Review
Economic Measures of Pollination Services: Shortcomings and Future Directions

Tom D. Breeze,1,* Nicola Gallai,2 Lucas A. Garibaldi,3 and Xui S. Li4

Over the past 20 years, there has been growing interest in the possible economic impacts of pollination service loss and management. Although the literature area has expanded rapidly, there remains ongoing debate about the usefulness of such exercises. Reviewing the methods and findings of the current body of literature, this review highlights three major trends: (i) estimated benefits are heterogeneous, even when using the same method, due to several often-neglected factors. (ii) The current body of literature focuses heavily on the developed world, neglecting the effects on developing countries. (iii) Very few studies are suitable for informing management and policy. The review highlights the need for fully interdisciplinary work that embeds stakeholders and economic impacts into primary ecological research.

Valuing Pollination Services
The concept of ecosystem services, the benefits (see Glossary) received by human society from natural ecological processes, is a major catalyst for current ecological and interdisciplinary research. Quantitative measures of ecosystem service benefits are often expressed in monetary terms. Monetisation of ecosystem service benefits is alleged to support biodiversity and ecosystem service conservation by raising awareness of impacts and facilitating budget-efficient management [1]. However, critics of monetisation argue that it has produced some political impetus but seldom any observable benefits to biodiversity or sustainable land management, with most studies remaining largely illustrative [2,3]. Furthermore, many ‘payments for ecosystem services’ schemes, which aim to develop markets for ecosystem service provision with defined buyers and sellers, do not base their exchanges on estimates of the monetary benefits (e.g., [4]). This has resulted in substantial debate about the worth of economic valuation in current biodiversity conservation [2,5,6].

Pollination is one of the most widely studied ecosystem services globally, underpinning 78% of global flowering plant reproduction [7] and enhancing production in 75% of globally important crops [8]. As such, monetisation of this service has attracted great interest and scrutiny, particularly regarding the methods used to elicit benefit estimates and the quality of input data [9,10]. This review presents a detailed overview of trends within the methods, locations and findings of the current literature to highlight a number of shortcomings that limit the capacity of the current knowledge base to support decisions.

Trends
Pollination is a major, economically significant ecosystem service that is threatened by biodiversity losses. Economic measures of ecosystem services are thought to support better, more sustainable management strategies and are increasingly used to justify pollinator conservation.

Converting 63 available studies that economically measure pollination services into a common currency (2015 US$), this review identifies three major shortcomings within the current literature: highly heterogeneous results, biases towards the developed world and producers, and limited adaptability for decision-making. The review proposes next steps to enhance the effectiveness and applicability of future economic studies.

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Methods for Measuring the Economic Benefits of Pollination Services

The present body of literature on the economic benefits of pollination services takes a number of approaches of varying complexity (Table 1) and often involving a number of significant assumptions (see [9,10] for a detailed critique). Early studies used the full crop price of pollinated crops as a proxy for the benefits of the service itself (e.g., [11]), which unrealistically overattributes the

<table>
<thead>
<tr>
<th>Method</th>
<th>Definition</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crop price</td>
<td>Sum market price of insect pollinated crops</td>
<td>• Minimal data requirements</td>
<td>• Does not reflect the benefits of pollination services – only the market price of the crops sold</td>
</tr>
<tr>
<td>Managed pollinator prices</td>
<td>Sum market price of managed pollinators hired or purchased for pollination services</td>
<td>• Reflects the benefits of pollination in a manner comparable to other inputs</td>
<td>• Ignores wild pollination services</td>
</tr>
<tr>
<td>Yield analysis</td>
<td>Market price of output of pollinated crops versus crop without access to pollination services based on field studies</td>
<td>• Directly captures benefits of pollination services</td>
<td>• Only appropriate for very local scales</td>
</tr>
<tr>
<td>Dependence ratios</td>
<td>Total market price of crop output multiplied by a crop-specific dependence ratio (metric of the proportion of yield lost without pollination)</td>
<td>• Captures the varied benefits of pollination across crops equally applicable at all scales</td>
<td>• Assumes producer benefits</td>
</tr>
<tr>
<td>Production functions</td>
<td>Models of the effects of pollinators and pollination services on total crop output</td>
<td>• Can accurately assess the value of pollination service stocks</td>
<td>• Only estimates producer benefits</td>
</tr>
<tr>
<td>Replacement costs</td>
<td>The cost of replacing pollination services technologically or with managed pollinators</td>
<td>• Not linked to crop prices</td>
<td>• Replacements may not be effective</td>
</tr>
<tr>
<td>Partial equilibrium models</td>
<td>Estimates the welfare value of price change on available income to producers and consumers of a single crop market</td>
<td>• Can assess consumer and producer benefits</td>
<td>• Assumes producer willingness and ability to pay</td>
</tr>
</tbody>
</table>

