

# Pollination ecosystem services: A comprehensive review of economic values, research funding and policy actions

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## Abstract

Economic valuation of crop pollination services, including potential monetary losses in agricultural production induced by insufficient pollination, is a strategy to quantify the impacts of this critical ecosystem service on food production, food security and the global economy, and to drive policy actions. We examined how the economic valuation of crop pollination services has been investigated across the ecological and economics literature and review estimates of monetary values of crop pollination services, as well as the investments (research funding/grants) and policy actions associated with pollinators and pollination. We documented an increase in the number of economic valuation studies on pollination services in the last two decades, with a substantial growth over the last five years, which represented 54% of all publications. However, we emphasize that there is a marked lack of data on regionally important commercial crops that are essential for the food security of many millions of people, particularly in developing countries. Estimated global values of the crop pollination service, adjusted for inflation in March/2020, range widely from US\$195 billion to ~US\$387 (US\$267–657) billion annually — due to methodology, input data and a historical increase in production costs of pollinator-dependent crops. There is an increasing trend over time in the values of crop pollination service estimates for the full set of main globally-grown crops, although estimates for specific crops are widely variable at local to regional scales. Research funding on pollination/pollinators is mainly in developed countries, which have published all the reviewed policy papers on the economic value of crop pollination services. Although the valuation of pollination services, and associated economics and policy remain embryonic areas of research, animal-mediated pollination is clearly a high-value environmental service, which greatly strengthens conservation arguments worldwide.

**Keywords** Animal-mediated pollination · Agriculture · Food security · Monetary values · Pollinator-dependent crops · Scientometrics

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## 1 Introduction

Pollination is an ecosystem service of incontrovertible economic value linked to human well-being through agricultural production and food security (IPBES 2016). Pollinators impact food supply at a global scale, as pollinator-dependent crops contribute to ~35% of overall crop production by volume (IPBES 2016). It is estimated that 87 out of the 115 major crops grown worldwide depend on biotic pollination, to at least some degree, to set fruits and seeds (Klein et al. 2007). Additionally, over three quarters of the leading types of global-scale food crops rely to some extent on animal pollination for yield, quality, or both (IPBES 2016), and nearly 90% of all wild flowering plant species depend, at least partially, on animal pollination services (Ollerton et al. 2011).

It is vital that modern societies understand the importance of pollination for food security and for their very existence

(Oliveira et al. 2020). The IPBES assessment on pollinators, pollination and food production recognized evidence of wild pollinator decline in northwest Europe and North America, and also identified data shortfalls and an urgent need for monitoring pollinators and pollination elsewhere in the world (IPBES 2016). The causes of pollinator decline include the indiscriminate use of pesticides, biological invasions, genetically modified (GM) crops, intensification and expansion of agricultural practices and parasites (Dicks et al. 2016; IPBES 2016; Potts et al. 2016), as well as habitat loss and fragmentation associated with the accelerated intensification of anthropogenic actions (e.g. Potts et al. 2010; Xiao et al. 2016).

The continued expansion of human-modified landscapes is directly associated with the disruption of pollination as a diffuse ecological function (Aguilar et al. 2006; Aguilar and Galetto 2004) and service (Garibaldi et al. 2016; Gibbs et al. 2016; Ricketts et al. 2008). Populations of both pollinators and flowering plants, mainly those with specialized reproductive traits, are frequently reduced or driven to local extinction in human-modified landscapes (e.g. Girão et al. 2007; Lopes et al. 2009; Tabarelli et al. 2010). Furthermore, geographic isolation of populations in forest remnants within hyperfragmented landscapes limits the flow of pollen among populations, further reducing plant reproductive success (e.g. Llorens et al. 2012; Ricketts et al. 2004; Ricketts et al. 2008). Agriculture is both a beneficiary of pollinator abundance and the leading driver of pollinator declines through land-use change, agro-chemical use and other traditional or mechanized large-scale farming practices (e.g. De Marco and Coelho 2004; Dicks et al. 2016).

The ongoing situation is not favourable to the maintenance of many species of pollinators, since many of these threats appear to be increasing in intensity across continents (e.g. Calderone 2012; Potts et al. 2016). Meanwhile, research and development (R&D) expenditures are highly uneven across high-income (developed) and low- and middle-income (developing) countries. Available evidence suggests that returns on R&D investments should be extremely high (Goñi & Maloney 2017). In the context of agricultural R&D, in recent years, governments of middle-income nations are investing more than those of high-income, yet low-income countries invest a far lower share of GDP compared to wealthy countries, not only in R&D but also in technology licensing, managerial technologies and training (Goñi & Maloney 2017). However, worldwide investment in R&D directly related to pollination and pollinators are still poorly understood.

Continuous state-of-the-art analyses to detect predominant patterns on the status of pollination ecosystem services are necessary to identify major information gaps and to support a more effective use of natural resources associated with food production in agricultural fields. One approach is to deploy continuous assessments of the economic value of pollination

in time, space and across different crops (Basu et al. 2011; Gallai et al. 2009; Hanley et al. 2015; Lautenbach et al. 2012; Leonhardt et al. 2013; Winfree et al. 2011), which was reviewed by Breeze et al. (2016), Garibaldi et al. (2014) and Potts et al. (2016). The welfare impacts of an ecosystem service can be expressed in monetary terms and included as part of a cost-benefit analysis to inform policy makers. This represents an ecosystem input to agricultural production, reveals the net benefits of conserving crop pollinators and highlights the risks of declining service (Abson and Termansen 2011; Allsopp et al. 2008; Hanley et al. 2015; Hein 2009). This also provides an insight into poorly functioning institutional arrangements that fail to reflect the true socioeconomic costs of environmental degradation more generally (Radford and James 2013). Those outcomes can also bring awareness of increase productivity and land-use revenues through ecological intensification of agroecosystems (Hipólito et al. 2018; Kovács-Hostyánszki et al. 2017). Although the economic value of pollination services has been previously estimated, the amount and dynamics of research funding/grants allocations associated with the generation of policy documents related to pollination services worldwide are still poorly understood.

In this review study, we examined how the economic valuation of crop pollination services has been investigated and reported in the scientific literature, with a focus on the economic valuations themselves, as well as the investments and policy actions and government and media documents related to pollination and pollinators. We identified general trends in the scientific literature in relation to crop pollination services, the types of economic benefit and the measurement techniques applied and provide a synthesis of the previously estimated economic values of agricultural pollination at a global scale.

## 2 Materials and methods

### 2.1 Economy aspects of pollination services - scientometrics and review

A systematic search and scientometric review of pollination services was carried out using quantitative techniques to map the science, policy and management contexts to quantify several aspects of the development of this area of pollination ecology (see Milojević and Leydesdorff 2013 for details on information metrics). The survey of scientific publications included all publications on crop pollination services from 1945 (the year of first publication registration in the Web of Science platform) to December 2018 (<https://www.webofknowledge.com>). We searched for the argument “*pollinat\* service\* and econom\* val\**” appearing in the title, keywords and body of the text. After a careful check, we considered only articles that discuss or contain at least one form of pollination ecosystem

service valuation (see Fig. 1 for details). To avoid double-counting in some of the analyses, we classified all the articles into two main groups as either qualitative studies or quantitative synthesis (meta-analysis or bibliographic survey). The screening path, exclusion criteria and final data set are detailed in the Fig. 1, which is based on The PRISMA Statement: Preferred Reporting Items for Systematic Reviews and Meta-Analyses (sensu Moher et al. 2009; <http://www.prisma-statement.org/PRISMAStatement/FlowDiagram>). After the body of literature was consolidated (Appendix 1 in Electronic Supplementary Material), we classified information from all articles into 10 items for analysis (Table 1).

