Author's personal copy

ECOLOGICAL ECONOMICS 68 (2009) 810–821

available at www.sciencedirect.com

ScienceDirect

www.elsevier.com/locate/ecolecon

ANALYSIS

Economic valuation of the vulnerability of world agriculture confronted with pollinator decline

Nicola Gallai[a,b,*], Jean-Michel Salles[c], Josef Settele[d], Bernard E. Vaissière[a]

[a]INRA, Laboratoire Pollinisation & Ecologie des Abeilles, UMR406 Abeilles & Environnement, 84914 Avignon Cedex 9, France
[b]INRA, UMR LAMETA, 2 place Viala, 34060 Montpellier Cedex 1, France
[c]CNRS, UMR LAMETA, 2 place Viala, 34060 Montpellier Cedex 1, France
[d]UFZ, Helmholtz-Centre for Environmental Research, Department of Community Ecology, Theodor-Lieser-Str. 4, 06120 Halle, Germany

ARTICLE INFO

Article history:
Received 8 November 2007
Received in revised form 6 May 2008
Accepted 24 June 2008
Available online 3 August 2008

Keywords:
Pollination
Valuation
Vulnerability
Agriculture
Ecosystem service
Crop

ABSTRACT

There is mounting evidence of pollinator decline all over the world and consequences in many agricultural areas could be significant. We assessed these consequences by measuring 1) the contribution of insect pollination to the world agricultural output economic value, and 2) the vulnerability of world agriculture in the face of pollinator decline. We used a bioeconomic approach, which integrated the production dependence ratio on pollinators, for the 100 crops used directly for human food worldwide as listed by FAO. The total economic value of pollination worldwide amounted to €153 billion, which represented 9.5% of the value of the world agricultural production used for human food in 2005. In terms of welfare, the consumer surplus loss was estimated between €190 and €310 billion based upon average price elasticities of – 1.5 to – 0.8, respectively. Vegetables and fruits were the leading crop categories in value of insect pollination with about €50 billion each, followed by edible oil crops, stimulants, nuts and spices. The production value of a ton of the crop categories that do not depend on insect pollination averaged €151 while that of those that are pollinator-dependent averaged €761. The vulnerability ratio was calculated for each crop category at the regional and world scales as the ratio between the economic value of pollination and the current total crop value. This ratio varied considerably among crop categories and there was a positive correlation between the rate of vulnerability to pollinators decline of a crop category and its value per production unit. Looking at the capacity to nourish the world population after pollinator loss, the production of 3 crop categories – namely fruits, vegetables, and stimulants - will clearly be below the current consumption level at the world scale and even more so for certain regions like Europe. Yet, although our valuation clearly demonstrates the economic importance of insect pollinators, it cannot be considered as a scenario since it does not take into account the strategic responses of the markets.

© 2008 Elsevier B.V. All rights reserved.

---

[*] *Corresponding author*. INRA, UMR LAMETA, 2 place Viala, 34060 Montpellier Cedex 1, France. Tel.: +33 4 99 61 29 67; fax: +33 4 67 54 58 05.
E-mail address: gallai@supagro.inra.fr (N. Gallai).

0921-8009/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.ecolecon.2008.06.014

Author's personal copy

1. Introduction

The production of 84% of crop species cultivated in Europe depends directly on insect pollinators, especially bees (Williams, 1994). And Klein et al. (2007) found that 87 crops, that is 70% of the 124 main crops used directly for human consumption in the world, are dependent on pollinators. Insect pollination is both an ecosystem service and a production practice used extensively by farmers all over the world for crop production. It is an ecosystem service in that wild pollinators, in particular wild bees, contribute significantly to the pollination of a large array of crops (Kremen et al., 2002; Morandin and Winston, 2005; Greenleaf and Kremen, 2006; Winfree et al., 2007, 2008). And it is also a management tool in that honeybees, bumblebees and a few other bee species are purchased or rented by farmers in many countries to supplement the local pollinator fauna (McGregor, 1976; Olmstead and Wooten, 1987; Robinson et al., 1989; Free, 1993; Dag et al., 2006). Thus the economic benefit of insect pollination is clear for farmers and the market of colony rental is now well developed and organized for honey bees in the United States of America (Sumner, and Boriss, 2006) and Europe (Carreck et al., 1997) as well as for bumble bees all over the world (Velthuis and van Doorn, 2006). This practice also suggests that there is already not enough wild pollinators to insure adequate pollination of all crops throughout the year in these countries. Yet the abundance and diversity of wild bees as well as the abundance of honeybees are now declining and some species are clearly at risk (Biesmeijer et al., 2006; National Research Council, 2007; Olroyd, 2007; Stokstad 2007). The current decline of insect pollinator populations emphasizes the need to better assess the potential loss in terms of economic value that may result from this trend and the possible ultimate disappearance of pollinators, and to estimate the level of vulnerability of the world agriculture to insect pollinators.