Glossary

- **Benefits**: the positive impacts of an ecosystem good or service. These benefits can be quantified (e.g., the total market price of crop production loss) or valued (e.g., the change in consumer surplus from a change in crop prices across the market) economically.
- **Consumer price index (CPI)**: an index of the price of a selection of consumer goods. The index is reviewed by national banks and statistical authorities on a regular basis, using a select time period as the starting point for the index (which is given a value of 100). The difference between the CPI of a select year and another year is used as the basis for estimating price inflations between the two years.
- **Consumer surplus**: a theoretical measure of the disparity between the price paid by a consumer for a good or service and their maximum willingness to pay for that good or service. For example, a consumer who acquires a good for US$5 when they have a willingness to pay US$9 for that good will have a consumer surplus of US$4.
- **Exchange rate**: a metric used to convert one currency into an equivalent amount of another currency. For example, £1 buys US $1.3. Conversion rates fluctuate daily based on a range of market forces.
- **Dependence ratio**: dependence ratios are theoretical metrics that represent the proportion of total crop output lost in the absence of pollination services. These values can vary between crops and varieties. See [6] for a review and [7] for a detailed critique.
- **Economic value**: the welfare impacts of an ecosystem good or service expressed in monetary terms.
- **Inflation**: a measure of the change in prices of common goods within the consumer price index between two time periods. Values less than 1 in the later period indicate that prices have risen since the reference period, while values more than 1 indicate that prices have fallen. This is used to adjust the value of a currency between time periods to allow for greater comparison based on the relative purchase power of that currency in each period.
- **Natural capital**: biophysical resources from the natural environment that can form part of the
Table 1. (continued)

<table>
<thead>
<tr>
<th>Method</th>
<th>Definition</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
</table>
| Generalised equilibrium models | Estimates the welfare value of price changes on producers and consumers 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 to estimate and analyse  
• 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 nonmarket benefits such as the existence of pollinators | • Values nonmarket benefits, including the existence of pollinator species  
• Not tied to market prices or factors  
• Can be used to analyse 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 modelling to analyse  
• Expensive to test and implement  
• Monetary valuation is not always applicable |

These biophysical impacts are primary, based on the direct value of pollinators to crops. The above methods do not capture the economic value of pollination services (i.e., the impact of pollinators on producer and consumer economic welfare). Some studies have attempted to correct this using econometric partial equilibrium models to estimate the impacts of pollinator loss on consumer welfare (measured as consumer surplus) [21,22]. These models estimate the impact that a rise in prices, following a change in the supply of pollinated crops, will have on consumer welfare. More recently, Bauer and Wing [23] have expanded this approach using a more comprehensive general equilibrium model to examine both the capacity of producers to compensate for pollinator losses with other inputs and the effects that such losses would have on external markets, such as the agrochemical industry. Finally, stated preference survey methods can be used to elicit the economic value of nonmarket benefits from pollination services (e.g., maintaining landscape aesthetics [24]) or pollinators basis of economic activity. For example, soil, which is required for the planting of crops.

Power purchase parity: a measure of the relative purchasing power (i.e., the amount of goods and services) of a common currency (US$) between different regions/countries.

Price: the monetary cost ascribed to a good or service traded on a market, as affected by a number of market forces including supply of the good and demand for it or competing goods or services.

Stakeholders: a specific individual or group of individuals (e.g., farmers, supermarkets, consumers).

Although broad, the aforementioned methods do not capture the economic value of pollination services (i.e., the impact of pollinators on producer and consumer economic welfare). Some studies have attempted to correct this using econometric partial equilibrium models to estimate the impacts of pollinator loss on consumer welfare (measured as consumer surplus) [21,22]. These models estimate the impact that a rise in prices, following a change in the supply of pollinated crops, will have on consumer welfare. More recently, Bauer and Wing [23] have expanded this approach using a more comprehensive general equilibrium model to examine both the capacity of producers to compensate for pollinator losses with other inputs and the effects that such losses would have on external markets, such as the agrochemical industry. Finally, stated preference survey methods can be used to elicit the economic value of nonmarket benefits from pollination services (e.g., maintaining landscape aesthetics [24]) or pollinators
themselves [25]. Although these measures have unique value and all suffer from data limitations [9,10], to date, however, the estimates produced by these methods and the impact these limitations have on decision support have not been critically compared.

Evidence

The state of the art on estimating the economic benefits of pollination services was reviewed using a keyword search (‘pollination value’, ‘pollinators value’, ‘value ecosystem services’, ‘pollination economics’, ‘pollinator economics’) on Web of Science and Google Scholar, followed by a review of references and cited articles. In total (Table S1 in supplemental material online), 63 studies included an estimate of the economic benefits of pollination services.