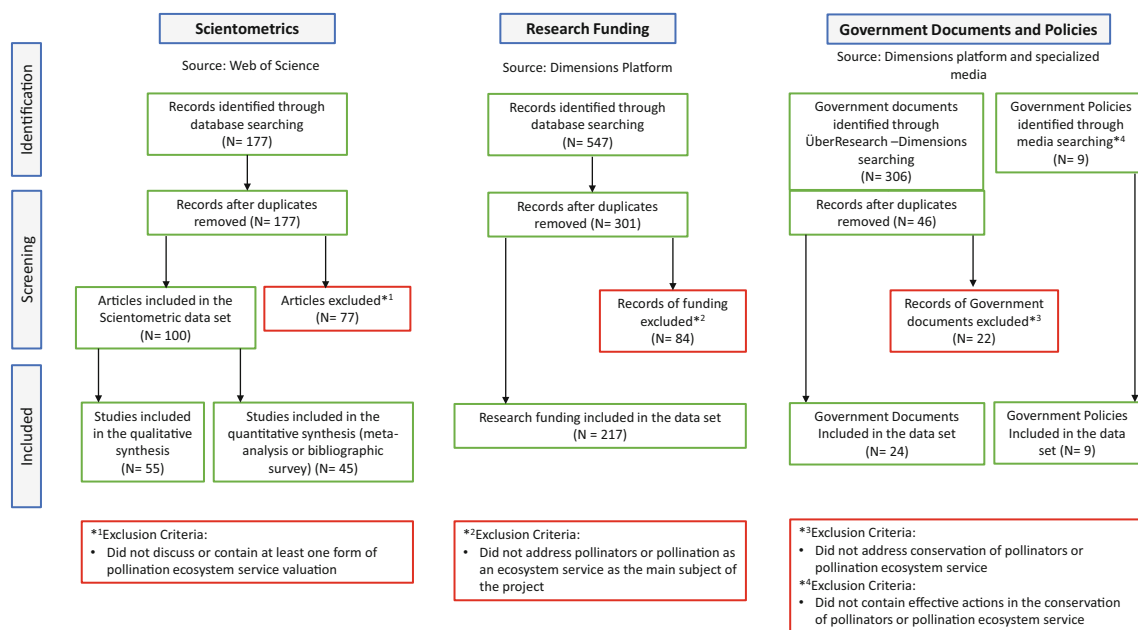
## 2.2 Estimated values of crop pollination services

To evaluate changes in the economic value of crop pollination services, by geographic locations and periods of estimation, we used the entire bibliography generated by our data mining effort. We adjusted for inflation (until March 2020) the published estimates of economic values for biotic pollination. We used as initial reference for the adjustment for inflation the publication year or the year of the database applied in the estimates if they were more than two years before the publication (see details in Table 2) (<https://www.inflationtool.com>).

After, other currencies were converted into US dollars (US\$) on the same day using common exchange rates (as April 4, 2020) available on the Brazilian Central Bank website (<https://www.bcb.gov.br/conversao>).

## 2.3 Pollinator dependence of agricultural production

We further extracted global scale data on the total amount (metric tonnes, t) of agricultural production of 2016 from the Food and Agriculture Organization database (FAOSTAT 2018) from each country that appeared in our scientometric review. We then classified the degree to which each crop type depends on biotic pollination (sensu Klein et al. 2007). Based on the improvement in production and quality associated with pollination by animals, the analysed crops were classified into one of the six following categories (sensu Klein et al. 2007): (1) essential; production is reduced by 90% or more when pollination services are lacking; (2) high: a reduction of 40% to 90%; (3) modest: a reduction of 10% to 40%; (4) little: a reduction of 0% to 10%; (5) no increase under conditions of animal-mediated pollination; and (6) unknown, when empirical studies for that crop were entirely missing. We then aggregated the classes of dependence (1 to 4) to assess the amount of pollinator-dependent agricultural production by country, compared to non-dependent (5) and unknown (6).



**Fig. 1** Flow diagram representing the body of literature reviewed, research funding and government documents and policies considered in this study of pollination ecosystem services (including counts of sources and exclusion criteria used to filter the body of literature, grants and policy documents into the final dataset reviewed. Search argument for the scientometric analysis in the Web of Science: “*pollinat\* service\* and econ\* val\**”; search arguments for research funding in Dimensions Platform (2018; (<https://www.dimensions.ai/>): pollinator(s), pollination, sustainability, conservation, biodiversity-friendly practice, crop,

agriculture and farming; search arguments for Government documents and policies in Dimensions Platform (2018) and specialized media: pollination, pollinator(s), conservation, law, measure, protective, regulation, state, government, policy (keywords were searched in English, Spanish, Portuguese, German, Danish, Japanese, Italian and French). This diagram is based on The PRISMA Statement: Preferred Reporting Items for Systematic Reviews and Meta-Analyses (sensu Moher et al. 2009; <http://www.prisma-statement.org/PRISMAStatement/FlowDiagram>)

**Table 1** Items and categories selected for the scientometric analysis of the economic valuation of pollination services (adapted from Viana et al. 2012)

Items for analysis	Categories
1. Publication year	–
2. Correspondence author	–
3. Country of the author of correspondence	–
4. Authors	–
5. Article title	–
6. Journal	–
7. Study Area (country)	
8. Nature of study	1. editorial, 2. modelling, 3. opinion, 4. conceptual, 5. meta-analysis, 6. review, 7. empirical
9. Nature of method (Methodology)	1. descriptive, 2. modelling, 3. meta-analysis, 4. observation (sampling), 5. experimental, 6. bibliographic survey
10. Economic situation of correspondence author's country and study area according to UN	1. developed, 2. developing

## 2.4 Research funding, government documents and policies related to pollination services

In order to review research funding/grants and government documents related to the conservation of pollinators and pollination ecosystem services worldwide, we used Dimensions Platform (<https://www.dimensions.ai/>). The Dimensions Platform is a new scholarly search database that focuses on the broader set of use cases. The database includes research articles and their citations, books, grants awarded, patents, clinical trials and policy documents with a standard set of research classifications employing machine-learning techniques (Hook et al. 2018). Dimensions has gathered, cleaned and rendered unambiguous a global database, while checking all sources on grant data for new data each month.

Data on research funding/grants and government documents were searched by combining the keywords: pollinator(s), pollination, sustainability, conservation, biodiversity-friendly practice, crop, agriculture and farming. The search was conducted in November 2018 and included all research funded and government documents since 1992, the year of the first record. All research funding records and government documents were individually checked for duplicates and we only considered funds that address pollinators or pollination ecosystem services as the main subject of the project proposed (see Fig. 1 for details). For government documents we considered only documents that address conservation of pollinators or pollination ecosystem services (see Fig. 1 for details). Data of scientific publications, research funding and policy documents were grouped into two categories represented by developing and developed economy countries according to the United Nations (2019).

In addition, a global media search on specialized websites was conducted for government policies with the following key

words: pollination, pollinator(s), conservation, law, measure, protective, regulation, state, government, policy (see Fig. 1). Those key words were translated and applied in English, Spanish, Portuguese, German, Danish, Japanese, Italian and French to cover the largest number of countries and to minimize the Anglophone bias in conducting a search in English only.

## 3 Results

### 3.1 Scientometrics of studies on the economic value of pollination services

Our search in the Web of Science returned 177 articles, 100 of which were selected to investigate the economic value of pollination services (see Table S1 in the Electronic Supplementary Material for the full list). The remaining 77 scientific articles addressed other types of ecosystem services or cited pollination as a peripheral example of ecosystem services and did not discuss or contain at least one form of pollination ecosystem service valuation.

