in pollination service arising from changes in populations of pollinators and hence farmers can make decisions to grow particular types of varieties to cope with that situation. Alternatively, knowing the profitability losses of pollinators could be used to invest in measures to mitigate loss (such as flower strips) (Wratten *et al.*, 2012; Garibaldi *et al.*, 2014).

6.3.2 Use of valuation at producer level

If a group of farmers is involved in, for example, seed production, then they can measure the profit gain or loss due to pollinators change (using e.g., production function models; Section 2.2.3.) to guide their decision-making for appropriate production and marketing strategies. If there is a trend in the profit changes from linked pollinator gains and losses in the area, seed producers can make decisions to adjust their operations accordingly and establish a collaborative grower response. They can adopt certain strategies to bring additional managed pollinators or to change the type of crops that depends less on pollinators.

As described by Fisher *et al.* (2009), pollination services are provided omni-directionally and their benefits affect much of the surrounding landscape. When this service is offer by wild insects providing by a natural habitat, economic valuation can be used to incentivise a group of farmers who benefit from this service because their fields are in the surrounding landscape to maintain it.

6.3.3 Use of valuation at industry level

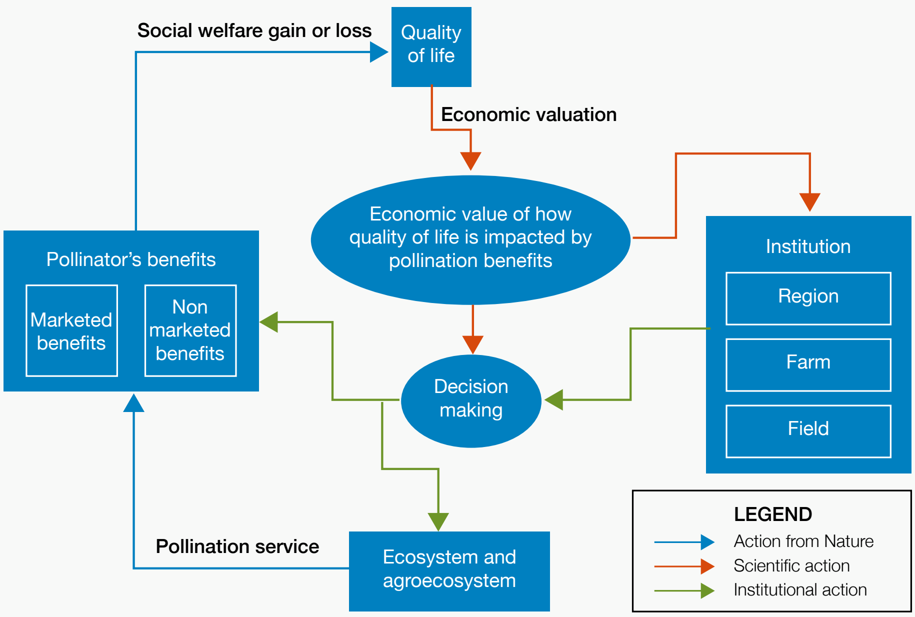
Industry' scope is local, national and global. Industry that deals in sales and marketing of seed, oilseed crops, horticultural crops and other food products dependent on pollination can develop their strategies to respond to any change in pollinators' populations. Industry can forecast the production figures, financial profits or losses and responses to shareholders based on profit valuation studies. For example, in cases were an industry is highly dependent on insect pollination, being able to illustrate the projected profit loss of a pollinator shortage (Allsopp *et al.*, 2008) can allow this industry to more effectively lobby with government for pollinator friendly regulations or concessions (de Lange *et al.*, 2013).

6.3.4 Use of valuation at government level

While the farmer, producer and industry levels are concerned with private values of pollination, governments (local, national or international) focuses on the effects on social welfare arising from pollinator gains and losses. Social

FIGURE **4.5**

Schematic representation of how economic valuation is used by institutions and for decision making at different scales as embedded in the IPBES framework (adapted from Díaz *et al.* 2015).



welfare encompasses the firm profits but also the consumer welfare. Governments can use the economic valuation as a policy tool to respond to the changing needs of constituents mostly farmers in many parts of the world. Appropriate agricultural and food policies can be developed by using the information on valuation of pollination services (TEEB, 2010). For example, if there are significant changes in the population of pollinators, then governments can guide, through appropriate regulation or incentive, changes in the cropping patterns in the agricultural area. They can promote other crops with relevant inputs and market support to overcome any predictable losses due to the crops that are more dependent on pollinators (Garibaldi *et al.*, 2014). Alternatively, government can support landowners more directly to maintain pollinator habitat through subsidies and/or regulations in cases where the pollinator-dependent crop is too valuable to society in terms of produce, export or employment provision, to replace. Pollinator maps showing varying level of abundance, habitat and key species can also be developed. These maps can be used along with economic valuation by decision makers (governments) for resource allocation to support agriculture. For instance, it could be helpful to know where the pollination potential is high, and simultaneously the crop production dependence on pollinators is high. It is also helpful for governments to have some monetary values to support some decisions. Government can also evaluate the non-marketed benefits of the pollination and use this economic valuation to estimate the interest or not in managing pollinator populations. The difficulties of such a valuation is that private and public interest are and measure the amount of the subsidy or taxes sufficiently high to incentivise landowners to change their practices.

6.4 Step-wise guide for using economic valuation for decision-making

Decision-making aims to protect or maintain the private and public benefit due to pollination service, and this for both wild and managed pollinators. Regardless of the scale used for economic valuation, there are a set of sequential steps to be taken to enable decision-making.

1. Determine the level of pollinator dependence of the plant as crop, crops grown or wild plant. This can be achieved with field studies (e.g. Yield analysis or production function models, Section 2.2.1 and 2.2.3) or through published resources such as Klein *et al.* (2007).

2. Determine the scale of production affected – the number of producers, the area of crops or the wild plants' landscape, the distribution within the region, etc. This is typically based on existing national statistics. It is also necessary to determine the beneficiaries of pollination services at this stage in order to identify appropriate temporal or spatial scales of benefits measurement. If the benefit of the pollination service is marketed as a crop, the beneficiaries are typically farmers and consumers (including secondary consumers). Similarly, the contribution of pollination to overall agricultural production and the rural sector can be calculated. Ideally, valuation should be accompanied with consultation of these stakeholders to accurately incorporate their wants, needs and constraints and to identify any mis-matches between their objectives (Ratamaki *et al.*, 2015).

3. The proportion contribution of wild versus managed pollination needs to be determined. This can be achieved through observational field studies (e.g. Winfree *et al.*, 2011), cage studies of individual pollinator efficiency or through pollination production function models (Section 2.2.3).

4. The current availability of wild or managed pollinators now needs to be determined, ideally to act as a baseline. This can be achieved though current information on the numbers of managed pollinators within the country or using modelling approaches such as InVEST to predict wild pollinator populations (Lonsdorf *et al.*, 2009). As stocks of managed pollinators can be used to offset any pollinator service shortage (Breeze *et al.*, 2014), they should ideally be considered even when wild pollinators dominate the service providing community. In contrast, if managed pollination is not available and there is no wild pollinator replacement, substitution is limited.

5. Now, the economic valuation of pollination services should be undertaken to establish baseline estimates and monitor or project the impacts of changes. If the output of the pollination service is an amenity, the beneficiaries of this amenity should be distinguished. The valuation method used will depend on who the stakeholders are and the case over which the assessment is to occur – e.g. local farmers will be informed sufficiently by a Yield analysis (Section 2.2.1) or Production Function model (Section 2.2.3.) while larger scale analyses should consider surplus valuation (Section 2.4.). Some methods (e.g. stated preferences) are suitable at al scales.

6. Once benefits have been valued (or quantified) introduce economic valuation in a tool for decision making (e.g., CBA or MCA) to determine the impacts of actions. This step is necessary to decide whether to protect or maintain pollination service relatively to the constraints (in terms of time or budget or social, economic and environmental priorities, etc.) of the decision-makers.