Two main ways have been used to date to assess the monetary value of pollinators. The first one consists in simply assessing the total value of insect-pollinated crops. This approach has been used at a national scale in the USA (Martin, 1975; Levin, 1984; Metcalf and Metcalf, 1992) as well as on a world scale (Costanza et al., 1997; Pimentel et al., 1997). Since the production of most crops is only partially reduced in the absence of insect pollinators, a second more refined approach to improve the previous estimate has been to introduce a dependence ratio that takes into account the real impact of insect pollinators on crop production. This dependence ratio enables the calculation of the production loss in case of a complete disappearance of pollinators, and the economic value of insect pollination service is assimilated with the corresponding loss of crop value. Thus the monetary assessment is directly related to reported values of the dependence of crop production on the level of insect pollination and, in this paper, it will be called a bioeconomic approach. This type of assessment has also been done at national and larger scales (France — Borneck and Bricout, 1984; Hungary — Benedek, 1983; Switzerland — Fluri and Frick, 2005; United Kingdom — Carreck and Williams, 1998; USA — Robinson et al., 1989, Morse and Calderone, 2000, Losey and Vaughan, 2006; 12-member-states European Community — Borneck and Merle, 1989). Unfortunately, these studies have used a wide range of dependence ratios for the same crops (Table 1). Indeed, these ratios were estimated based largely on personal communications and interpretation of review material, such as McGregor (1976) and Free (1993), which do not provide dependence ratios. None of the bioeconomic studies to date have evaluated the impact of insect pollinators at the world scale, nor did they make a geographical analysis of the impact of pollinators in terms of the possible vulnerability of agriculture or examined the potential impact of pollinator loss on production compared with the consumption structure.

Our first objective was to quantify the economic loss that could result from the total disappearance of insect pollinators on world agricultural output and we based our calculations on the dependence ratios recently published for the crops used directly for human food (Klein et al., 2007). Due to the many crop species and the heterogeneity of the structure of the agricultural production, the vulnerability to pollinator decline is likely to vary widely among the different continents and regions. Our second objective was therefore to provide a measure of the vulnerability of the regional and world agriculture when confronted to the decline, or even the total disappearance, of insect pollinators. Finally our third objective

Table 1 – Heterogeneity of the dependence ratios reported for the production of some selected crops in regards to insect pollination (extrema are underlined)

Crop species	Common name	Borneck and Bricout (1984)			Robinson et al. (1989)	Southwick and Southwick (1992)	Morse and Calderone (2000)	Klein et al. (2007)		
		Min	Max	Mean				Min	Max	Mean
Fruits										
Fragaria × ananassa	Strawberry	0.100	0.200	0.150	0.4	0.30	0.2	0.1	0.4	0.25
Malus domestica	Apple	0.100	0.200	0.150	1.0	0.80	1.0	0.4	0.9	0.65
Vitis vinifera	Grape	0.001	0.010	0.006	0.1	0.15	0.1	0.0	0.0	0.00
Nuts										
Amygdalus communis	Almond	0.100	0.200	0.150	1.0	0.90	1.0	0.4	0.9	0.65
Vegetables										
Cucumis melo	Melon (incl. cantaloupe)	0.100	0.200	0.150	0.8	0.70	0.9	0.9	1.0	0.95
Mean				0.120	0.66	0.57	0.64			0.50

Author's personal copy

was to compare the production and consumption of insect-pollinated crop categories at the regional and world scale in the face of pollinator loss in order to draw some insight on potential local shortages and impacts on trade. Our calculations were based on the assumption of a total pollinator loss, but our results can be extended to any level of pollinator decline as there is empirical evidence that the yield of entomophilous crops – that is crops that are pollinated by insects solely or in a dominant way – responds linearly to pollinator density (Dedej and Delaplane, 2003; Steffan-Dewenter, 2003; Clement et al., 2007).