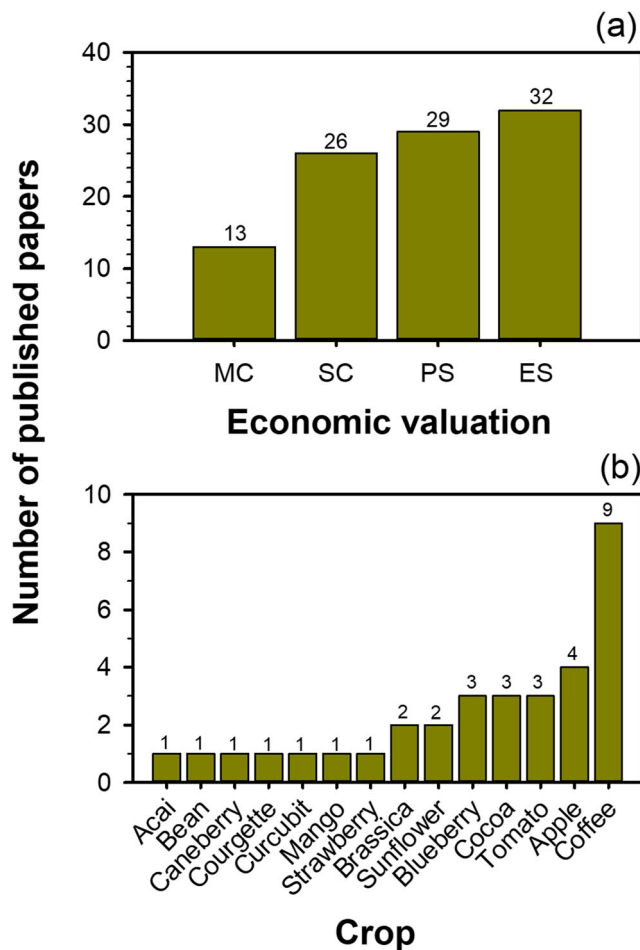
Among the 100 articles that estimated the economic value of pollination services, 32% developed an estimate of economic values of ecosystem services (including pollination services) while 29% estimated the value of the pollination services exclusively (Fig. 2a). Other articles were case studies that explore the value of pollination for a single crop (26%) or for multiple crops (13%) (Fig. 2a). Articles investigating the economic value of pollination of coffee ( $N=9$ ) and apple ( $N=4$ ) account for 39.4% of all studies that explored at least one crop (Fig. 2b).

We observed three publications peaks in 2013, 2014 and 2016. Prior to 2006, only eight articles had been published

**Table 2** Publications containing annual estimates of the economic benefits of biotic pollination services. Economic estimation methods include: 1. CV, crop value; 2. DR, dependency ratio; 3. CS, consumer surplus; 4. RC, replacement costs; 5. YA, yield analysis; and 6. WTP, willingness to pay. Published values, current values after adjusted for inflation until March 2020 (<https://www.inflationtool.com>) and converted into US dollars (US\$) through the Brazilian Central Bank website (<https://www.bcb.gov.br/conversao>)

GLOBAL VALUE OF BIOTIC POLLINATION SERVICE		METHOD	Published value (for one year)	Current value (for one year)
Costanza et al. 1997		CV	US\$117 billion	US\$206 billion <sup>1</sup>
Pimentel et al. 1997		DR	US\$200 billion	US\$324 billion <sup>2</sup>
Gallai et al. 2009		DR	€153 billion	US\$ 210 billion <sup>1</sup>
Lautenbach et al. 2012		DR	~US\$340 billion (235–577 billion)	~US\$387 billion <sup>1</sup> (267–657 billion) <sup>1</sup>
Bauer and Wing 2016		DR	US\$140 billion	US\$195 billion <sup>1</sup>
BIOTIC POLLINATION SERVICE FOR A SINGLE COUNTRY		METHOD	Published value (for one year)	Current value (for one year)
Matheson and Schrader 1987	New Zealand	CV	£1.83 billion	US\$5.4 billion <sup>2</sup>
Robinson et al. 1989	USA	DR	US\$9.3 billion	US\$19 billion <sup>2</sup>
Allsopp et al. 2008	South Africa	RC	US\$358 million	US\$484 million <sup>1</sup>
JianDong and Chen 2011	China	DR	US\$52.2 billion	US\$63 billion <sup>1</sup>
Basu et al. 2011	India	DR	US\$726 million	US\$888 million <sup>1</sup>
Calderone 2012	USA	DR	US\$15.2 billion	US\$18 billion <sup>1</sup>
Giannini et al. 2015b	Brazil	DR	US\$12 billion	US\$13 billion <sup>1</sup>
Breeze et al. 2015	UK	WTP	£379 million	US\$512 million <sup>2</sup>
BIOTIC POLLINATION SERVICE FOR A SINGLE CROP		METHOD	Published value (for one year)	Current value (for one year)
Marco and Coelho 2004	Brazil	YA	US\$1860.55/ha	US\$2595.42/ha <sup>1</sup>
Whittington et al. 2004	Canada	YA	US\$2700/ha	US\$3767.54/ha <sup>2</sup>
Greenleaf and Kremen 2006	USA	YA	US\$26 million	US\$37 million <sup>1</sup>
Olschewski et al. 2006	Indonesia and Ecuador	YA	US\$43–76/ha	US\$63.55–112.33/ha <sup>1</sup>
Winfree et al. 2011	USA	RC, YA, CS	US\$0.18 million, US\$2.25 million, US\$3.4 million	US\$0.24million, <sup>1</sup> US\$3.04 million <sup>1</sup> , US\$4.5 million <sup>1</sup>
Lyc et al. 2011	UK	RC	£1170/ha	US\$1737.27/ha <sup>2</sup>
Garratt et al. 2014	UK	YA	£36.7 million	US\$50 million <sup>2</sup>
Stanley et al. 2013	UK	YA	€3.9 million	US\$4.5 million <sup>2</sup>
Bravo-Monroy et al. 2015	Colombia	YA	US\$146/ha	US\$159/ha <sup>2</sup>
Gibbs et al. 2016	Canada USA	YA	US\$20,655/ha US\$26,541/ha £166/ha	US\$22,457/ha, <sup>2</sup> US\$28,857/ha <sup>2</sup>
Knapp and Osborne 2017	UK	YA	£166/ha	US\$219.57/ha <sup>2</sup>
Klatt et al. 2014	European Union	YA	US\$0.32 billion	US\$0.35 billion <sup>2</sup>

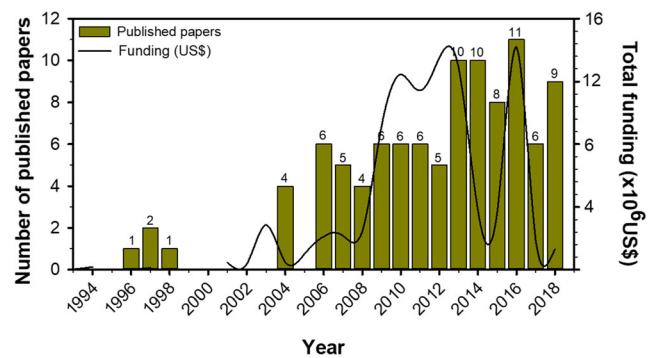
<sup>1</sup> adjusted for inflation using year of the database applied for the estimate; <sup>2</sup> adjusted for inflation using year of publication



**Fig. 2** Articles containing estimates of the economic value of pollination services. (a) Number of articles that developed an economic valuation estimate of ecosystem services (including pollination services - ES), pollination service (PS), economic values of pollination services of a single crop (SC), and estimated value of pollination for multiple crops (MC) ( $N=100$ ). Reviews and meta-analyses were included in the ES or PS bars depending on their focus. (b) Number of articles containing economic estimates of pollination services of at least one crop ( $N=33$ ). Searches were carried out using the Web of Science with the argument “*pollinat\* service\* and econ\* val\**”

(Fig. 3). Most of the studies (57.1%) were conducted in developed countries (i.e. the study areas were situated within developed countries), 33.3% in developing countries, while other papers had a global focus or involved no specified study area (9.5%) (Fig. 4a). Considering the affiliation of the corresponding authors, 81% were affiliated to institutions in developed countries while only 19% were affiliated to institutions in developing countries (Fig. 4b). Regarding the methodology (nature of method), 34% of all studies were represented by bibliographic surveys, while 31% were based on experimental approaches (Fig. 5a). In terms of the nature of the study, most were empirical (56%) or reviews (20%) (Fig. 5b).