7. The last step is the action of protecting or maintaining the pollinators using the economic instruments (PES, incentives/taxes, subsidies, etc. See Chapter 6, Section 5).

There are very substantial uncertainties at each of these steps (see Chapter 6, Section 7), particularly regarding the availability of wild and managed pollinators in a particular place, and the relative contribution of wild and managed pollinators to a particular crop, which are clearly linked.

The next section discusses case studies in details from local to global scale. Some of these cases highlight how economic valuation can be used for decision-making (Ricketts *et al.*, 2004; Cook *et al.*, 2007; Allsopp *et al.*, 2008).

SECTION 7. CASE STUDIES: FROM LOCAL TO GLOBAL

Since the late 1960s, there has been substantial increase in interest for the economic value of pollinators through their pollination service (Helliwell, 1969; Costanza *et al.*, 1997). The topic received particular interest in the US, several European countries, Australia and New Zealand, where estimates of the value of pollination have been made for a wide range of different crops. A range of studies have shown that pollination makes a very significant contribution to the agricultural production of a broad range of crops, in particular fruits, vegetables, fibre crops and nuts. Estimates of the annual economic value of pollination have been made for the global scale.

Less information is available from many parts of the developing countries, much of which focuses on pollination services to coffee, one of the world's highest priced agricultural crops, where pollination contributes significantly to economic outputs (Klein *et al.*, 2003). This section reviews some of the most significant studies into the economic impacts of pollination services from across the world at various spatial scales.

As currencies vary between studies and the strength of currency can vary throughout time (Section 3), all monetary figures presented in this section have been converted to 2015 US$ using average annual spot exchange rates from the Bank of England (Bank of England, 2015). These dollar estimates were inflated to 2015 US$ using Consumer Price Index (CPI) data from the United Stated Federal Government's Bureau of Labour and Statistics (BLS, 2015a). Inflation was based on the CPI for July of the year the estimate was related to compare with the CPI in July 2015 (BLS, 2015b). If this year was not stated, then the year before the study was published was used instead. If estimates are based on data average across several years, the average exchange and inflation rates across all the relevant years were used. These inflations only represent a change in the value of currency and do not capture any changes such as the relative input prices, price controls or subsidies.

For example – Gallai *et al.* (2009a) estimated global crop pollination benefits in 2005, using a dependence ratio method at €153bn. This is divided by the exchange rate (0.8053€ per US$) and then multiplied by the rate of inflation (the proportionate change in the consumer price index between 2005 and 2015: 1.221), giving a value of $232bn. Similarly, Lautenbach *et al.* (2012), widely cited in this report, estimate the economic benefits of global pollination services at $212-$520bn in international dollars (a monetary unit that adjusts all prices based on power purchasing parity) in 2009. As US dollars are the basis of the international dollar, no currency conversion is required so the value is simply inflated by multiplying it by the inflation rate (1.108), resulting in a value of $235bn-$577bn in 2015 US dollars.

7.1 Local and regional scale

At the smallest scales (farms, communities etc.), changes in pollination services are unlikely to affect consumer wellbeing as the loss of production is likely to have little to no impact on crop prices (Section 2.5). As such, almost all studies examining the economic impacts of pollination service losses at these scales have used the Yield Analysis method (Section 2.2.1) to examine the potential market output loss that would occur following a complete loss of pollinators. Kasina *et al.* (2009) used this method to estimate the economic returns from bee pollination in smallholder farming systems in the Kakamega region of western Kenya in 2005. The net benefit (after accounting for costs) that Kakamega farmers received from bee pollination of eight focal crops was estimated at $3.9M, almost 40% of the annual market value of these crops in 2005. In Brazil, DeMarco and Coelho (2004) assessed the economic benefits of pollination to coffee grown close to native forests in 2003. Pollination resulted in a 14.6% average yield increase in areas close to native vegetation. This increase refers to 25.4 more coffee sacks per ha for the producer, equivalent to $2,414/ha/year (2015 US$).

Coffee has also been the focal crop in a number of studies examining the value of pollinator natural capital from the surrounding landscape. Ricketts *et al.* (2004) analysed pollination in 480 ha of coffee fields that are within 1km of two forest patches in Costa Rica compared with a hand-pollinated control at each site to represent maximum pollination. Their findings indicate that pollination increases coffee yields by ~21%, with benefits declining towards the centre of the plantation. Considering the differences in coffee yields, coffee prices and the costs of production, they estimate the surrounding forest on the plantation generates annual benefits $82,901 (2015 US$), representing ~7% of the annual income from the plantation.

Olschewski *et al.* (2006) used a regression based model alongside data from Klein *et al.* (2003) and locally collected yield data to estimate the marginal benefits of pollination services per hectare of forest patches at different distances to coffee plantations in Indonesia and Ecuador. They found that the marginal benefits of forest patches to coffee depends on the quantity of forest converted, estimating that pollination services increase producer net income by $0-$63/ha (Ecuador, 2015 US$) and $0-$66/ha (Indonesia, 2015 US$) depending on the distance between the habitat and plantation.

A more advanced study was undertaken by Ricketts and Lonsdorf (2013) who adapt the InVEST model of Lonsdorf *et al.* (2009) using the information from Ricketts *et al.* (2004). The findings indicate that each hectare of forest fragments provided between $0-$936/year (2015 US$) of pollination services depending on their location relative to the coffee and other forest patches. The highest marginal values are found in forests that provide high-quality resources for which there are few substitutes. The average marginal value of forest parcel declined exponentially with forest cover within a 500 m radius.

More recently, Winfree *et al.* (2011) estimated the benefits and economic value of pollination services by native bees and honeybees to watermelon pollination in New Jersey and Pennsylvania, USA using both replacement costs and yield analysis. Unlike many other studies, this analysis explicitly considers how producer costs may change because of changing yield. Surplus modelling was not undertaken as the two states contribute less than 2% to US national watermelon supply. Their findings estimate the benefits of pollination services to producer net margins at $4.0M (2015 US$); less than half the benefits estimated if producer costs were not accounted for ($8.5M – 2015 US$). The costs of replacing native pollinators and existing honeybees' colonies with new honeybees' colonies provided even smaller estimates of $0.23M (2015 US$) and $0.2M (2015 US$) respectively. This study highlights the differences in the scale of estimates between methods and the potential over-estimation of benefits if changing producer costs are not considered. However, the study does not specify what variable costs it assumes will change with changing yields and therefore may overestimate the cost change if inputs that are applied before harvest (e.g., fertilizer) are included in this calculation.

Local economic benefits can also be considered from the perspective of indigenous and local knowledge (see Chapter 5 for more details). In several cultural contexts, before the introduction of money or in parallel, indigenous people use honey, and sometimes beehives, as an exchange value (non-monetary). Among forest hunter-gatherers, honey is shared within the group as it is collected and then taken back to the village for further distribution. According to Ichikawa (1981), honey is the medium by which the Mbuti pygmies regulate their social relations. Although honey belongs to the individual who finds it out, the owner alone does not consume it. It is distributed to other members of the camp and it is frequent that the owner of a nest asks the other men to collect his honey. The practice of honey distribution and labour exchange compensates the separatism among the camp members, which is liable to occur during honey season (Ichikawa, 1981). Terashima (1998) stated that like sharing economic reciprocation is important to maintain a strong and durable relationship in the group, but also with neighbours: in exchange for honey, the Efe pygmies obtain from their neighbours, named Lese, clothes and agricultural food like plantain and manioc, which constitute a significant portion of their diet.