2. Methods

2.1. Principles

Among the main crops that contribute to human food, some, such as most cereals, do not depend on insects for their pollination, while others can be highly or totally dependent on insect pollination, such as many fruits, vegetables and stimulant crops (Klein et al., 2007). Our study is based on the hypothesis that the economic impact of pollinators on agricultural output is measurable through the use of dependence ratios quantifying the impact of a lack of insect pollinators on crop production value. This decrease in the production value could result from a reduction in yield as well as in quality (Free, 1993). Unfortunately, this impact on production value is unknown for most crops as what is usually reported is solely the degree of dependence of the production on insect pollinators (Borneck and Bricout, 1984; Robinson et al., 1989; Southwick and Southwick, 1992; Morse and Calderone, 2000; Klein et al., 2007). It is this dependence ratio that we used again in our study to calculate the economic impact of pollinators and the vulnerability of the agricultural output at various scales.

Because of the lack of substitution among agricultural produce, the economic impact and the vulnerability of the agricultural output is not enough to assess the full value of insect pollinators as, indeed, one ton of rice is not an appropriate substitute for one ton of coffee or of cantaloupe. Thus, in addition to looking at individual crops, we examined the vulnerability to pollinator decline of the FAO crop categories to which each crop belonged based upon the assumption that crops within a category could be considered as potential appropriate substitute for one another while this would not be the case for crops in different categories. We used the following 10 categories based on FAO: cereals, edible oilseed crops, fruits, nuts, pulses, roots and tubers, spices, stimulant crops, sugar crops, vegetables.

2.2. Indicators and formulae

We used a bioeconomic approach to calculate the economic value of the impact of pollinator loss as well as the overall vulnerability of the agricultural output to such a loss. The variables used for each crop *i*, where $i \in [1;I]$, in each world region *x*, where $x \in [1;X]$, were the quantity produced (Q_{ix}), the quantity consumed (C_{ix}), the dependence ratio of the crop *i* on insect pollinators (D_i) and the price of crop *i* per unit produced in region *x* (P_{ix}). We used the price of each crop in each of the 5 regions of the world (sensu FAO; see supplementary data — Appendix A) because, despite the growing interdependence of agricultural markets, producer prices for the same crop may vary widely from one region to another and therefore cannot be appropriately summarized by a single average world price. Indeed, we found that neither the FAO database nor that of any other world organization provided these prices on a worldwide basis for all our study crops. The total economic value of insect pollination (IPEV) was then calculated as follows:

$$\mathrm{IPEV} = \sum_{i=1}^{I} \sum_{x=1}^{X} (P_{ix} \times Q_{ix} \times D_i) \qquad (1)$$

Following White (1974), a precise definition of vulnerability was given by Turner et al. (2003) and used by Schröter et al. (2005) to assess the vulnerability of Europe faced with global change. Vulnerability is a function of three elements: exposure, sensitivity and adaptive capacity. In this context, we used the ratio of the economic value of insect pollination to the economic value of the crop (EV) to calculate a level of vulnerability since it provides a measure of the potential relative production loss attributable solely to the lack of insect pollination. The ratio of vulnerability (RV) for the world output used for human food was thus calculated as follow:

$$\mathrm{RV} = \frac{\mathrm{IPEV}}{\mathrm{EV}} = \frac{\sum_{i=1}^{I} \sum_{x=1}^{X} (P_{ix} \times Q_{ix} \times D_i)}{\sum_{i=1}^{I} \sum_{x=1}^{X} (P_{ix} \times Q_{ix})} (\%) \qquad (2)$$

So defined, the agricultural vulnerability to pollinator decline depends upon crop dependence to pollinators, and farmers' capacity to adapt to pollinator decline. We used part of the overall matrix to calculate the vulnerability of a crop, of a crop category, and of the agricultural industry in a given region when faced with pollinator decline.

To compare production with consumption per region and per crop category, we calculated the 2005 relative overproduction as:

$$\frac{\sum_{i=1}^{I} \sum_{x=1}^{X} (Q_{ix} - C_{ix})}{\sum_{i=1}^{I} \sum_{x=1}^{X} (C_{ix})} \qquad (3)$$

The corresponding matrix after total pollinator loss was:

$$\frac{\sum_{i=1}^{I} \sum_{x=1}^{X} (Q_{ix}(1 - D_i) - C_{ix})}{\sum_{i=1}^{I} \sum_{x=1}^{X} (C_{ix})} \qquad (4)$$

2.3. Data collection

The geographical scale of our study was the world based upon the 2005 data from the FAO database (http://www.fao.org) and thus restricted to the 162 countries that are members of this international organization. Following FAO definitions, we gathered these countries into 5 main regions (Africa, Asia and Oceania, Europe, North America and Caribbean, South and Central America), and, within each region, into subregions (see supplementary data — Appendix A).