Of these studies, 13% (n = 8) were international in scale, covering either global or regional values. Another 67% (n = 42) of studies were conducted or extrapolated to either a national or subnational regional scale. The remaining 21% (n = 13) of studies focused on more local scales, providing estimates of benefits per hectare or per farm. Based on United Nations (UN) subregions, 63% (n = 40) of these national, regional, and local studies focused partially or exclusively on the Western Europe and Others Group of developed nations (Figure 1A). By contrast, in six UN subregions, the only available estimates were from international studies.

In terms of methodologies (Figure 1B), most studies (71%) used either dependence ratio methods (27 studies) or yield analysis based on field data (18 studies). Although most studies purport otherwise, only 14% (n = 9) of studies estimated the economic value of pollination services to crops, most of which use partial equilibrium models (but see [23,26]). Only 8% (n = 5) of studies estimate economic benefits aside from crop pollination: [24,25,27,28] estimate the existence value of pollination services and [23] estimates the impacts of pollination service losses on noncrop markets.

To properly compare estimated economic benefits, the results of each study were converted into 2015 US$ using average annual spot exchange rates from the Bank of England [29] and consumer price index (CPI) data from the United States Federal Government’s Bureau of Labor and Statistics [30,31]. Inflation was based on the CPI for July of the year the estimate related to compared with the CPI in July 2015. If this year was not stated, then they were
assumed to be the year before the study was published. As total estimates will be larger in countries/regions with greater crop area, per-hectare benefits of pollination (Table 2) were calculated by dividing the total benefits estimated in each study by area of all animal-pollinated crops in each study. This area was taken from the study itself or, if this was not included, the data sources cited. This was not possible for all studies due to incomplete or inaccessible data sets. Finally, as benefits are affected by the relative market price of the crops considered [9], the per-hectare benefits to apple (Table 3), the most common crop among the studies reviewed, were

Table 2. Summary of Estimates of the Direct Economic Benefits per Hectare of Pollination Services to Crops in 2015 US$

<table>
<thead>
<tr>
<th>Refs</th>
<th>Region</th>
<th>Crops</th>
<th>Method</th>
<th>Year</th>
<th>2015 US$/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Farm/local scale</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[32]</td>
<td>Canada</td>
<td>Sweet peppers (Cubico)</td>
<td>Yield analysis</td>
<td>1992</td>
<td>47,784–75,190</td>
</tr>
<tr>
<td>[33]</td>
<td>Canada</td>
<td>Tomatoes</td>
<td>Yield analysis</td>
<td>2001</td>
<td>434–2344</td>
</tr>
<tr>
<td>[34]</td>
<td>Brazil</td>
<td>Coffee</td>
<td>Yield analysis</td>
<td>2003</td>
<td>2415</td>
</tr>
<tr>
<td>[36]</td>
<td>New Zealand</td>
<td>NA</td>
<td>Hive rental</td>
<td>2004</td>
<td>78–81</td>
</tr>
<tr>
<td>[37]</td>
<td>Kenya</td>
<td>Sunflower</td>
<td>Yield analysis</td>
<td>2005</td>
<td>2072/farm</td>
</tr>
<tr>
<td>[38]</td>
<td>South Africa</td>
<td>Apples (Granny Smith)</td>
<td>Yield analysis</td>
<td>2007/2008</td>
<td>18,216</td>
</tr>
<tr>
<td>[39]</td>
<td>UK</td>
<td>Raspberries</td>
<td>Yield analysis</td>
<td>2010</td>
<td>7641</td>
</tr>
<tr>
<td>[40]</td>
<td>Colombia</td>
<td>Coffee</td>
<td>Yield analysis</td>
<td>2011</td>
<td>155</td>
</tr>
<tr>
<td>[29]</td>
<td>Thailand</td>
<td>Longan</td>
<td>Dependence ratio</td>
<td>2013</td>
<td>3211</td>
</tr>
<tr>
<td>[41]</td>
<td>Canada</td>
<td>Blueberry</td>
<td>Yield analysis</td>
<td>2013</td>
<td>20,655</td>
</tr>
<tr>
<td>[41]</td>
<td>USA</td>
<td>Blueberry</td>
<td>Yield analysis</td>
<td>2013</td>
<td>26,541</td>
</tr>
<tr>
<td></td>
<td>Regional scale</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[14]</td>
<td>South Africa (Cape Floristic Region)</td>
<td>Apples, plums, apricots</td>
<td>Dependence ratio</td>
<td>2005</td>
<td>12,579</td>
</tr>
<tr>
<td>[42]</td>
<td>New Jersey, USA</td>
<td>Watermelons</td>
<td>Partial equilibrium model (CS only)</td>
<td>2009</td>
<td>5393–5407</td>
</tr>
<tr>
<td>[42]</td>
<td>New Jersey, USA</td>
<td>Watermelons</td>
<td>Replacement costs</td>
<td>2009</td>
<td>267–312</td>
</tr>
<tr>
<td>[43]</td>
<td>Oregon, USA</td>
<td>Blueberry</td>
<td>Partial equilibrium model (CS only)</td>
<td>2011</td>
<td>1242–1510</td>
</tr>
<tr>
<td></td>
<td>National scale</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[44]</td>
<td>UK</td>
<td>16 Crops</td>
<td>Dependence ratio</td>
<td>1996</td>
<td>842</td>
</tr>
<tr>
<td>[45]</td>
<td>USA</td>
<td>49 Crops</td>
<td>Dependence ratio</td>
<td>1997–2009</td>
<td>4666–7311</td>
</tr>
<tr>
<td>[46]</td>
<td>Kenya (small holdings)</td>
<td>8 Crops</td>
<td>Yield analysis</td>
<td>2005</td>
<td>163</td>
</tr>
<tr>
<td>[47]</td>
<td>India</td>
<td>6 Vegetable crops</td>
<td>Dependence ratio</td>
<td>2007</td>
<td>458</td>
</tr>
<tr>
<td>[47]</td>
<td>India</td>
<td>6 Vegetable crops</td>
<td>Partial equilibrium model (CS only)</td>
<td>2007</td>
<td>804</td>
</tr>
<tr>
<td>[48]</td>
<td>UK</td>
<td>18 Crops</td>
<td>Dependence ratio</td>
<td>2007</td>
<td>1161</td>
</tr>
<tr>
<td>[49]</td>
<td>Ireland</td>
<td>Oilseed rape</td>
<td>Yield analysis</td>
<td>2009–2011</td>
<td>652</td>
</tr>
</tbody>
</table>
calculated in the same way. For both tables, the mean and standard deviation of estimated benefits were calculated for each method used by three or more studies.