Césard (2007) recorded that the Punan Tubu in Indonesian Borneo have exchanged honey and other forest resources with their farming neighbours and with traders for goods that were used in marriage payments. Merchants travelled upstream to trade directly with collectors the products in demand then, using various measurement standards to establish their exchange value. In the Danau Sentarum region, wax was also traded (Césard and Heri, 2015). Hunters, beekeepers, now small-scale herders and agriculturalists, the Ogiek people in Kenya have long traded honey with their Maasai, Kikuyu and Kipsigis neighbours in exchanged for livestock, dogs or grains. Honey and honey beer are also consumed in ceremonies. Muchemi *et al.* (2011) reported that even if money is now the main medium of exchange, honey is still used in matrimonial payments. During marriage negotiations and as part of the bride price, the boy's relatives give to the girl's relatives several bags of honey and calabashes of honey brew. More than ten large bags (about fifteen litres each) can be demanded and beehives are also exchanged between families in the marriage process (Samorai Lengoisa, 2015).

7.2 National scale

Stanley *et al.* (2013) assessed the benefits of pollination services to oilseed rape at the national scale in Ireland by extrapolating the results of a yield analysis (Section 2.1.) conducted in ten fields in 2009-2011 across the country. All fields were at least 1 km apart, and only one field was selected per farm to avoid potential bias due to specific management practices on one particular farm. Exclusion of pollinators resulted in a 27% decrease in the number of seeds produced, and a 30% decrease in seed weight per pod in winter crops, with comparable values from a spring oilseed rape field. Extrapolating the results to a national scale, the economic value of insect pollination to winter oilseed rape in Ireland was estimated at $3.9M (2015 US$) per annum, while the contribution to spring oilseed rape was $1.9M (2015 US$), resulting in an overall value of $5.8 M (2015 US$) per annum.

Although upscaling yield analysis has been used for specific crops, the national scale benefits of pollination services to multiple crops are usually estimated using a dependence ratio methodology. Several interlinked studies have used this method to estimate the benefits of pollinators to agriculture in the USA; beginning with Robinson *et al.* (1989) which estimated that honeybee pollination services added to agricultural production in 1986, estimating a total market price of $20.3bn (2015 US$). Subsequent studies have gradually updated and refined this value; Morse and Calderone (2000) updated the information for 1996-1998 ($21.8bn 2015 US$). Losey and Vaughn (2006) used the same dependence ratios to estimate the value of wild pollinators in 2003 ($4bn 2015 US$), alongside other ecosystem services totalling ~$74bn (in 2015 US$ – $0.5bn for dung burial, $4bn for pollination, $5.8bn for pest control of native herbivores, and $64.8bn for recreation). Most recently, Calderone (2012) estimated the annual benefits of pollination services per hectare of US crop agriculture from 1997-2009, indicating that this value had steadily risen from $4,666.38/ha in 1997 to a peak of $7,399/ha in 2008 (2015 US$). The total value of pollination services in the USA across this time period follows similar but less substantial trends, rising from $15.6bn in 1996 to $17.07bn in 2009 (2015 US$) even as the area of insect pollinated crops gradually decline, indicating that price rises and a growing prevalence of higher value crops drive the average per hectare rise.

Although increasingly comprehensive, these studies only estimate the market benefits rather than societal value. Southwick and Southwick (1992) addressed this shortcoming by analysing the consumer surplus (Section 2.4) related to crop pollination by honeybees in the US in 1987. Based on ~20 years of price and consumption data, they estimate the demand curve for 50 different crops. Furthermore, the study includes a number of weights to reflect the capacity of wild pollinators to substitute for lost honeybee pollination services. The estimated value of honeybee pollination services to 17 crops was estimated at between $3.4bn (partial substitution by wild pollinators) to $11.6bn (2015 US$ – no substitution). Like many consumer surplus studies, this study unrealistically assumed that producers could freely switch between wind pollinated and animal pollinated crops without costs and therefore suffer no welfare loss from pollinator declines (see Section 2.4. for a full discussion). Furthermore, this study, like Morse and Calderone, Losey and Vaughn (2006) and Calderone (2012), primarily uses the dependence ratios of Robinson *et al.* (1989) which are mainly drawn from expert opinion rather than field study.

The annual migration of monarch butterflies (*Danaus plexippus*) has high cultural value and recent surveys indicate monarch populations are declining. Understanding how much, and where, humans place value on migratory species can facilitate market-based conservation approaches. Diffendorfer *et al.* (2014) performed a contingent valuation study of monarchs to understand the potential for such approaches to fund monarch conservation. The survey asked U.S. respondents about the money they would spend, or have spent, growing monarch-friendly plants, and the amount they would donate to monarch conservation organizations. The study found nearly three-quarters of those surveyed support conservation efforts for the species. Combining planting payments and donations, the survey indicated U.S. households valued the existence of monarchs (as a total one-time payment) at $5bn–$6.9bn, levels similar to many endangered vertebrate species. This value is likely an over-estimate as it is based on the assumption that all households would be willing to pay an average of $32-$42 (2015 US$). Nonetheless, it highlights that the financial contribution of even a small percentage of households could generate new funding and resources for monarch conservation through market-based approaches.

Beyond the USA, Gordon and Davis (2003) examined the consumers and producers surplus value of honeybee pollination in relation to 35 crops grown in Australian agriculture using a partial equilibrium model (Section 2.4.). This study calculates demand curves for both domestic and imported production of each crop in order to capture consumer's ability to switch between domestic and imported product. The import elasticity is usually larger the domestic demand elasticity as, on the international market, the Australian products are, in many cases, relatively easily be replaced by products from other countries. The producers' surplus is calculated for three assumptions regarding the loss of income, following a decline in the pollination service that farmer will incur before they switch to another crop; 0%, 30% or 100%. If farmers, following a loss of the pollination service, immediately switch to a new crop that does not depend on pollination, the producers' surplus is zero (equivalent to Southwick and Southwick, 1992). The results estimate the value of pollination services to Australian consumers at $720M (2015 US$), while the producers' surplus varied depending on when producers switched crops from $0 (producers immediately switch to other crops) to $762M (producers switch to other crops at 100% income loss) (2015 US$).

An and Chen (2011) found that the stock of honeybee colonies in China had increased by 161% between 1961 and 2009, while the area of fruit and vegetable cultivation had increased by 472%, and their production had increased by 833%. The total economic value of insect pollination of Chinese fruits and vegetables amounted to $57bn (2015 US$) in 2008, which represented 25.5% of the total production value of the 44 crops produced in China. Similarly, Liu *et al.* (2011), using a dependence ratio method, assessed the economic benefits of honeybee pollination services to 36 crops during 2006-2008. In total 60-87.95 million colonies were required to supply Chinese pollination demands in 2008.The average economic benefits of honeybee pollination between 2006-2008, was estimated at $56.1bn (2015 US$), equivalent to 76 times the value of apicultural production, 12.3% of the gross output value of agriculture in China. These results indicate that Chinese agriculture benefits substantially from pollination, particularly from managed honeybees with the greatest demand from vegetables, fruits and cotton.

One of the principle challenges in dependence ratio studies is the potential for inaccurate measurements of benefits to bias dependence ratios. Garratt *et al.* (2014) estimate, based on a yield analysis extrapolated up to a national scale, that insect pollination increases the net income of producers of two major apple cultivars (Cox and Gala) in the UK by of $62.1M (2015 US$). This study found that insect pollination affects the quality and harvesting costs of apples as well as the number of fruits set. These effects are variety-specific however, with greater effects on yield and quality in Gala ($25,020/ha) than Cox ($20,119/ha) (2015 US$). Accounting for the differences between cultivars and the effects on costs and quality, the estimated national scale benefits were over $10.5M (2015 US$) greater than estimates considering the effects on fruit set alone. Furthermore, the study examined the gap between actual and potential yields, identifying a production gap in Gala worth up to $9.6M (2015 US$) at market prices. This case study highlights the importance of accurate, cultivar specific estimates of pollination service benefits on all facets of output (quality, quantity and costs), particularly at larger scales.