Journals containing most publications were *Ecological Economics* and *Agriculture, Ecosystems and Environment*, with 10 and seven articles, respectively (Fig. 6). These

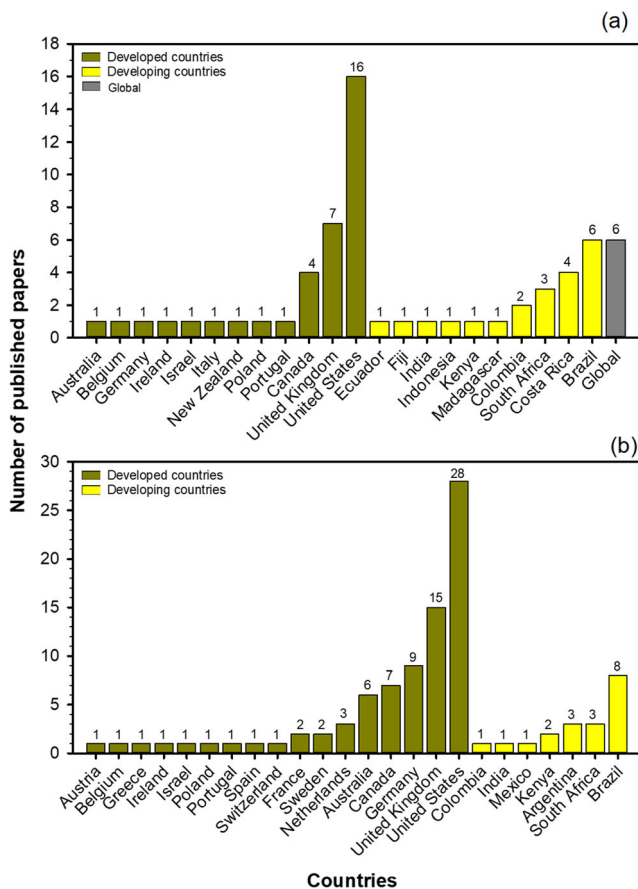


**Fig. 3** Number of published papers on the economic valuation of pollination services over time. This body of literature contains 100 papers that discuss or contain at least one form of pollination service valuation (Source: Web of Science). Line represent the 217 records of investments in projects that address pollinators or pollination as an ecosystem service as the main project subject (Source: Dimensions Platform 2018; <https://www.dimensions.ai/>). We observed a positive correlation between level of investments and number of publications ( $r=0.80$ ,  $P<0.0001$ )

journals were ranked in 2018 as number 151 and 132 among all scientific journals in environmental sciences (SCImago 2018). An article authored by Klein et al. (2007) and published in the *Proceedings of the Royal Society B* was the most cited (1403 citations until 2017); the second most cited article (authored by Gallai et al. 2009) was published by *Ecological Economics* (636 citations). These two articles set the methodological foundation applied thereafter. The Klein et al. (2007) paper established the major categories of crop pollinator dependence, whereas Gallai et al. (2009) applied these dependency categories to a widely used bioeconomic equation to estimate the economic value of pollination, which was later officially adopted by the Food and Agriculture Organization (FAO).

### 3.2 Spatiotemporal variation in crop pollination values

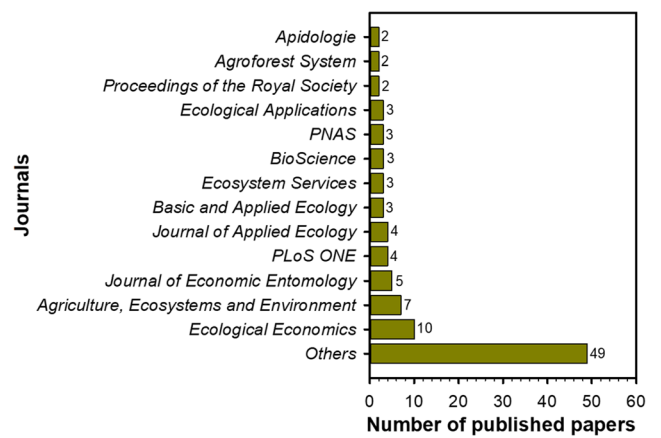
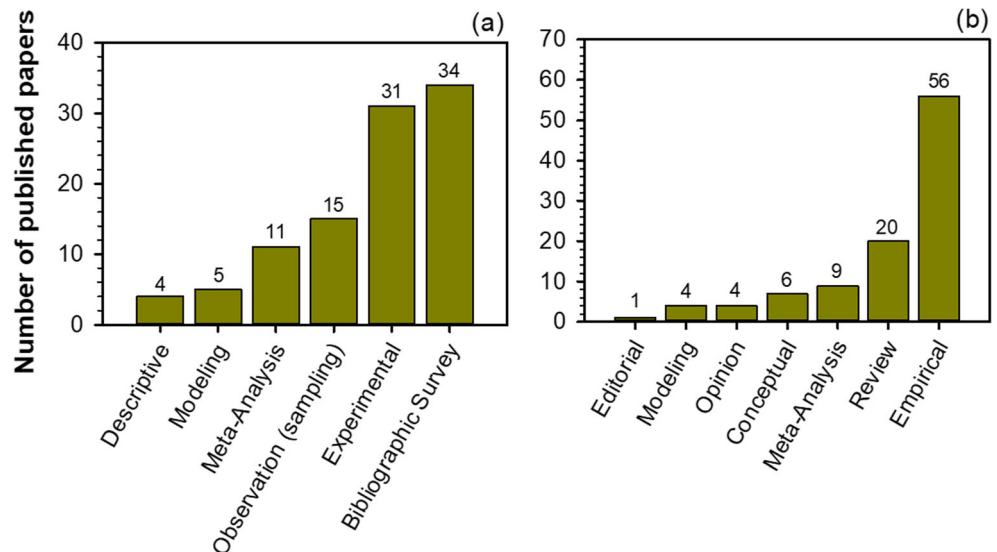
The annual economic value of pollination service globally, per unit area and for some crops, are presented on the basis of six different methods presented in Table 2. We updated the global scale pollination services estimates adjusting for inflation and converting to US\$ when authors published in different currencies, current/adjusted values are US\$206 billion (Costanza et al. 1997), US\$324 billion (Pimentel et al. 1997), US\$210 billion (Gallai et al. 2009), approximately US\$387 billion (US\$267–657) (Lautenbach et al. 2012), and more recently at US\$195 billion (Bauer and Wing 2016). These estimates represent the fraction of global food production attributed to animal pollination and can therefore be considered as an assessment of the gross overall monetary value of animal pollination services. This of course excludes many plant food items sourced from natural ecosystems that also depend on pollination service from either native or exotic pollinators.



**Fig. 4** Number of articles on the economic valuation of pollination services classified by (a) articles with study areas in these countries (N=63; review articles and meta-analyses were not included) and (b) countries whose corresponding authors were affiliated to (N=100 including review articles and meta-analyses). Searches were carried out using the Web of Science with the argument “*pollinat\* service\* and econ\* val\**”

The fraction of national cropland production that depends on biotic pollination is variable across countries, from 27.5%

**Fig. 5** Number of articles on the economic valuation of pollination services classified by the nature of (a) the method and (b) the study. Our body of literature contains 100 articles that discuss or contain at least one form of pollination service valuation



**Fig. 6** Number of articles on the subject of pollination service valuation per journal until 2018. Search was made in the Web of Science with the argument “*pollinat\* service\* and econ\* val\**”. Our search returned a total of 177 articles, 100 of which explicitly focused on crop pollination services. Total number of journals: 62; the category “others” includes 49 journals, each of which with only one article

in the United Kingdom to as much as 38.6% and 49.1% in Sweden and Fiji, respectively (Table 3; N=29 countries with developed and developing economies). Combining country-scale FAO agricultural production data with our review shows that in some countries were the demand for agricultural biotic pollination services is high, there is no studies (with the study area in the country; Fig. 4a) on the economic valuation of pollination services (e.g. Argentina, France) (Fig. 7). This is particularly evident for China, which has the highest agricultural production dependent on biotic pollination and no study on the theme was developed there (Fig. 7). In addition, the total agricultural production sourced from crops for which the degree of dependence on natural pollinators is unknown is substantial and around 20–30% (from 23.2% in Sweden to 33.2% in Indonesia) in a diverse set of countries,