From this review, three notable shortcomings within the literature are apparent: first, despite a few methods dominating the literature, estimates remain heterogeneous, even for the same crop in the same region. Second, present literature is biased toward highly developed nations and international market economies with little attention in many regions and particularly developing nations. Finally, examining the literature more deeply, only a small number of studies are suitable to apply to decision-making.

Table 2. (continued)

<table>
<thead>
<tr>
<th>Refs</th>
<th>Region</th>
<th>Crops</th>
<th>Method</th>
<th>Year</th>
<th>2015 US$/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>[15]</td>
<td>UK</td>
<td>Apples (2 cultivars)</td>
<td>Yield analysis</td>
<td>2010</td>
<td>20,199–25,201</td>
</tr>
<tr>
<td>[50]</td>
<td>UK</td>
<td>18 Crops</td>
<td>Dependence ratio</td>
<td>2011</td>
<td>1321</td>
</tr>
<tr>
<td>[51]</td>
<td>Brazil</td>
<td>85 Crops</td>
<td>Dependence ratio</td>
<td>2012</td>
<td>1321</td>
</tr>
<tr>
<td>[52]</td>
<td>UK</td>
<td>Apples (4 cultivars)</td>
<td>Yield analysis</td>
<td>2012</td>
<td>14,032–24,433</td>
</tr>
</tbody>
</table>

**Multinational scale**

<table>
<thead>
<tr>
<th>Region</th>
<th>Crops</th>
<th>Method</th>
<th>Year</th>
<th>2015 US$/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe Union</td>
<td>Strawberries</td>
<td>Yield analysis</td>
<td>2009</td>
<td>14,968</td>
</tr>
</tbody>
</table>

**Global scale**

<table>
<thead>
<tr>
<th>Region</th>
<th>Crops</th>
<th>Method</th>
<th>Year</th>
<th>2015 US$/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>All</td>
<td>Crop value</td>
<td>1996</td>
<td>34</td>
</tr>
<tr>
<td>Global</td>
<td>All</td>
<td>Partial equilibrium model</td>
<td>2004</td>
<td>439–526</td>
</tr>
<tr>
<td>Global</td>
<td>All</td>
<td>General equilibrium model</td>
<td>2004</td>
<td>1010–1891</td>
</tr>
<tr>
<td>Global</td>
<td>All</td>
<td>Dependence ratio</td>
<td>2005</td>
<td>624</td>
</tr>
<tr>
<td>Global</td>
<td>All</td>
<td>Surplus analysis</td>
<td>2005</td>
<td>624–1721</td>
</tr>
<tr>
<td>Global</td>
<td>All</td>
<td>Dependence ratio</td>
<td>2009</td>
<td>717–1760</td>
</tr>
</tbody>
</table>

Average, standard deviation (SD; main methods)

- US$6976/ha (±US$11,977)
- US$3588/ha (±US$3216)
- US$3994/ha (±US$6872)
- US$1081/ha (±US$388)
- US$11,929/ha (±US$16,522)

*The cited reference in which the original value was found.