7.3 Global scale

Since the 1990s, there have been several attempts to analyse the value of the pollination service at the global scale. Costanza *et al.* (1997) provide an early estimate of $177.9bn/year (2015 US$) for pollination services, however this value is based on the assumption that 100% of insect pollinated crop yields would be lost without pollination services (see Section 2.1).

More recently, Gallai *et al.* (2009a) used a dependence ratio method to estimate the contribution of pollinators to the production of 100 crops used directly for human food worldwide as listed by FAO in 2005. The total market price of this additional production from pollination was estimated at $232bn (2015 US$) worldwide, representing 9.5% of the value of the world crop production in 2005. The market price of a ton of the crop categories that do not depend on insect pollination averaged $174/tonne (2015 US$) while that of those that are pollinator-dependent averaged $876/tonne (2015 US$). The study also estimated the economic value of this pollination service loss at $176.2bn-$302.9bn (2015 US$) (based upon a crop price elasticity of −1.5 to −0.8, respectively) in lost consumer surplus using a partial equilibrium model. This difference illustrates that standard dependence ratio models are unlikely to be effective proxies for the true value of pollination services. However, like most consumer surplus studies applied to pollination, these findings are based on the unrealistic assumption that the producers will be able to freely switch between insect pollinators and non-pollinated crops (see Section 2.4.). Gallai *et al.* (2009a) also identified the economic vulnerability of different regions to pollination service losses by estimating the proportion of the regions total output of crop agricultural that would be lost without pollination services. This analysis identifies Middle East Asia, Central Asia and East Asia as the regions most vulnerable to pollination service losses, with pollination responsible for 15%, 14% and 12% of output respectively.

Lautenbach *et al.* (2012), used dependence ratio method to develop maps of global pollination service benefits on 5' by 5' latitude-longitude grid based on cropping patterns in the year 2000. Unlike other dependence ratio studies, the price of production estimated is weighted by the Power Purchasing Parity of each country, adjusting the market prices depending on the relative purchasing power (the amount that can be bought, reflecting the general costs of living in that country) from one US dollar in each country (see Section 3). As such, benefits are adjusted upwards in countries where the cost of living is low and downwards in countries with a high cost of living, making the estimates more comparable between countries. Globally the contribution of pollination to market output, estimated at an aggregate $235bn-$577bn (2015 US$), shows an increasing trend from 1993 to 2009. Spatially, these benefits are focused on a small number of countries: particularly China, India, the USA, Brazil, Japan and Turkey. Comparing the proportion of agricultural GDP that depends on pollination for 1993 vs. 2009: countries like Azerbaijan (3% vs. 13.8%), Russia (2% vs. 6.6%) or Armenia (1.2% vs. 7.6%) have increased their pollination dependency, while China (20% vs. 15.3%). Brazil (15.9% vs. 10%), India (9.4% vs. 4.5%), have decreased their vulnerability. Others such as Canada (7.7% vs. 7.6% in 2008) have remained stable. Pollination benefits show a strong spatial pattern at the sub national scale. For the USA, highest values are observed in parts of California and further north along the West Coast. The highest pollination benefits per hectare arable land in Asia can be found in east China, Japan and South Korea. In Europe, large parts of Italy as well as Greece are exceptional.

The spatial distribution of pollination service benefits also depends on crop species. Soybean is an example of a widely grown, pollination-profiting crop with relative high impact on pollination benefits (values up to $543/ha -2015 US$). Pollination benefits through cotton show a similar widely spread pattern that is generally shifted towards the Equator. The highest benefits (up to $1,662/ha – 2015 US$) can be identified on regional scale in the Chinese provinces Jiangsu, Hubei and Shannxi. Apples and pears show strong overlapping patterns of pollination benefits (Lautenbach *et al.*, 2012).

Although an estimate of economic value, the partial equilibrium modelling employed by Gallai *et al.* (2009a) is limited by its inability to account for producer input substitution and only considers the producers and consumers of a single market rather than a broader, multi-market perspective. Bauer and Wing (2014), address this by comparing consumer and producer surplus estimates resulting from global pollinator losses using both a partial equilibrium model and a general equilibrium model (Section 2.4) that considers losses on other markets besides crop production e.g., agricultural inputs. These markets will be affected by widespread changes to farming practices, affecting the consumers and producers within the market. Their findings indicate that the partial equilibrium model tends to overestimate the value of services to crop markets, ($259.8bn-$351bn – 2015 US$) compared to in the general equilibrium model ($160bn-$191bn – 2015 US$) due to the latter's capacity to account for producers changing strategies to adapt to pollinator losses. However, because it focuses only on a single market the partial equilibrium model underestimates total benefit ($367.9bn-$689.3bn – 2015 US$). At a regional level, the findings indicate that a loss of local pollination services in South America would have the most negative impacts on local crop markets ($6.4bn – 2015 US$) while Eastern Asia would suffer the largest losses to other markets ($115.4bn – 2015 US$) and North America the largest total losses ($90.5bn – 2015 US$). In some regions, the loss of pollinators would increase total crop market value, particularly in East Asia ($26.3bn – 2015 US$) and crop markets in all regions benefit from the loss of services in any other region, with the loss of services in North America increasing crop pollination value in other regions by $15.8bn (2015 US$).

7.4 Synthesis of case studies

7.4.1 Comparing estimates

The studies highlighted above are part of a larger body of literature that has evolved continuously over the last 20 years. However, estimates of the economic benefits of pollinators can vary strongly between countries, regions and crops. Furthermore, price inflation and the resultant changes in the buying power of currency make comparisons between years difficult. To illustrate the impact of these variations, **Table 4.9** collects available studies from a wide range of sources and expresses them in 2015 US$.

Scale issues can create substantial difficulties in comparing estimates of the economic benefits of crop pollination. Studies covering larger areas and crops with a higher market price inherently produce higher estimates than smaller scale studies on crops with a lower market price. Comparison of estimates can be further facilitated by considering values on a per hectare scale by dividing aggregates by the number of ha for crop production considered in the study of concern **(Table 4.10)**. When considering the six studies at the global scale, the average benefits of pollination services per ha (in 2015 US$) is between $34/ha (2015 US$ – Costanza *et al.*, 1997) and $1,891/ha (2015 US$ – Bauer and Wing, 2014, using a general equilibrium model – Section 2.5.). However, these estimates are hard to accurately compare as they are in reality expressing different things – from the market price of crops (Costanza *et al.*, 1997) to the welfare value of pollination services (Bauer and Wing, 2014). Furthermore, the per hectare values from surplus valuation studies only represent an average of the welfare loss resulting from the complete loss of pollination services and will shift if anything less than the total area of pollinated crop experiences pollinator losses. Of the three global scale dependence, ratio studies two produce relatively similar estimates (Gallai *et al.*, 2009a; Lautenbach *et al.*, 2012). However, Gallai *et al.* (2009a) only presents a single estimate of value, based on the median dependence ratios in Klein *et al.* (2007). Furthermore, it does not weight estimates in different regions by the purchasing power parity of the region. As such, although the figures appear very similar, they are actually strongly divergent. Using the same median dependence ratio values as Gallai *et al.* (2009a), Lautenbach *et al.* (2012) estimates total global benefits of $400bn (2015 US$), an increase largely due to the weighting effect of purchasing power parity increasing benefits in regions where the cost of living is low (as 1$ is worth more). This average is similar to the estimate by Pimentel *et al.* (1997) however, this study bases its estimates on an upscaling of the estimates from Robinson *et al.* (1989), assuming that the USA accounts for approximately 20% of the global benefits of pollination services.

Table 4.10 also illustrates that estimated benefits differ strongly between crops **(Table 4.10)** due to differences in the prices of the crops. For example, in the UK the benefits per ha of raspberries ($7,641/ha 2015 US$; Lye *et al.*, 2011) are lower than the one of apples ($25,210/ha 2015 US$; Garratt *et al.*, 2014). Secondly, studies considering multiple crops return smaller estimates than those considering only a single crop (e.g., the pollinator-dependent market output to all 18 UK crops collectively is estimated at $1,321/ha

2015 US$ – Vanbergen *et al.*, 2014). To facilitate further discussion, **Table 4.11** compiles all estimates of benefits on a per-hectare scale for apple (*Malus domestica*), a widely studied and grown fruit crop with high market value.