**Table 3** Total production of crops dependent on pollinators (PPDC), non-dependent on pollinators (PPNDC) and crops with unknown dependence (PUPDC). Production is represented in tonnes per country and in percentages according to their dependence on biotic pollinators (sensu Klein et al. 2007). Source: FAOSTAT (2018)

Developed countries	PPDC	PPNDC	PUPDC
Australia	61,527,350 (29.9%)	83,335,583 (40.5%)	60,961,506 (29.6%)
Austria	9,522,888 (31.5%)	11,383,760 (37.5%)	9,415,382 (31%)
Canada	66,252,327 (29.1%)	96,360,308 (42.3%)	65,168,062 (28.6%)
France	87,948,129 (30.5%)	115,452,783 (39.8%)	85,999,980 (29.7%)
Germany	68,780,660 (30.2%)	92,109,554 (40.2%)	67,765,768 (29.6%)
Greece	15,233,830 (33.2%)	16,545,083 (35.8%)	14,314,898 (31%)
Italy	49,304,577 (32.9%)	54,165,518 (36.4%)	46,003,355 (30.7%)
Netherlands	16,681,963 (31.9%)	18,906,795 (36.2%)	16,681,963 (31.9%)
New Zealand	3,542,208 (35.4%)	3,558,494 (35.8%)	2,884,806 (28.8%)
Poland	55,009,369 (32.6%)	62,234,804 (36.9%)	51,409,240 (30.5%)
Portugal	6,498,914 (34.2%)	6,338,636 (33.4%)	6,130,615 (32.4%)
Spain	60,179,009 (32.7%)	65,355,985 (35.5%)	58,286,481 (31.8%)
Sweden	4,159,770 (38.6%)	4,118,210 (38.2%)	2,484,110 (23.2%)
Switzerland	2,871,381 (32.9%)	3,110,822 (35.7%)	2,724,717 (31.4%)
United Kingdom	23,423,466 (27.5%)	38,219,404 (44.9%)	23,423,466 (27.6%)
United States	696,213,697 (32.5%)	752,107,302 (35.2%)	687,674,422 (32.3%)
Developing Countries	PPDC	PPNDC	PUPDC
Argentina	148,357,072 (32.2%)	165,794,668 (35.9%)	147,232,164 (31.9%)
Brazil	1,032,885,154 (33.3%)	1,038,725,172 (33.7%)	1,022,405,968 (33%)
China	1,658,171,076 (33.6%)	1,737,252,639 (35.2%)	1,534,303,239 (31.2%)
Colombia	65,492,621 (33.5%)	65,565,035 (33.6%)	64,480,569 (32.9%)
Costa Rica	12,531,627 (33.5%)	12,561,997 (33.6%)	12,315,569 (32.9%)
Ecuador	23,896,604 (33.4%)	23,878,403 (33.5%)	23,717,493 (33.1%)
Fiji	1,973,653 (49.1%)	1,981,662 (49.4%)	63,679 (1.5%)
Indonesia	364,677,581 (33.5%)	363,891,746 (33.3%)	362,778,268 (33.2%)
Israel	3,829,747 (35.8%)	3,778,445 (35.3%)	3,094,828 (28.9%)
Kenya	20,765,746 (33.9%)	20,823,175 (34.1%)	19,572,983 (32%)
Madagascar	13,133,041 (33.4%)	13,458,383 (34.3%)	12,721,257 (32.3%)
Mexico	134,244,810 (33.3%)	135,226,168 (33.7%)	133,051,113 (33%)
South Africa	36,686,182 (33.5%)	37,565,084 (34.3%)	34,960,524 (32.2%)

independently if they have developed or developing economies, excepting for Fiji, where this percentage is only 1.5% (Table 3).

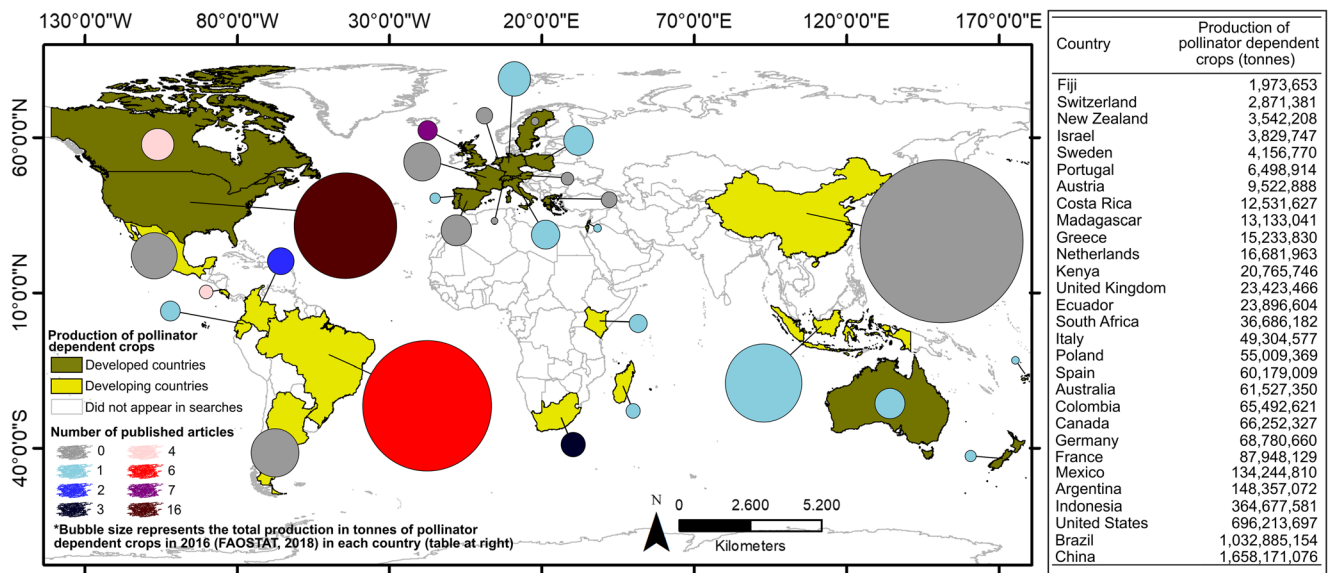
### 3.3 Research funding records related to pollination services

Our search returned 547 records of research funding related to pollination services, 217 of which were analysed in this study (see Table S2, Electronic Supplementary Material). The funded projects related to pollination services in developed countries accounted for 94.93% ( $N=206$ ) while developing countries received only 5.06% ( $N=11$ ) of the total funds (Fig. 8). Records of funds on pollination services started in 1993, increased sharply after 2006, doubling in value from 2005 to 2006, and trebling in value from 2008 to 2009 (Fig. 3). Investments exceeded US\$12 million in 2010, reaching a

maximum of US\$14 million in 2016 (Fig. 3). There was a positive temporal correlation between the scale of investments and number of publications ( $r=0.80$ ,  $P<0.0001$ ).

The overall research funding contributions on pollination service researches from 1992 to 2018 exceeded US\$ 155 million; 23 countries received funds, which ranged from US\$0.016 million in India to US\$51.3 million in the United States (Fig. 8). The highest investments were in the United States (US\$51.3 million) and the UK (US\$25.5 million). Together these two countries received 79.6% of the investments. The United States and the United Kingdom were also the countries with more scientific publications in the literature body in our review (Fig. 4a; Fig. 8). Among the developing countries, Colombia (US\$1.23 million) and Brazil (US\$1.14 million) received the highest amount of research funding, however together they accounted for only 1.53% of investments (Fig. 8).