Author's personal copy

We limited the scope of our study to the direct crops and commodity crops used directly for human food as reported by FAO (see supplementary data — Appendix B). Direct crops are those listed individually with their production by the FAO while a commodity is an aggregation of different crops for which the production figures are pooled together and most are reported as Not Elsewhere Classified. Commodity production figures are based on a questionnaire that countries fill out to include important crops for the world market that are not listed individually by the FAO. We included the commodity crops in the study because they represent a significant part of the agricultural world output.

For Q_{ix} and $C_{ix,}$ we used the 2005 FAO production and consumption data, respectively (http://www.fao.org). For P_{ix}, we needed the mean 2005 producer price per unit weight for each crop or commodity and each region as we opted to take into account regional specialization, geographical context, and socio-economic factors. We chose this approach because producer prices vary with many factors such as crop management, climate, varieties and market in such a way that a regional approach should provide more accurate price estimates than a worldwide approach. To fit complex geographical patterns as well as to be able to concentrate on large producing regions without having to go to the level of individual countries for which many price data are not available either, we used the five main world regions defined previously (see supplementary data — Appendix A). Major world field crops, like most cereals and sugar crops, are produced on a large scale and have a large-enough commercial value to be traded on financial markets. For these crops, we used the "free on board" (FOB) prices, which are future contracts for 2005. These prices are available on the websites of financial market places specialized in commodities such as the Chicago Board of Trade (CBOT) and the New York Board of Trade (NYBOT). For most other crops, prices are not available on the financial market place because of lower interest in their international trading on a large scale. For these crops, we used the 2005 producer prices for each world region that were provided by the European database Eurostat (http://epp.eurostat.ec.europa.eu) and by the United States Department of Agriculture (http://www.fas.usda.gov). For minor crops, defined as those for which the 2005 producer price was not available in either of these two large databases, as well as for all the commodities, we used the average producer price listed on the FAOSTAT website for the period 1991–2002 for the most important producing country of each world region. We used this method to reduce the effect of year-to-year price variation as well as the biases on prices that might take place in small producing countries. Furthermore, when a country or a world region largely exceeded its expected share of world production for a given crop based on its sole size, we considered it to be specialized in this crop. For example, Asia produced 90% of the rice, so we assumed that the world demand for rice, and thus its world price, would be influenced by the Asian supply. In this example, we took the producer price of Asia rice and applied it on a worldwide basis. In all cases, we used the local currency and the exchange rate of the years of the data collected to calculate the prices and production values in 2005 euros.

We calculated the dependence ratios D_i based upon the five levels of the extensive recent review of Klein et al. (2007; see supplementary data — Appendix B). Starting with the complete set of direct and commodity crops used for human food, we selected the ones for which we had production and price data. For the individual crops among the 11 commodities, neither the production nor the producer price was available and the crops that composed each of these commodities were not all dependent on insect pollination at a similar level for their production. Consequently we could not calculate the economic value of pollinators for these commodity crops and they were not considered further. For the direct crops, we focused on those reviewed in Appendices 1 and 2 of Klein et al. (2007) for which we calculated the average dependence ratio based on the reported range of dependence to animal-mediated pollination in this work (See supplementary data — Appendix B).

3. Results

We found 89 direct crops and 11 commodities used for human food (100 lines in Appendix B). Among these, 46 direct crops in 7 categories are dependent on insect pollinators for their production and pollinators are essential for 6 of these crops. The contribution of insect pollinators is also reported as great for 13 direct crops, modest for 13 and little for 14 (See supplementary data — Appendix B). It is noteworthy that within each crop category, there was considerable variation among the crops as to their level of dependence on pollinators.

The 2005 world production value for crops used for human food was €1618 trillion, and the total value of the 46 insect-pollinated direct crops was €625 billion, that is 39% of the world production value (Table 2 and supplementary data in Appendix C). The economic value of insect pollination was €153 billion (Table 2). The most pollinator-dependent crop categories ranked by decreasing economic value of insect pollination were vegetables, fruits, and edible oil crops (Table 2). It is noteworthy that the production value of a ton of the crop categories that do not depend on insect pollination – namely cereals, sugar crops, and roots and tubers – averaged 151 € while that of those that are pollinator-dependent averaged 761 €, or five times more, and these values were significantly different ($t = 4.851$; $n = 3$ and 7, respectively; $P = 0.0013$; t test on the Log-transformed values to have similar variance among the two groups).

The rate of vulnerability of the world agricultural production used for human food in the face of total pollinator loss was 9.5% (Table 2). This overall value may seem small, but it does not reveal the large range of values among the different crop categories. The stimulant crops with a total production value of only €19 billion had the highest vulnerability ratio (39%). And vegetables, the category with the highest crop production value (€418 billion) still had a vulnerability ratio of 12%. Interestingly, there was a positive correlation between the rate of vulnerability of a crop category to pollinators and its value per production unit ($r = 0.729$, $n = 10$, $P = 0.017$).