Table 4.11 illustrates that estimates still differ strongly between countries and regions for the same crop e.g., the benefits of pollination service to apples in China ($10,399/ha – 2015 US$) are lower than in the USA (maximum $17,365/ha 2015US$ – Calderone, 2012; **Table 4.11**). There are also notable differences between benefits estimated with different valuation methods for the same crop **(Table 4.11)** – with replacement costs producing substantially smaller estimates ($791-$1,634 2015 US$, Allsopp *et al.*, 2008) than most dependence ratio studies ($1,566-$21,744 2015 US$; Zych and Jakubiec, 2006; Calderone, 2012). Even with these controls however, it is difficult to compare the different methods as, although each is expressed in monetary units, all methods measure fundamentally different benefits (see Section 2). However, at both aggregate and per hectare scales, it is apparent that the choice of method can influence the magnitude of impacts that decisions are based on, highlighting the need for transparent, clear and comprehensive assessments of economic benefits in the decision process.

7.4.2 Constraints and limits of current economic valuations

Many studies give an economic valuation of pollinators and pollination service and demonstrate the societal impacts a change in pollinators could potentially have. However, most of these valuation studies focus upon the contribution of pollinators to agricultural production without directly linking it with farmer decision-making. While a great number of studies have illustrated the impacts of animal pollination services on the agricultural sector, studies examining the impacts of pollinator management on producer profits (e.g., Ricketts *et al.*, 2004) and marginal producer welfare (e.g., Kasina *et al.*, 2009) are relatively rare, limiting the extent of decision support that can be provided by these estimates. Various knowledge gaps also limit the capacity to accurately transfer these benefit estimates to other regions. Finally, most studies that have estimate the economic value of pollination services (Southwick and Southwick, 1992; Gallai *et al.*, 2009a; Winfree *et al.*, 2011; Ritter, 2013 – **Table 4.9**) have almost exclusively focused on the benefits to consumers rather than considering the potential benefits to producers from rising prices (but see Bauer and Wing, 2014).

Most studies focus on pollination services in their entirety – assuming a complete loss of wild and managed pollinators. While this demonstrates the benefits of pollinators as whole, it can under- or over-state the contextual importance of one group or the other, with several studies suggesting that managed pollinators are perfect substitutes for wild species (e.g., Winfree *et al.*, 2011) or that wild species are incapable of fully replacing managed pollinators (e.g., Southwick and Southwick, 1992). In reality Garibaldi *et al.* (2013) demonstrates that in many systems, wild pollinators cannot be perfectly substituted with managed honeybees (the most widespread managed pollinator) and Rader *et al.* (2009) illustrate the contextual importance of both groups. Understanding and measuring the relative importance of both groups to crop production would allow for more targeted and effective management strategies.

Finally, as illustrated in the TEV diagram **(Figure 4.1)**, the benefit to society offered by pollination service is broader than food production alone. The benefits of landscape aesthetics, wild plant diversity and crop genetic resources to present and future generation are also essential for the maintenance of the social welfare. However, very few studies have directly addressed this point, limiting the perspective of benefits to just the most overtly consumable (Mwebaze *et al.*, 2010; Diffendorfer *et al.*, 2014; Breeze *et al.*, 2015).

TABLE **4.9**
Summary of estimates of the economic value of pollination services in 2015 US$

Study	Region	Crops	Method	Year	2015US$
Farm/local scale					
Shipp *et al* (1994)	Canada	Sweet Peppers (cubico)	Yield analysis	1992	$47,784- $75,190/ha
Priess *et al* (2007)	Indonesia	Coffee	Yield analysis	2001	$55.34/ha
Olschewski *et al* (2006)	Indonesia	Coffee	Yield analysis	2001	$63/ha
Olschewski *et al* (2006)	Indonesia	Coffee	Yield analysis	2001	$66/ha
Whittington *et al* (2004)	Canada	Tomatoes	Yield analysis	2001	$434-$2,344/ha
De Marco and Coelho (2004)	Brazil	Coffee	Yield analysis	2003	$2415/ha
Sandhu *et al* (2008)	New Zealand	NA	Hive rental	2004	$78-$81/ha
Nderitu *et al* (2008)	Kenya	Sunflower	Yield analysis	2005	$2072/farm
Lye *et al* (2011)	UK	Raspberries	Yield analysis	2010	$7641/ha
Mouton (2011)	South Africa	Apples (Granny smith)	Yield analysis	2007/2008	$18,216/ha
Regional scale					
Turpie *et al* (2003)	South Africa (Cape Florsitic Region)	All	Dependence ratio	1999	$426.1M
Greenleaf and Kremen (2006)	California, USA	Hybrid sunflower	Yield analysis	2002	$34.6M
Guerra-Sanz (2008)	Almeria, Spain	8 Glasshouse crops	Dependence ratio	2002	$764.6M
Allsopp *et al* (2008)	South Africa (Cape Florsitic Region)	Apples, plums, apricots	Dependence ratio	2005	$413.2M
Allsopp *et al* (2008)	South Africa (Cape Florsitic Region)	Apples, plums, apricots	Replacement costs	2005	$94.2M-$529.7M
Chaplain-Kramer *et al* (2011)	California, USA	All	Dependence ratio	2007	$3.1bn-$7.2bn
Barfield *et al* (2015)	Georgia, USA	30 Crops	Dependence ratio	2009	$673.8M
Winfree *et al* (2011)	New Jersey, USA	Watermelons	Partial equilibrium model (CS only)	2009	$4.02M-$4.03M
Winfree *et al* (2011)	New Jersey, USA	Watermelons	Replacement costs	2009	$0.2M-$0.23M
Ritter (2013)	Oregon, USA	Blueberry	Partial equilibrium model (CS only)	2011	$9.7M-$11.8M
National scale					
Metcalf and Flint (1962)	USA	30 Crops	Crop value	1957	$38.2bn
Levin (1984)	USA	All	Crop value	1984	$4.5bn
Matheson and Schrader (1987)	New Zealand	All	Crop value	1986	$2.6bn
Robinson *et al* (1989)	USA	All	Dependence ratio	1986	$20.3bn
Southwick and Southwick (1992)	USA	All	Partial equilibrium model (CS only)	1987	$3.4bn-$11.9bn
Gill *et al* (1989)	Australia	35 Crops	Partial equilibrium model (CS only)	1989	$0.9bn-$1.8bn
Carreck and Williams (1998)	UK	All	Dependence ratio	1996	$479.1M
Calzoni and Speranza (1998)	Italy	Plums	Replacement costs	1996	$394.1M
Calderone (2012)	USA	All	Dependence ratio	1997-2009	$4,666-$7,311/ha
Canadian Honey Council (2001)	Canada	All	Dependence ratio	1998	$770.7M
Losey and Vaughn (2006)	USA	51 Crops	Dependence ratio	2003	$4.0bn
Brading *et al* (2009)	Egypt	All	Dependence ratio	2004	$3.0bn
Zych and Jakubiec (2006)	Poland	19 Crops	Dependence ratio	2004	$311M
Kasina *et al* (2009)	Kenya (small holdings)	8 Crops	Yield analysis	2005	$3.9M
Basu *et al* (2011)	India	6 Vegetable crops	Dependence ratio	2007	$831.8M
Basu *et al* (2011)	India	6 Vegetable Crops	Partial equilibrium model (CS only)	2007	$1.5bn
Smith *et al* (2011)	UK	18 Crops	Dependence ratio	2007	$986.1M
An and Chen (2011)	China	Horticultural crops	Dependence ratio	2008	$57.0bn