**The region over which the estimates of benefit were conducted.

**The crops that were assessed for value with ‘All’ denoting all possible insect-pollinated crops in the region for which data were available (total number unreported).

**Method used to estimate benefit (Table 1).

**The year the estimate relates to, usually based on what year the data relate to.

**The per hectare monetary estimate of the study inflated (and in many cases converted) to 2015 US$ as of July 2015.

**Denotes studies where the method does not apply to a specific crop.

**Only values of pollination services to consumers.
### Table 3. Summary of the Estimates of the Economic Value of Pollination Service to Apple in 2015 $USD per Hectare

<table>
<thead>
<tr>
<th>Refs</th>
<th>Region</th>
<th>Crops</th>
<th>Method</th>
<th>Year</th>
<th>2015 US$/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Farm/local scale</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>South Africa</td>
<td>Apples</td>
<td>Yield analysis</td>
<td>2007/08</td>
<td>18,216</td>
</tr>
<tr>
<td></td>
<td>Regional scale</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[14]</td>
<td>South Africa (Cape Floristic Region)</td>
<td>Apples</td>
<td>Dependence ratio</td>
<td>2005</td>
<td>12,137</td>
</tr>
<tr>
<td></td>
<td>National scale</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[56]</td>
<td>Australia</td>
<td>Apples</td>
<td>Dependence ratio</td>
<td>1999–2003</td>
<td>15,229</td>
</tr>
<tr>
<td>[45]</td>
<td>USA</td>
<td>Apples</td>
<td>Dependence ratio</td>
<td>2002</td>
<td>15,639</td>
</tr>
<tr>
<td>[57]</td>
<td>USA</td>
<td>Apples</td>
<td>Dependence ratio</td>
<td>2003</td>
<td>13,078</td>
</tr>
<tr>
<td>[58]</td>
<td>Poland</td>
<td>Apples</td>
<td>Dependence ratio</td>
<td>2004</td>
<td>1566</td>
</tr>
<tr>
<td>[45]</td>
<td>USA</td>
<td>Apples</td>
<td>Dependence ratio</td>
<td>2007</td>
<td>21,774</td>
</tr>
<tr>
<td>[48]</td>
<td>UK</td>
<td>Dessert apples</td>
<td>Dependence ratio</td>
<td>2007</td>
<td>20,730</td>
</tr>
<tr>
<td>[59]</td>
<td>China</td>
<td>Apples</td>
<td>Dependence ratio</td>
<td>2008</td>
<td>10,399</td>
</tr>
<tr>
<td>[15]</td>
<td>UK</td>
<td>Apples (Cox and Gala)</td>
<td>Yield analysis</td>
<td>2010</td>
<td>20,199–25,201</td>
</tr>
<tr>
<td>[45]</td>
<td>USA</td>
<td>Apples</td>
<td>Dependence ratio</td>
<td>2010</td>
<td>17,365</td>
</tr>
<tr>
<td>[50]</td>
<td>UK</td>
<td>Dessert apples</td>
<td>Dependence ratio</td>
<td>2011</td>
<td>18,902</td>
</tr>
<tr>
<td>[51]</td>
<td>Brazil</td>
<td>Apples</td>
<td>Dependence ratio</td>
<td>2012</td>
<td>7,715</td>
</tr>
<tr>
<td>[52]</td>
<td>UK</td>
<td>Apples (4 varieties)</td>
<td>Yield analysis</td>
<td>2012</td>
<td>14,032–24,433</td>
</tr>
<tr>
<td></td>
<td>Multinational scale</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[60]</td>
<td>Himalayan region</td>
<td>Apples</td>
<td>Partial equilibrium model (CS only)</td>
<td>2008/09</td>
<td>3,975</td>
</tr>
<tr>
<td></td>
<td>Global scale</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[22]</td>
<td>Global</td>
<td>Apples</td>
<td>Dependence ratio</td>
<td>2005</td>
<td>4,961</td>
</tr>
<tr>
<td>[22]</td>
<td>Global</td>
<td>Apples</td>
<td>Partial equilibrium model (CS only)</td>
<td>2005</td>
<td>8,012</td>
</tr>
<tr>
<td></td>
<td>Average, standard deviation (SD; all)</td>
<td></td>
<td>US$15,614/ha ($US$16,583)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Average, SD (restitution costs)</td>
<td></td>
<td>US$1212/ha ($US$596)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Average, SD (dependence ratio)</td>
<td></td>
<td>US$16,988/ha ($US$20,631)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Average, SD (yield analysis)</td>
<td></td>
<td>US$20,866/ha ($US$3958)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Average, SD (partial equilibrium model)</td>
<td></td>
<td>US$5630/ha ($US$2144)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*The cited reference in which the original value was found.
†The region over which the estimates of benefit were conducted.
‡The crops that were assessed for value with ‘All’ denoting all possible insect-pollinated crops in the region for which data were available.
§Method used to estimate benefit (Table 1).
∥The year the estimate relates to, usually based on what year the data relate to.
¶The monetary estimate of the study inflated (and in many cases converted) to 2015 US$ as of July 2015. Average estimates include both the highest and lowest estimates for a study.
*Only values of pollination services to consumers.
Heterogeneity of Outcomes