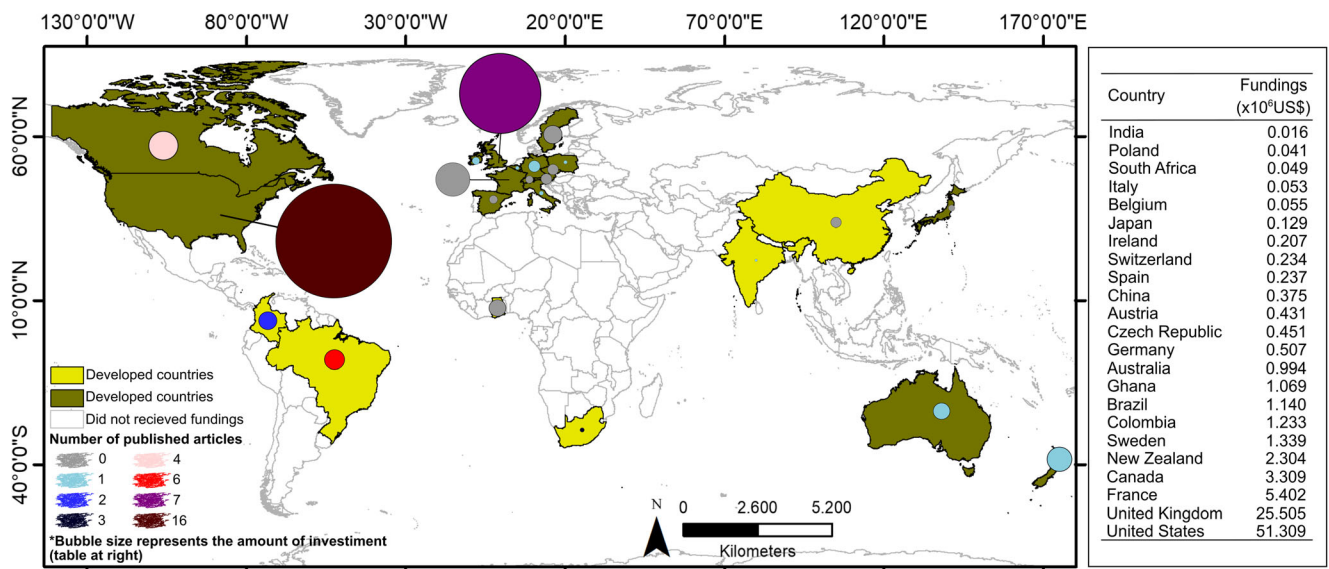
**Fig. 7** Distribution of agricultural production and research effort in countries that appeared in the scientometric survey in this study. Countries that produce any crop dependent on biotic pollination and appeared in our search are coloured in two categories: developed or developing economies according to the United Nations (2019) ( $N=29$  countries). Bubble size indicates the proportional production (tonnes) of all pollination-dependent crops in each country during the year of 2016

(according to the FAO database); values are informed in the box at right. Bubble color represents the number of published articles on economic valuation of pollination services by countries in which the studies were carried out (i.e. study area in the country) until December 2018 (Source: ISI Web of Science; <https://www.webofknowledge.com>). For the inclusion and exclusion criteria when searching articles at ISI Web of Science, please see the Flow diagram in Fig. 1

### 3.4 Government documents and policies related to pollination services

The search returned 306 government documents. After removing duplicates and documents that did not match our

screening criteria (see Fig. 1 for details), 24 documents remained in the analysis (see Table S3 in the Electronic Supplementary Material). The 24 government documents were published by Canada ( $N=1$ ), France ( $N=1$ ), European Union ( $N=1$ ), Australia ( $N=2$ ), the government and



**Fig. 8** Distribution of research funding and effort in countries that appeared in the scientometric survey in this study. Countries that received any research funding/grant and appeared in our search are coloured in two categories: developed or developing economies according to the United Nations (2019) ( $N=23$  countries). Bubble size indicates the amount of research funding in million dollars (US\$). Bubble color represents the number of published articles on the economic valuation of

pollination services in countries with developed and developing economies until December 2018 (Source: ISI Web of Science; <https://www.webofknowledge.com>). Source for research funding/grants: Dimensions Platform (2018; <https://www.dimensions.ai/>). For the inclusion and exclusion criteria when searching articles at Web of Science, please see the Flow diagram in Fig. 1

parliament of the United Kingdom ( $N = 11$ ) and FAO ( $N = 8$ ). These government documents addressed the following five major themes: (1) status, monitoring and preservation of pollinators; (2) pollinator conservation strategies; (3) reports and recommendations on the use of pesticides, especially neonicotinoids; (4) Actions and recommendations for healthy environments for pollinators; (5) value of pollinators in agriculture, ecological intensification and sustainable agriculture.

Our internet media search returned nine positive ongoing policies to protect pollinators and pollination ecosystem services. These documents were initiatives ( $N = 5$ ), laws ( $N = 3$ ), and decree ( $N = 1$ ) in effect between 2011 and 2018 in France, Canada, Ireland, Australia, Porto Rico and European Union. The measures deliberated over the five main topics covered in government documents (mentioned above), but also addressed the improvement of knowledge on pollination and pollinators and established efforts to increase socio-awareness about the preservation of pollinators and their importance for human well-being. These policies are summarized in Table S4 of the Electronic Supplementary Material.

## 4 Discussion

### 4.1 Economic value of pollination services: scientometric perspective

Our results indicate an increase in the number of economic valuation studies focused on pollination services in the last two decades, with a substantial growth in the last six years to 2018 (ca. 55% of all publications). However, there is a marked lack of data on regional and local important commercial crops that are essential for the food security of many millions of people, particularly in tropical developing countries [e. g. acerola in south America (Schreckinger et al. 2010); baobab in eastern Africa (Meinhold et al. 2016)]. Those data could support future discussions on the economic contribution of pollinators to agricultural production at different scales. The available studies on the economic benefits of pollination services have not yet been well incorporated into public policy formulation and decision making (Breeze et al. 2016).

In our analyses there were only four articles based on experimental research in tropical environments (Bos et al. 2007; Bravo-Monroy et al. 2015; Cunningham and Le Feuvre 2013; Sandhu et al. 2016), all of which assessed the contribution of pollinators to commercial crops grown across the tropics (e.g. coffee, passion fruit and cocoa). The value of pollination services to many crops grown at smaller continental scales remains entirely unknown.

Despite recent attention on applied pollination ecology, there is still a major research gap linking crop pollination requirements to the conservation of pollinators and natural habitats around the world (Breeze et al. 2016). Most

agricultural pollination ecologists are based and work in temperate countries. We believe that more experimental analyses under different environmental and socioeconomic contexts should be conducted in tropical agroecosystems, especially in emergent developing countries, such as China and Brazil, where agricultural production from food crops that are highly dependent on pollinators is expanding rapidly (Giannini et al. 2012; Giannini et al. 2015a). The relationship between pollination services and agricultural production is often diverse and context-specific, which makes it difficult to apply the lessons learned from studies in Europe and North America to the rest of the world. However, those gaps provide research opportunities to understand what would be more suitable, in terms of research strategies, for developing countries (Timberlake and Morgan 2018).

Increased technology favours access to information that may have resulted in a growing number of published articles over time. Although some studies were carried out in developing countries (29.4%), one third of them were led by authors affiliated with developed (and mid-latitude) countries. Economic factors contribute to the higher science productivity of wealthier nations, while some countries with greater agricultural potential continue subject to scarcity of research (Moreddu et al. 2017). After the USA, the following countries appear sequentially in terms of number of publications per country of the corresponding author: the UK, Germany, Brazil, Canada and Australia (Fig. 4b). However, Australia ranks 31st in the world ranking of agricultural production, whereas Brazil is now the world's fourth largest food producer, the third largest food exporter, the third fruit producer (MAPA 2017) and the leading nation in terms of productivity growth (Bojanic 2017; Hubbard et al. 2017; Moreddu et al. 2017), but even so, the dependence on pollinators of 1/3 of its agricultural production is still unknown (Table 3, source FAOSTAT 2018).