TABLE **4.9**
Summary of estimates of the economic value of pollination services in 2015 US$

Study	Region	Crops	Method	Year	2015US$
National scale					
Calderone (2012)	USA	All	Dependence ratio	2009	$17.1bn
Mwebaze *et al* (2010)	UK (pollinators)	NA	Stated preferences (contingent valuation)	2009	$3.0bn
Garratt *et al* (2014)	UK	Apples (2 Cultivars)	Yield analysis	2010	$62.1M
Calderone (2012)	USA	All	Dependence ratio	2010	$17.9bn
Breeze *et al* (2015)	UK (pollination service benefits)	NA	Stated preferences (choice experiments)	2010	$1175M-$640M
Vanbergen *et al* (2014)	UK	18 Crops	Dependence ratio	2011	$1,173.4M
Giannini *et al* (2015)	Brazil	85 Crops	Dependence ratio	2012	$12.5bn
Gill *et al* (1991)	Australia	35 Crops	Partial equilibrium model (CS only)	1986/1987	$523M-$10,858M
Morse and Calderone (2000)	USA	All	Dependence ratio	1996-1998	$21.8bn
Gordon and Davis (2003)	Australia (honeybees)	35 Crops	Partial equilibrium model	1999-2000	$1.5bn
Cook *et al* (2007)	Australia (honeybees)	25 Crops	Dependence ratio	1999-2003	$16.8M-$39.9M*
Sanjerehei (2014)	Iran	32 Crops	Dependence ratio	2005-2006	$7.9bn
Stanley *et al* (2013)	Ireland	Oilseed rape	Yield analysis	2009-2011 av	$5.8M
Multinational scale					
Klatt *et al* (2014)	EU	Strawberries	Yield analysis	2009	$1.6bn
Partap *et al* (2012)	Himalayan region	All	Partial equilibrium model (CS only)	2008/09	$3.0bn
Leonhardt *et al* (2013)	Europe	All	Dependence ratio	1991-2009 av	$24.0bn
Global scale					
Pimentel *et al* (1997)	Global	All	Dependence ratio	1986	$435.9bn
Costanza *et al* (1997)	Global	All	Crop value	1996	$177bn
Bauer and Wing (2014)	Global	All	Partial equilibrium model	2004	$160bn-$191.5bn
Bauer and Wing (2014)	Global	All	General equilibrium model	2004	$367.9bn-$689.3bn
Gallai *et al* (2009)	Global	All	Dependence ratio	2005	$232.1bn
Gallai *et al* (2009)	Global	All	Surplus analysis	2005	$176.2bn-$486bn
Lautenbach *et al* (2012)	Global	All	Dependence ratio	2009	$235.1bn-$577bn**

*: These values are subject to discounting on a 30 years time scale
: These values are not reported directly in the paper but can be read from **Figure 4.1

Study: The cited reference in which the original value was found. **Region**: The region over which the estimates of benefit was conducted. **Crops**: The crops that were assessed for value with all denoting all possible insect pollinated crops in the region for which data was available. NA denotes studies where the method does not apply to a specific crop. **Method**: Denotes the method used to estimate benefit: Crop Value (2.2.1), Hive Rental (2.1.2), Yield Analysis (2.2.1.), Dependence Ratio (2.2.2.), Replacement Costs (2.3), Partial Equilibrium Analysis (CS = Consumer Surplus; PS = Producer Surplus) and General Equilibrium Analysis (2.4) and Stated Preferences (2.5.). **Year**: the year the estimate relates to, usually based on what year the data relate to, studies denoted av = average of the years. **2015 US$**: The monetary estimate of the study inflated (and in many cases converted) to 2015 US$ as of July 2015 – this was done to standardize the estimates to some extent.

All estimates were converted into US dollars using average annual spot exchange rates from the Bank of England (Bank of England, 2015). These dollar estimates were inflated to 2015 US$ using Consumer Price Index (CPI) data from the United Stated Federal Government's Bureau of Labour and Statistics (BLS, 2015a, Table 24). Inflation was based on the CPI for July of the year the estimate was related to compared with the CPI in July 2015 (BLS 2015b, Table 1). If this year was not stated then they were assumed to be the year before the study was published. Where a study used average data from across several years (e.g., Lui *et al.*, 2011), conversion and inflation rates were averaged across the years concerned. These inflations only represent a change in the value of currency and do not capture any changes such as the relative input prices, price controls or subsidies. Note that the value of $1 will still vary between countries based on their purchase power piety (see Section 3).

TABLE **4.10**
Summary of estimates of the economic value of pollination services per hectare in 2010 US$ for several crops in different regions of the world

Study	Region	Crops	Method	Year	2015US$/ha
Farm/local scale					
Shipp *et al* (1994)	Canada	Sweet Peppers (cubico)	Yield analysis	1992	$47,784- $75,190/ha
Priess *et al* (2007)	Indonesia	Coffee	Yield analysis	2001	$55.34/ha
Olschewski *et al* (2006)	Indonesia	Coffee	Yield analysis	2001	$63/ha
Olschewski *et al* (2006)	Indonesia	Coffee	Yield analysis	2001	$66/ha
Whittington *et al* (2004)	Canada	Tomatoes	Yield analysis	2001	$434-$2,344/ha
De Marco and Coelho (2004)	Brazil	Coffee	Yield analysis	2003	$2415/ha
Sandhu *et al* (2008)	New Zealand	NA	Hive rental	2004	$78-$81/ha
Nderitu *et al* (2008)	Kenya	Sunflower	Yield analysis	2005	$2072/farm
Lye *et al* (2011)	UK	Raspberries	Yield analysis	2010	$7641/ha
Mouton (2011)	South Africa	Apples (Granny smith)	Yield analysis	2007/2008	$18,216/ha
Regional scale					
Allsopp *et al* (2008)	South Africa (Cape Florsitic Region)	Apples, plums, apricots	Dependence ratio	2005	$12,579/ha
Allsopp *et al* (2008)	South Africa (Cape Florsitic Region)	Apples, plums, apricots	Replacement costs	2005	$2,867-$16,127/ha
Winfree *et al* (2011)	New Jersey, USA	Watermelons	Partial equilibrium model (CS only)	2009	$5,393-$5,407/ha
Winfree *et al* (2011)	New Jersey, USA	Watermelons	Replacement costs	2009	$267-$312/ha
Ritter (2013)	Oregon, USA	Blueberry	Partial equilibrium model (CS only)	2011	$1,242-$1,510/ha
National scale					
Carreck and Williams (1998)	UK	All	Dependence ratio	1996	$842/ha
Calderone (2012)	USA	All	Dependence ratio	1997-2009	$4,666-$7,311/ha
Kasina *et al* (2009)	Kenya (small holdings)	8 Crops	Yield analysis	2005	$163/ha
Basu *et al* (2011)	India	6 Vegetable crops	Dependence ratio	2007	$458/ha
Basu *et al* (2011)	India	6 Vegetable Crops	Partial equilibrium model (CS only)	2007	$804/ha
Smith *et al* (2011)	UK	18 Crops	Dependence ratio	2007	$1161/ha
Garratt *et al* (2014)	UK	Apples (2 Cultivars)	Yield analysis	2010	$20,199-$25,201
Vanbergen *et al* (2014)	UK	18 Crops	Dependence ratio	2011	$1,321/ha
Giannini *et al* (2015)	Brazil	85 Crops	Dependence ratio	2012	$1321/ha
Stanley *et al* (2013)	Ireland	Oilseed Rape	Yield analysis	2009-2011 av	$652/ha
Multinational scale					
Klatt *et al* (2014)	EU	Strawberries	Yield analysis	2009	$14,968/ha
Leonhardt *et al* (2013)	Europe	All	Dependence ratio	1991-2009 av	$75/ha
Global scale					
Costanza *et al* (1997)	Global	All	Crop value	1996	$34/ha
Bauer and Wing (2014)	Global	All	Partial equilibrium model	2004	$439-$526/ha
Bauer and Wing (2014)	Global	All	General equilibrium model	2004	$1,010-$1,891/ha
Gallai *et al* (2009)	Global	All	Dependence ratio	2005	$624/ha
Gallai *et al* (2009)	Global	All	Surplus analysis	2005	$473-$1,306/ha
Lautenbach *et al* (2012)	Global	All	Dependence ratio	2009	$717-$1,760/ha