Ideally, the economic impacts of pollination services should be estimated in a consistent, manner that facilitates comparison of status and trends across space, time, and stakeholders. As most estimates are closely tied to crop prices and producer costs, some variation is to be expected, however converting estimates into a common currency (2015 US$) illustrates high heterogeneity in estimates, even between studies with common elements such as method and focal crops (Table S1 in supplemental material online). For example, of the two studies that have used the dependence ratio method to estimate the global benefits of pollination services, the benefits estimated by [22], US$232 billion, is only as high as the lower-bound estimate from [13], US$235 billion–US$577 billion. Comparisons of estimates per hectare (Table 2) also show substantial variation among crops (e.g., [41,52]) and countries using the same methods. For example, despite using the same method, estimated benefits of pollination to coffee are orders of magnitude greater in Brazil (US$22415/ha) [34] than Colombia (US$155/ha) [40] and Costa Rica (US$173/ha) [35]. Different methods also produce similarly large differences in estimates, with dependence ratio producing the smallest average estimates (US$3588/ha) with low relative variation, while yield analyses produce higher estimates (US$11,929/ha), as they mostly focus on high price crops (but see [49]), but with substantial variation.

Comparing benefits for a single crop (apples, Table 3) further highlights substantial variations between methods, with replacement costs producing substantially lower estimates (average US $1212/ha) than other methods (average US$4987/ha to US$20,866/ha), while yield analyses produce the highest estimates. There are also notable variations between years (e.g., [45]) and countries (e.g., [50,58]). Methods also have substantial differences in the relative standard deviations, with the dependence ratio method having a standard deviation in excess of its mean (±US$20,631; Table 3). This stems from the high degree of variation in the dependence ratios used for apples between studies, from 0.65 [22] to 1 [57], and variations in available pollinator natural capital between landscapes (e.g., [41]).

Although crop prices will naturally vary between regions and time periods, estimates are also influenced by a number of factors that are seldom considered in the literature reviewed. Foremost, the degree of pollinator dependence can have a substantial impact on estimates of economic value, particularly among dependence ratio studies [9]. This is further complicated by crop varieties often having different degrees of pollinator dependence and, in the case of certain high-value crops, different market prices [15,61]. Some studies have attempted to address these using a range of dependence ratios for each crop to present minimum and maximum measures of benefits (e.g., [13,23]). Second, estimates of economic benefits are usually tied directly to relative crop prices and production volumes, with studies considering multiple crops (e.g., [13]) often resulting in estimates being down weighted by widely grown crops with a lower market price or pollinator dependence (e.g., oilseed rape in the UK [50]).

Data availability often limits the accuracy and consistency of estimates, particularly over larger scales. For example, many studies (e.g., [13,22,23]) have utilised data from the freely available Food and Agriculture Organization database [62]. Within this database, however, there is substantially less available price data than production data, resulting in a large proportion of pollinator-dependent production either being excluded from the analysis [23] or included using price proxies [22]. This is particularly notable as price data are more likely to be absent or inconsistent in developing nations that may be more affected by pollination service losses [22,62]. Some studies use additional data to account for other factors such as quality or variety price premiums or changes in producer costs resulting from pollination-mediated yield changes [15,42].

Differences in producer costs (e.g., labour, fuel) between countries also affect the interpretation of replacement cost studies in particular and may have substantial effects on the transferability of
economic surplus models [23]. Lower labour costs, for instance, will make replacement costs lower but will have smaller effects on cost reductions, and therefore prices, when production is reduced by pollinator losses. Understanding and accounting for these drivers of values within a common framework is essential to further developing more robust, transferable estimates to larger-scale decision-making. Economic metrics, such as power purchase parity can facilitate such comparisons, but their use within the literature is relatively rare [13].