### 4.2 Economic value of pollination services

Our review and synthesis found recent literature showing a growing trend in the global scale monetary value of pollination services, due to methodological improvements and increasing production and market prices of pollinator-dependent crops (Breeze et al. 2016; Hanley et al. 2015; Lautenbach et al. 2012). Despite this increasing trend over time in the estimated values of pollination services from the full set of main globally grown crops, when individual crops are analysed at local and regional scales the economic contribution of pollination to some crops varies greatly and does not follow this global pattern (see Table 2).

In 2004, the economic value of coffee pollination in Brazil was estimated at US\$2595.42/ha (De Marco and Coelho 2004), in 2006 it was estimated in Indonesia and Ecuador at US\$63.55/ha and US\$112.33/ha respectively (Olschewski

et al. 2006), while in 2015 the estimated value was US\$159/ha in Colombia (Bravo-Monroy et al. 2015) (all values adjusted for inflation until March 2020, Table 2). These fluctuations in local estimates varies mostly due to methodological differences, such as the accuracy of the database, the diversity of experimental design in field researches and even the equation applied to estimate the value. Although methodologies have become increasingly sophisticated, the studies available to date have generally failed to propose new approaches that can easily be applied to diverse localities and cultural contexts, rendering difficult comparisons of different scenarios that can be used to extrapolate results (see Bauer and Wing 2016; Gallai et al. 2009).

Most studies on the economic value of pollination services at regional scales emphasize that enhanced levels of pollination and pollinator abundance increase the economic value of production by improving qualitative aspects of fruit and/or seed yields, their nutritional content, and general appearance including fruit size (e.g. Matheson and Schrader 1987; JianDong and Chen 2011; Lye et al. 2011; Garratt et al. 2014; Breeze et al. 2015; Giannini et al. 2015a; Giannini et al. 2015b; Knapp and Osborne 2017). For example, in general, a production increase of between 5% and 50% can be achieved with an adequate animal pollination service, mainly represented by bees (e.g. Greenleaf and Kremen 2006; Gallai and Vaissière 2009; Stanley et al. 2013). Specifically for strawberry, the commercial value of strawberry pollinated by bees increases by 38.6% compared with wind-pollinated production, and by 54.3% compared with self-pollination (Klatt et al. 2014). The persistence or restoration of natural habitats embedded within agricultural landscapes for pollination services can be as cost-effective and productive as conventional agricultural approaches, justifying the retention of as much as 8% of spared habitat supporting wild pollinators in relation to overall cropland area (Dicks et al. 2016).

Our comprehensive survey found five estimates on the global value of agricultural pollination, reported by Bauer and Wing (2016), Costanza et al. (1997), Gallai et al. (2009), Lautenbach et al. (2012), and Pimentel et al. (1997). Although the values reported were increasingly higher over time, the comparison among these values is difficult due to differences in data input and methodologies applied. The seminal paper by Costanza et al. (1997) estimated the value of pollination services from the overall production value of pollinator-dependent crops, honey and beeswax in the USA. These values were then simplistically extrapolated to analogous agricultural production in the rest of the world by assuming that agricultural products in the USA are equivalent to 10% of the global value. Pimentel et al. (1997) estimated the economic value of insect pollination worldwide to be at least five times higher than the value estimated

by Robinson et al. (1989) for the USA. The annual estimates from either Costanza et al. (1997) or Pimentel et al. (1997), adjusted for inflation and exchange rates until March 2020, are around US\$206 billion and US\$324 billion, respectively. The estimate of Pimentel et al. (1997) was relatively high because they included the value of insect-pollinated legumes that are fed to cattle. When it is considered in their estimated value of pollination service only the crops used directly for humans, the estimated value will represent ~US\$64 billion (adjusted for inflation in March 2020). These values (US\$206 billion and ~US\$64 billion) are lower than the US\$210 billion estimated by Gallai et al. (2009), which, according to them, is ~9.5% of the total value of the crops used directly for human food. Costanza et al. (2014), more recently, provided a new estimate based on updated data on global agricultural production and land use change between 1997 and 2011. Unfortunately, however, they only presented aggregate global values, categorised by biomes, without differentiating ecosystem services individually, and in doing so completely omitted the contemporary value of pollination services at a global scale.

Even while accounting for several valuation components that had been entirely neglected in previous estimates, Gallai et al. (2009) did not consider supply-demand curves in market responses to insufficient yields, since a generalized decline in pollinators can lead to increased prices of pollination-dependent crops (Hein 2009). Gallai et al. (2009) recognized this bias and assumed the importance of price elasticity and market responses, but they did not apply this concept to more accurately adjust their estimate. The global value estimated by Lautenbach et al. (2012), ~US\$387 billion (adjusted for inflation in March 2020, see Table 2), is the highest of those published so far and was 1.9 times higher than the value estimated by Gallai et al. (2009). The use of purchasing power parities (PPPs) to compare realistic values between different countries substantially raises the final value of pollination services since it increases the value in almost all developing countries, where labour input tends to be cheaper. This effect is stronger than any reduction in pollination values in developed countries (Lautenbach et al. 2012), making a global estimate even higher than otherwise expected.

The most recent estimate of the overall monetary value of crop pollination is US\$195 billion (adjusted for inflation in March 2020) (Bauer and Wing 2016). This estimate considered the benefits of pollination across all sectors, including indirect effects on meat, vegetable oils and fats, dairy products, and beverages, nevertheless this value is lower than adjusted values of the previous estimates. Interestingly the estimate by Gallai et al. (2009), which computed benefits only from crops directly consumed by humans and that are dependent on biotic pollination (US\$210 billion), is still slightly higher than the value estimated by Bauer and Wing (2016), both adjusted for inflation in March 2020.

### 4.3 Comparison among methods for economic valuation of pollination services

Based on the analysed articles, six distinct methods of economic valuation of pollination services are often applied (see Table 2). Differences in these approaches are mainly based on crop market prices, losses in yield production associated with pollination disruption, and the association between production and prices. The most frequent method to estimate the economic value of pollination services has employed yield analysis (YA), which simulates the absence and presence of animal pollination in field experiments following proposals of Klein et al. (2007). The dependency ratio (DR), represented by the maximum benefits of pollination services for cultivated species, is frequently applied together with production data in order to estimate the economic value of pollination, according to the analysed articles (Basu et al. 2011; Calderone 2012; Giannini et al. 2015b; Lautenbach et al. 2012). Although the dependence of pollinators was at some level previously considered by authors, this improved standard procedure has been widely applied in many case studies (Basu et al. 2011; Calderone 2012; Giannini et al. 2015b; Lautenbach et al. 2012). Crop value (CV) is a sum of crop market prices positively affected by pollination services (e.g. Costanza et al., 1997). Replacement costs of pollinators (RC) with technological solutions or management of pollinators is considered an accurate alternative for estimating the ecosystem value of pollinators (Allsopp et al. 2008). Similarly, the consumer surplus (CS) method applies partial and general equilibrium models to analyse market responses to changes in production due to pollination deficit, the ability of producers to compensate for losses with other inputs, and the effects these losses would have on the external market (Bauer and Wing 2016; Gallai et al. 2009). Articles also valued pollination ecosystem services on the basis of citizen's willingness to pay (WTP) for the maintenance or improvement of nonmarket benefits, in this case pollination benefits, through a questionnaire-based economic survey (Breeze et al. 2015). For local scales, YA analyses are more frequently applied. Alternatively, at global and regional scales, DR is more frequently applied and tends to generate higher values of pollination services compared to the other methods, according to our review.

Studies on pollination services in agricultural landscapes are complex and have been conducted to improve the understanding of the ecology of pollinators, the relationship of pollinators with landscapes, and crop yields (Breeze et al. 2016; Nogué et al. 2016). The density of floral visitors, the level of agricultural conventional intensification and the isolation of semi-natural or natural areas are the factors that most influence pollinator-dependent crop yields (Gret-Regamey et al. 2014). Ricketts et al. (2004) demonstrated that two isolated tropical rainforest fragments (46 and 111 ha with a distance of 1 km from extensive natural habitat) increased coffee yields by 20%

and reduced the frequency of deformed seeds by 27% through pollination services, generating a surplus of US\$60,000 per year for a Costa Rican farm. This amount was equivalent to 7% of annual profits and represented a much larger amount than current conservation incentive payments (Ricketts et al. 2004). The increase in natural habitats in agricultural landscapes can be as cost-effective and productive as conventional approaches, even with up to 8% of land use for habitats that support beneficial organisms (Dicks et al. 2016).