Study: The cited reference in which the original value was found. **Region**: The region over which the estimates of benefit was conducted. **Crops**: The crops that were assessed for value with "All" denoting all possible insect pollinated crops in the region for which data was available. **Method**: Denotes the method used to estimate benefit: Crop Value (2.2.1), Hive Rental (2.1.2), Yield Analysis (2.2.1.), Dependence Ratio (2.2.2.), Replacement Costs (2.3), and Partial Equilibrium Analysis and General Equilibrium Analysis (2.4). **Year**: the year the estimate relates to, usually based on what year the data relate to, studies denoted av = average of the years. **2015 US$/ha**: The per hectare monetary estimate of the study inflated (and in many cases converted) to 2015 US$ as of July 2015 – this was done to standardize the estimates to some extent. Per hectare values were calculated by dividing the value estimates by the area of crop reported by either the paper itself or the data sources it cites.

All estimates were converted into US dollars using average annual spot exchange rates from the Bank of England (Bank of England, 2015). These dollar estimates were inflated to 2015 US$ using Consumer Price Index (CPI) data from the United Stated Federal Government's Bureau of Labour and Statistics (BLS, 2015a, Table 24). Inflation was based on the CPI for July of the year the estimate was related to compared with the CPI in July 2015 (BLS 2015b, Table 1). If this year was not stated, then they were assumed to be the year before the study was published. These inflations only represent a change in the value of currency and do not capture any changes such as the relative input prices, price controls or subsidies. Note that the value of $1 will still vary between countries based on their purchase power piety (see Section 3).

TABLE **4.11**
Summary of the estimates of the economic value of pollination service to apple in 2015 $USD per hectare

Study	Region	Crops	Method	Year	2015US$/ha
Mouton (2011)	South Africa	Apples (Granny smith)	Yield Analysis	2007/08	$18,216
Garratt *et al* (2014)	UK	Apples (Cox and Gala)	Yield Analysis	2010	$20,199-$25,201
Gianni *et al* (2015)	Brazil	Apples	Dependence Ratio	2012	$7,715
Vanbergen *et al* (2014)	UK	Dessert Apples	Dependence Ratio	2011	$18,902
Calderone (2012)	USA	Apples	Dependence Ratio	2010	$17,365
Leonhardt *et al* (2013)	EU	Apples	Dependence Ratio	1991-2009 av	$8,016
An and Chen (2011)	China	Apples	Dependence Ratio	2008	$10,399
Smith *et al* (2011)	UK	Dessert Apples	Dependence Ratio	2007	$20,730
Calderone (2012)	USA	Apples	Dependence Ratio	2007	$21,774
Allsopp *et al* (2008)	South Africa (Cape Florsitic Region)	Apples	Dependence Ratio	2005	$12,137
Gallai *et al* (2009)	Global	Apples	Dependence Ratio	2005	$3,776
Zych and Jakubiec (2006)	Poland	Apples	Dependence Ratio	2004	$1,566
Losey and Vaughn (2006)	USA	Apples	Dependence Ratio	2003	$13,078
Cook *et al* (2007)	Australia	Apples	Dependence Ratio	1999-2003	$15,229
Calderone (2012)	USA	Apples	Dependence Ratio	2002	$15,639
Morse and Calderone (2000)	USA	Apples	Dependence Ratio	1996-1998	$10,654
Allsopp *et al* (2008)	South Africa (Cape Florsitic Region)	Apples	Replacement Costs	2005	$791-$1,634
Partap *et al* (2012)	Himalayan region	Apples	Partial Equilibrium Model (CS only)	2008/2009	$3,975
Gallai *et al* (2009)	Global	Apples	Partial Equilibrium Model (CS only)	2005	$6,083

Study: The cited reference in which the original value was found. **Region**: The region over which the estimates of benefit was conducted. **Crops**: The crops that were assessed for value with all denoting all possible insect pollinated crops in the region for which data was available. NA denotes studies where the method does not apply to a specific crop. **Method**: Denotes the method used to estimate benefit: Yield Analysis (2.2.1.), Dependence Ratio (2.2.2.), Replacement Costs (2.3) and Partial Equilibrium Analysis (2.4). **Year**: the year the estimate relates to, usually based on what year the data relate to, studies denoted av = average of the years. **2015 US$**: The monetary estimate of the study inflated (and in many cases converted) to 2015 US$ as of July 2015 – this was done to standardize the estimates and facilitate comparison.

All estimates were converted into US dollars using average annual spot exchange rates from the Bank of England (Bank of England, 2015). These dollar estimates were inflated to 2015 US$ using Consumer Price Index (CPI) data from the United Stated Federal Government's Bureau of Labour and Statistics (United States Bureau of Labour and Statistics, 2015a, Table 24). Inflation was based on the CPI for July of the year the estimate was related to compare with the CPI in July 2015 (BLS, 2015b, Table 1). If this year was not stated, then they were assumed to be the year before the study was published. These inflations only represent a change in the value of currency and do not capture any changes such as the relative input prices, price controls or subsidies. Note that the value of $1 will still vary between countries based on their purchase power piety (see Section 3). Where the area of apples was not reported within the study, the source material for the value of apple production was consulted and area data for the appropriate year were used to calculate these values.

SECTION 8. SYNTHESIS AND CONCLUSION

This chapter reviewed the conceptual framework and the different methods of economic valuation of pollinators and pollination services. Thus, more than 60 economic valuations of pollination were analysed at different spatial and temporal scales (**Table 4.9**, Section 7). These findings demonstrate the substantial economic benefits derived from pollinators and pollination in food production and biodiversity on several components of social welfare as represented by the different economic values (monetary and non-monetary).

The TEV of pollinators and pollination services

The chapter has identified and adapted the economics behind pollinators and pollination services. As explained in Section 1, economic theory gives a well-defined framework to comprehend the status and the value of pollinators and pollination for human wellbeing. There are multiple values identified by the TEV (Total Economic Value) associated pollinators and pollination services diagram **(Figure 4.1)**. The chapter has highlighted the breadth of benefits that pollinators and pollination services provide within the TEV framework, while the literatures has to date only considered pollination as a provision service and an indirect service (see for example Pascual *et al.*, 2010; Fisher *et al.*, 2009). Pollinators and the benefits they produce through pollination services can be both marketed (honey bees, crops) or non-marketed (wild pollinators, aesthetic wildflowers). While pollinators can be rival, for many crops and wild plants that depend on cross-pollination, their services are non-rival. As such, pollinators often provide valuable, potentially irreplaceable services to human wellbeing. However, despite the breadth of possible benefits, to date, attempts to value these benefits are largely confined to crop pollination services (Section 7), leaving many aspects of pollination services unvalued.

A well-structured framework of methods that largely remains to be applied

A wide range of methods have been developed and used to value the contribution of pollinators and pollination to our society, but also to address the economic consequences of their gains or losses, including both their use (Section 2.2, 2.3 and 2.4) and non-use values (Section 2.5). However, to date, the majority of these methods (Section 2) and the studies applying them (Section 7) do not estimate the true economic value of these changes. Furthermore, many of these methods are limited by available data (Section 5) and are only suitable for application on specific spatial scales (Section 3), or under very specific niche circumstances (Section 2). On local scales, where a shift in pollination services is unlikely to cause price changes, production function models (Section 2.2.3) are more relevant to estimate the impacts of pollinator gains and losses on local producers. On larger scales, however, production function models are better suited to inform more comprehensive surplus valuation models that estimate the impacts on both producers and consumer welfare (Section 2.4).