Geographic and Market Biases
Crop production practices and markets can vary substantially between countries and regions. As such, the benefits of pollination are likely to be very nuanced. While several global studies have suggested that the benefits of pollination services are greatest in the Mediterranean, the Middle East, and East Asia (e.g., [13,22]), to date, the more than half of published studies (63%) have only evaluated benefits to nations in the Western Europe and Others Group of developed nations (Table S1 in supplemental material online). Most of these studies focused on the UK or USA. By contrast, in seven UN regions, the benefits of pollination services have only been estimated as part of international-scale studies and there are few comprehensive, national-scale assessments of pollination service benefits in developing nations (but see [51]).

This lack of dedicated studies outside of highly developed nations is likely to result in an underestimate of the total benefits of pollination services at a local and national scale. For example, global crop databases used to estimate benefits across all regions are often lacking crops that are of little global significance but are key to local or national agriculture (e.g., Loman in Thailand [25,62]). By contrast, most of the studies into the economic value of pollinator natural capital have been conducted in developing nations. As the marginal value of natural capital increases with its scarcity within the landscape [19], such studies are likely to be particularly beneficial in developed nations where landscape homogenisation has reduced available habitat and natural capital.

Furthermore, almost all studies only examine the benefits to national crop markets, neglecting the impact of pollination services on crop trade (but see [23,40,42]). Trade has implications both for the economic value of services (by influencing prices, and thus consumer and producer welfare; [23]) and for the distribution of benefits between stakeholders. For instance, coffee is primarily produced in parts of the developing world but mainly consumed in the developed world [62] *. Much of this trade is in turn mediated by secondary traders who buy from producers at one price while selling to consumers at another [10], however no study accounts for this cross-market effect. Understanding the distribution of benefits across these markets is particularly important to many of the world’s rural poor, many of whom are highly reliant upon cash crops for their livelihoods [63] † and lack the capital to switch to different crops.

Overcoming these biases will require a focused effort to better understand the pollination service benefits in many low-to-middle income countries, as well as regions where the monetary benefits of pollination are particularly high [13]. This should be linked with focused ecological–economic research into the differing benefits of pollination services between cropping systems to identify how pollination can play a role in sustainable intensification [64].

Limited Decision-Making Tools
Ecosystem services are widely incorporated into policy and decision-making [65]. Projects including ecosystem services should be highly relevant to the stakeholders and incorporate a wide range of viewpoints (legitimacy), including economic and social impacts, to maximise their uptake [66]. Economic measures can be used in a number of ways (adapted from [67,68] *): (i) illustrating the benefits of services; (ii) measure the status and trends of pollinator natural capital (e.g., natural capital accounting); (iii) comparing trade-offs from policy and decision-making
actions (cost–benefit analysis); (iv) identifying opportunities for sustainable management (cost-efficiency analysis); and (v) designing instruments (e.g., agri-environment schemes). In common with the wider literature [69,70], this review indicates that most studies on the economic benefits of pollination services focus on illustrating impacts by presenting total values, without wider applicability (but see Box 1). Although these impacts can justify conservation policy and actions [69], often biodiversity and food security arguments alone are sufficient to drive large-scale action (e.g., the European Union’s restriction on neonicotinoid insecticides [71]).

To date, the few studies that have economically measured the status of pollinator natural capital [19,72,73] or pollination services [15,40,74] have been very specific, localised case studies that do not indicate wider trends. Similarly, almost all larger-scale studies do not distinguish between wild and managed pollination services (but see [20,52,56]), making them unsuitable for informing targeted management. This shortcoming stems from a lack of proper pollinator and pollination service monitoring data, making it impossible to determine their status, and subsequently economic value, across larger scales [75,76]. A small number of studies have examined the economic costs and benefits of specific pollination service management options [77–79], but have not isolated the impacts of pollination from other possible beneficial changes. Although some studies (Table 2) estimate the localised total value of pollination services per hectare, in reality, measures that affect pollination services will cause marginal shifts rather than absolute gains or losses [78]. As such, total benefits per hectare are only suitable for estimating the impacts of adding managed pollinators to a system without wild pollinators. Furthermore, cost–benefit analyses should include the full range of impacts that a change will have on productivity; however, to date, only four studies have examined the economic benefits of pollinators beyond crop production [24,25,27,28]. Evaluations of these trade-offs and synergies are limited by a lack of information on the impacts of interventions, pressures, or other inputs. Although new research is beginning to address these knowledge gaps (e.g., [17,48,80]), the economic

Box 1. Overview of Studies That Directly Link Pollination Economics to Decision-Making

Ricketts and Lonsdorf (2013) [19]: This study uses data collected from a yield analysis study [35] to estimate the economic value of pollinator natural capital in the surrounding landscape. The projected supply of pollination services from the surrounding landscape was then projected using the InVEST model by [87]. By reattributing projected pollination service benefits to the surrounding landscape, the study values the surrounding natural capital at US$0 (for distant habitat that is too far from plantations to provide services) to US$923 (2015 US$). The maps produced are useful to prioritise forest patches for conservation based on their economic benefits and assess the costs and benefits of land use changes.