High quality pollination services, associated with high density and diversity of pollinators, also increases the economic value of crop production by improving qualitative aspects of fruits such as their appearance, size and nutritional quality (Garratt et al. 2014; Giannini et al. 2015b). Gallai and Vaissière (2009) observed a production increase of between 5% and 50% induced by adequate biotic pollination service, mainly by bees. The commercial value of strawberry pollinated by bees increased by 38.6% compared to wind-pollinated production and by 54.3% compared to self-pollination (Klatt et al. 2014). Bees homogeneously allocate pollen into the receptacles, increasing the number of fertilized achenes in each fruit, which are responsible for the production and accumulation of auxin and gibberellic acid (Klatt et al. 2014). Together, these hormones induce cell growth and size, thus increasing the weight of individual strawberry fruits (Klatt et al. 2014).

Although methodological adjustments have been developed to address yield responses to pollination services (Breeze et al. 2016, Winfree et al. 2011), a major fraction of pollination-dependent fruit and vegetable crops consumed by humans is derived from diffuse systems of subsistence production or those commercialized only in informal local markets, so that both country-scale productivity and production values fail to be monitored and accounted for in estimates. Additionally, most crops important for human diets are not export commodities but constitute essential sources of vitamins and minerals, most of which are produced at local to regional scales (Eilers et al. 2011). Also, many plants cultivated at local scales or extracted from natural ecosystems are not even considered as crops, such as *Platonia insignis*, *Endopleura uchi*, *Myrciaria dubia*, *Astrocaryum aculeatum*, *Pouteria caimito*, *Caryocar villosum*, *Spondias mombim*, *Byrsonima crassifolia* in Brazil, even though they remain essential for local food security for millions of people, particularly in the context of family household and subsistence farming (EMBRAPA 2016). Many of these minor 'crops' have no export markets, are missing altogether from the periodically updated FAO agricultural databases and are, therefore, entirely unaccounted for. Nevertheless, this data shortage for crop plants such as those mentioned above (and many others elsewhere in Asia and Africa) may indicate that economic benefits of pollination to food production worldwide have been underestimated. The magnitude of this discrepancy remains

unclear given the data available and mainstream economic rationale at present. Additionally, estimates fail to consider other economic values of pollination services such as in providing raw materials for cosmetics and pharmaceutical industries, plants for florist trade, beehives and honey, for example.

Assessments of ecosystem services that consider only monetary aspects are limited, as several ecosystem benefits, such as pollination, are not accounted for in economic markets and are ecologically and socially context-dependent. In addition to economic evaluation, a multidimensional analysis is therefore essential to promote a balance between the financial, social, physical, human needs, and the natural environment, to ensure the maintenance of pollination services and human wellbeing (see Hipólito et al. 2016; Garibaldi et al. 2016). Surveys that demonstrate the broad range of measures that farmers and communities can or have been using that are beneficial to pollinators are important to demonstrate “win–win” scenarios and are highly appropriate to ensure better land-use decisions than several conventional agriculture practice (e.g. Garibaldi et al. 2016; Hipólito et al. 2016; Olschewski et al. 2006).

#### 4.4 Research funding and government responses to pollination services

Developed countries received more research funding for projects related to pollination services compared to developing countries. Additionally, developed countries published all the policy documents on pollination service protection. The main pathway to grow a science base is through financial investments. Targeted public or private sector financial contributions to research projects or research training are essential for high-quality scientific research, for science capacity and more comprehensive and diversified research enterprises at larger scales. For example, the United States, Germany and Canada on average allocate 2.15% of their Gross Domestic Product to scientific research, twice the amount invested in Brazil (World Bank in 2012). Research funding contributions for pollination research in the 1992–2018 period exceeded US\$115 million, and the highest investments were in the United States (US\$85 million) and the UK (US\$36 million).

Undeniably, global development required further efforts from wealthy developed countries to reconcile priorities, particularly for low-income developing countries. Although, some grants were designated to research in developing countries (in Brazil, Ethiopia, Mexico), 7 out of 11 were assigned to organizations located in developed countries (i.e. the United Kingdom, United States, Italy). In the last decade approximately 6% of all the UK research funding is estimated to involve developing countries or have direct relevance to international development (Timberlake and Morgan 2018). This may deliver research funding and expertise to countries that have been historically neglected, contributing to build valuable research capacity.

Many countries are building a consistent national policy framework to translate the wide body of research and management recommendations for pollination services into government policies (Table S4, Electronic Supplementary Material). Initiatives such as the IPBES pollination assessment (IPBES 2016) and the publication of 10 simple policy recommendations to safeguard pollination and pollinators (Dicks et al. 2016) could be applied to reinforce and support more effective policy decisions (e.g. “recognize pollination as an agricultural input in extension services”; “develop long-term monitoring of pollinators and pollination”; “fund participatory research on improving yields in organic, diversified, and ecologically intensified farming”). Recently, documents describing an effective framework have been published (Table S3). These government documents may be used by local researchers and technical consultants to strengthen more locally relevant recommendations, as well as update data and foster insights. However, stronger political will is required to implement such initiatives and put into practice well-established endorsements. This could evolve in a variety of ways, for example, through greater public awareness and pressure. Public interest in natural pollinators has recently grown in South Africa through social media, photography and citizen science, demonstrating increased civic and political engagement with these issues (Timberlake and Morgan 2018).

Furthermore, government responses are widely variable in content and in space and time. For example, in 2018, the EU banned neonicotinoids, the world’s most widely used insecticides, and many European countries are planting wildflowers and subsidizing agricultural set-asides to attract insects (Timberlake and Morgan 2018). Controversially, in the same period the Brazilian government regressed when pro-agribusiness congressmen voted to lift restrictions on harmful pesticides that are strictly banned in other countries.

## 5 Conclusions and recommendations

We documented that since the 1990s there has been a rapidly increasing trend of published estimates on the economic value of biotic pollination services, often highlighting the rising costs of the service in degraded landscapes. Although we observed an increasing pattern of estimates of global pollination values, some crops local and regional estimates tend to fluctuate over time and geographically. Rather than propose a simplification of methodologies, we encourage pluralism based on a wide range of approaches at multiple scales under different ecological and socioeconomic contexts that span from mechanized croplands serving global export markets to small-scale horticulture in local subsistence economies. To achieve this goal, will require an expansion of research since the current dearth of experimental data, especially for locally-grown crops in tropical countries, will continue to perpetuate

the severe underestimation of biotic pollination services from published values. Besides, estimates overlook other important economic values of pollination services such as in honey and beehives chain and in cosmetics and pharmaceutical industry.

However accurate we may be in estimating the value of pollination services, this value continues to fail in representing the complex sets of benefits of pollinators and describe the full importance of their ecological functions. It is widely known that pollination services provided by natural ecosystems influence the diversity and intensity of interactions between pollinators and crops, and many other plant species used for food by subsistence communities or in commerce, which are not usually defined as crops. All these caveats contribute to the continued systematic undervaluation of biotic pollinators in agroecosystems. Nonetheless the current incomplete literature on crop pollination services already reveals that the benefits of pollination for agriculture are very high, even if underestimated, which should strengthen the conservation and land-use planning agenda in human-modified landscapes around the world.

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## Compliance with ethical standards

**Conflict of interest** The authors declared that they have no conflict of interest.

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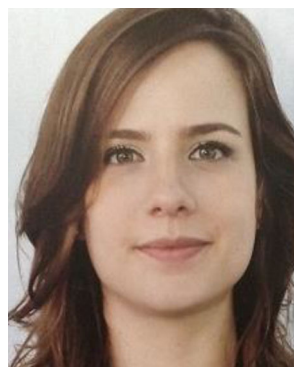
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