How to account for the spatial and the temporal scale?

The scales at which ecological processes occur can be different to those at which economic decisions are made. Not taking account of scales could generate biased economic valuations by assuming that benefits are more consistent across time and space than they are. The chapter has adapted existing categories of temporal and spatial scales to encompass the diverse array of variables that affect pollination valuation (Section 3; **Table 4.5**). Considering the temporal scale of ecological and/or agronomical processes is essential, whether to understand the renewal rate of pollinator populations or the timing of crop production, among others. It is important that studies consider a range of market prices and productions cycles, but also more theoretical factors such as the discount rate that represent the way we value the future and, the availability of consistent, long-term data sets. Some tools exist in order to address long-term economic valuations, such as the scenario or time-series analyses but to date their use in valuing pollination services has been limited. Considering spatial scale is also fundamental to valuation and land-use decisions, as mismatches can undermine the distribution of economic and conservationist benefits originated from the pollination service quality, with different approaches required between the micro-, meso- or macroeconomic levels. Declining data quality on large scales could be overcome by broader and more detailed record keeping and several spatially explicit methods are available to support multi-scale assessments of pollination benefits, including the effects of landscape design. Although these adaptations are possible within existing methodologies, they have rarely been applied, leaving numerous questions regarding the likely variation of pollination service benefits across the world and to future generations.

The value of pollinators and pollination services also involves risk, uncertainty and resilience values

Although pollinator gains and losses can affect both the levels of pollination services and the potential for future services provided, to date, no study has explicitly quantified the economic risks and uncertainties inherent to populations (Section 4) and few have addressed the uncertainties within the data used to estimate these impacts (Section 7). While a number of suitable methods exist (Section 4.3), they have yet to be applied to pollinator management. Without this information, decision-making may be at risk of over-valuing benefits or under-valuing impacts from management affecting pollinators and populations, particularly over longer time periods (Section 3).

Guiding decision-makers in protecting, maintaining and enhancing pollinators and pollination services, for society

Economic analysis provides powerful information for decision-makers for many reasons. Throughout the chapter, we have defined the status of pollinators and pollination services in relation to property right structure (private good, club good, common good or public good, Section 1), explained how to estimate the (use- or non-use) value of pollinators and pollination, and reviewed the main values.

The type of property rights informs the stakeholder of their level of implication in maintaining the natural service. The estimated value of pollinators or pollination generates a monetary (or non-monetary) indicator that gathers information on the positive or negative impact of pollinators or pollination gain or loss. This indicator can be used in a number of forms including cost benefit (and cost-effectiveness) analysis, Multi-Criteria Analysis, environmental accounting and decision support tools (Section 6). The use of economic valuation varies between stakeholders; a farmer will not use the values in the same way, or for the same reasons, than an industry or a government. This is why the chapter presents the different ways to address the economic value for each level of stakeholder as well as the step-wise guide for using economic valuation for decision-making (Section 6).

Conclusion

The economic valuation of pollinators and pollination services is, in many contexts, an essential step for decision-making by governments and policy makers. Although many studies have been done, they mainly concentrate on the provision role of pollinators while the impact of pollinators on our society is much broader (e.g., the pollination of wild plants that enhance the biodiversity of landscapes or the marginal value of wild pollinators). Furthermore, few of them actively consider these benefits in relation to the costs of management to sustain them (Chapter 6) or, conversely, the benefits of management that may be detrimental to pollinators (Chapter 2). Understanding and quantifying these trade-offs is essential for informed policy and decision making at all scales, but particularly over the long term (Section 3) where a lack of sustainability may hamper resilience (Section 4).

Even more importantly, more comprehensive assessments of the economic impacts of pollinator gains and losses are needed to improve the measurements of the welfare consequences on changing pollinator populations. Further work is required to accurately estimate the benefit on crop production and non-crop production, the impacts on present and future generations, and the local and international consequences. The methods of economic valuation should be developed in this way, taking into account both market and non-market-based approaches. Furthermore, many of the methods would benefit from standardization in order to facilitate the aggregation and comparison of values gathered around the world and over time.

The concept of value is broad and it goes beyond a mere economic approach (Díaz *et al.*, 2015). Chapter 5 addresses these other broader forms of values. Determining the full plurality of these values will be necessary to guide decisions that affect pollinators and secure these benefits for future generations. Chapter 6 gives a detailed presentation of the different tools and existing policies to help maintain pollinators, and their implementation that will strongly benefit from robust valuations of the numerous benefits of pollination services.

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GLOSSARY

Benefit
The positive impacts produced by pollinators and pollination services (e.g., increased yield or quality of crops).

Capital
Any good, service or skill that can potentially generate production within a market. There are 5 forms of capital: Human (skills, education etc.), Manufactured (tools, buildings etc.), Financial (shares, bonds etc.), Social (institutions etc.) and natural (ecosystem services etc.). Units of capital are called assets. The sum of capital is called wealth.

Profit
It is the difference between the benefit of a firm and her total cost, where total cost is the sum of fixed and variable costs.

Consumer surplus
Consumer Surplus is defined as the difference between what consummer would accept to pay (WTP) to get a service and the cost they actually bear.

Producer Surplus
Producer surplus is the difference the amount that a producer willing to sell a good (his marginal cost) and the amount that he receives.

Welfare
The welfare measure the well-being of a society. One method to measure the welfare is to summing the producer and the consumer surpluses. A more practical way to measure it is the Growth National Product per capita.

Cost-Benefit Analysis (CBA)
The CBA is a method where it is evaluating in monetary terms the environmtal impact of a project or an event (e.g., the climate change) and assessing the beenfits and the costs associated with different options of the project or to reduce the event (e.g., reducing the climate change).

Economic vulnerability
Vulnerability refers to the possibility that the environment could be degradated. Economic vulnerability can be declined in firms' vulnerability and consumers' vulnerability. The firms vulenrarbility would be the potential loss in profit due to pollinators loss and the consumer vulnerability would be the potential loss in utility due to pollinators loss. The vulnerability concept has been broadly study in the literature. We will retain one definition from Turner *et al.* (2003)[4] where vulnerability is a function of three overlapping elements: exposure, sensitivity, and adaptive capacity.

Intrinsic value
It is the value with give to pollination service just because the benefit of this service is good in and of itself. We are not supposed to use in order to acquiring something else. Intrensic value of pollinators is the value of their existence.

Instrumental value
It is a good for which we give a value because it provides the mean s for acquiring something else of value. Instrumental value of pollinators is the service provide by their activity as honey or crop production.

Monetary valuation
it is the valuation in money of the environmental service offers by pollinators.

Net present value
It is a temporal financial expression. It is the sum of actualized future cash flow, both incoming and outgoing.

Non-monetary valuation
It is the valuation of the impact of an environemental service in the society not expressed in money. This valuation can be quantitative (e.g., loss in CO2 production) and/or qualitative (e.g., sense of the impact positive or negative).

Price
The market (or pseudo-market) exchange value of a good or service.

Production functions
it is the function that model the process of transformation of inputs into final output. It could be also defined as the process to convert costs into revenue.

Purchasing power parity
Value of money expressed in terms of units of goods that money can command.

4. Turner, B. L., Kasperson, R. E., Matson, P. A., McCarthy, J. J., Corell, R. W., Christensen, L., Eckley, N., Kasperson, J. X., Luers, A., Martello, M. L., Polsky, C., Pulsipher, A., and Schiller, A. (2003). A framework for vulnerability analysis in sustainability science. *Proceedings of the National Academy of Sciences of the United States of America,* 100(14), 8074–8079. doi:10.1073/pnas.1231335100

Sustainability
A development process economically efficient, socially equitable and environmentally stable that will enable future generations to be at least as happy as we are.

Value
The impact of pollinators and pollination services on welfare via changes in benefits. This can be measured in economic or social terms.