Narjes and Lippert (2016) [25]: This study uses a combination of yield analysis to directly estimate the economic benefits of pollination services to longan (Dimocarpus longan) in northern Thailand and stated preference survey to estimate local willingness to pay for different conservation options. The findings indicate that although there is a strong willingness to pay for pollination-management measures, this is substantially lower than the scale of economic benefits to longan production, possibly due to constraints on producer income. Respondents expressed greater willingness to pay for native bee husbandry than for improving habitat quality and had a negative willingness to pay for bee-friendly pest control. This study demonstrates that the public support for pollination service management is influenced by the management strategy more than the benefits they provide.

Morandin et al. (2016) [88]: This study uses standard yield analysis methods to provide a cost–benefit analysis of hedgerows to oilseed rape production in heavily intensified agricultural areas in California, USA over several years. The findings indicate that net profits/hectare increase by 36% (US$158/ha 2015 US$) in the presence of hedgerows. However, the study notes that this is much smaller than the projected benefits from pest regulation services that are needed to make hedgerows economically profitable over the long term.

A number of other studies [77–79] estimate the economic benefits of changing pollinator management practices, however as none of these studies uses a ‘no pollination’ treatment, they do not actively demonstrate the economic benefits of changing pollination services. Other studies [15,41,73] also explore the economic costs of pollination service deficits in gala apples, blueberries and cotton, respectively, giving some measure of the potential benefits of alternative management.
implications of these shifts in marginal pollination services and the potential consequences for management have yet to be quantified. Understanding such trade-offs is particularly important in developing countries as the opportunity costs of managing for ecosystem services rather than expanding production are often greater than in developed nations [81], although the distribution of the crop within the market (see earlier discussion) may mean that it is consumers in other countries who receive the greatest benefits.

No study has yet incorporated the economic benefits of pollination services into instrument design or efficiency measures, although some studies have provided evidence of pollination deficits, indicating economically inefficient management [15,40,41,73,82]. Although policy and management decisions often have medium-to-long-term effects, the majority of studies are single-year evaluations of economic benefits (but see [13,45,53,78]) that do not indicate how these benefits are likely to change with wider crop markets. Quantifying uncertainty in input data is important to understanding how different factors may affect the impact of management over time [83], yet most studies reviewed only consider uncertainty in the dependence of pollination services (e.g., [13]). Finally, although suitable methods for developing ecosystem service management with respect to uncertainty exist (e.g., [84]), they have yet to be applied to pollination service management. Overall, the current body of literature is largely unsuitable for supporting policy and local decision-making due to its narrow focus on illustrating the sum benefits of pollination services to crops in a single year.

Concluding Remarks
Measuring the economic benefits of pollination services is a potentially useful tool for promoting positive management, particularly among stakeholders who might not otherwise engage with ecological management. Despite several uncertainties and variations, the current body of literature does fundamentally illustrate that pollination services are economically important and that their loss will have consequences for people around the world. The current body of literature remains limited by (i) data and methodological inconsistencies, (ii) an excessive focus on developed markets and (iii) continuing emphasis on illustrating benefits rather than supporting policy and decision-making (see Outstanding Questions).

Based on the findings of this review, the authors propose a series of priorities for future research: Collaborate with a broader range of stakeholders affected by pollination services and quantify the impacts of service changes to each of them specifically. This will facilitate the use of economic measures in decision-making and is likely to provide access to data beyond the limits of existing databases and insights into crop-specific market structures. Establish a standard typology of methods, including what methods to use to address which research questions, what data should be collected to account for uncertainty and make the results comparable and how to distinguish between different sources of pollination services. Presently, standardised frameworks have been developed for assessing pollination service benefits in the field [85,86] but not on how to translate these into economic measures for yield analysis. Refocus on functional applications of economic measures. In order to better inform decisions and policy, it is imperative that future studies have clear objectives such as (i) estimating the monetary value of pollinator natural capital, (ii) exploring the economic consequences of pressures on pollinator populations and (iii) examining the monetary benefits of pollination service management. Ideally, these objectives should be pursued as components of novel primary ecological research to simultaneously consider both ecological and economic impacts.

Resources

http://www.bankofengland.co.uk/boeapps/idadb/index.asp?first=yes&SectionRequired=I&HideNums=1&ExtraInfo=true&Travel=NlxSSt
Supplemental Information

Supplemental information associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.tree.2016.09.002.

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