Looking at the economic vulnerability ratios of the different crop categories among the regions of the world indicates that, in each region, there is a category that is highly vulnerable to pollinator loss with vulnerability ratios ranging from 22% to 94% (Table 4). Interestingly, nuts were the most vulnerable crop category over the largest area (7 sub-regions), followed by

Author's personal copy

Table 2 – Economic impact of insect pollination of the world agricultural production used directly for human food and listed by the main categories ranked by their rate of vulnerability to pollinator loss; the economic value of insect pollination was calculated following (1)

Crop category	Average value of a production unit	Total production economic value (EV)	Insect pollination economic value (IPEV)	Rate of vulnerability (IPEV/EV)
	€ per metric ton	10^9€	10^9€	%
Stimulant crops	1225	19	7.0	39.0
Nuts	1269	13	4.2	31.0
Fruits	452	219	50.6	23.1
Edible oil crops	385	240	39.0	16.3
Vegetables	468	418	50.9	12.2
Pulse	515	24	1.0	4.3
Spices	1003	7	0.2	2.7
Cereals	139	312	0.0	0.0
Sugar crops	177	268	0.0	0.0
Roots and tubers	137	98	0.0	0.0
All categories pooled together		1618	152.9	9.5

fruits and stimulant crops (5 sub-regions each). Furthermore, because some regions are specialized in the production of some pollinator-dependent crop category, the vulnerability of the world production for these categories is much higher than the overall worldwide value indicated on Table 3. For example, East Asia produced nearly 52% of the world vegetables with a vulnerability ratio of 15% while the worldwide value was 12% (Tables 2 and 4). Also North and South Americas produced 36% of the edible oil crops with a vulnerability ratio greater than 22%, while the worldwide value was 16% (Tables 2 and 4). And West Africa, South East Asia and North America together produced 36% of the nuts in the world with a vulnerability ratio ≥ 44% in all three regions. The situation appeared particularly critical for stimulant crops as West Africa produced 56% of the world production with a vulnerability ratio of 90% (Table 4). This region produced a lot of coffee and/or cocoa, both of which are dependent of insect pollinators for their production, and the consequences of a total pollinator loss on these crops could be considerable not only for the revenues that West Africa derives from these crops, but also

Table 3 – Geographical distribution of crop production value, economic impact of pollinators and vulnerability ratio among the 16 sub-regions of the world defined following FAO (http://faostat.fao.org); the economic value of insect pollination was calculated following (1); sub-regions with high vulnerability ratios (≥ 10%) are in bold

Geographical region and sub-region	Total production economic value (EV)	Insect pollination economic value (IPEV)	Rate of vulnerability for the region (IPEV/EV)
	10^9€	10^9€	%
Africa			
Central Africa	10.1	0.7	7
East Africa	19.6	0.9	5
North Africa	**39.7**	**4.2**	**11**
South Africa	19.2	1.1	6
West Africa	**48.9**	**5.0**	**10**
Asia			
Central Asia	**11.8**	**1.7**	**14**
East Asia	**418.4**	**51.5**	**12**
Middle East Asia	**63.5**	**9.3**	**15**
Oceania	18.8	1.3	7
South Asia	219.4	14.0	6
South East Asia	167.9	11.6	7
Europe			
European Union (25 members)	**148.9**	**14.2**	**10**
Non EU25	**67.8**	**7.8**	**12**
North America			
Bermuda, Canada and USA	**125.7**	**14.4**	**11**
South and Central America			
Central America and Caribbean	51.1	3.5	7
South America	187.7	11.6	6

Author's personal copy

Table 4 – Economic vulnerability ratio (in bold) and 2005 production figures in 10^6 metric tons (in italics) for the pollinator-dependent crop categories among the 16 sub-regions of the world defined following FAO (http://faostat.fao.org). X% highest value of the economic vulnerability ratio for the sub-region

Geographical region	sub-region	Edible oil crops	Fruits	Nuts	Pulse	Spices	Stimulant crops	Vegetables
Africa	Central Africa	**8%** *4.37*	**4%** *5.71*	**0%** *0.04*	**1%** *0.12*	**5%** *0.05*	**69%** *0.28*	**10%** *2.58*
	East Africa	**18%** *2.08*	**4%** *6.39*	**22%** *0.18*	**10%** *1.70*	**3%** *0.18*	**17%** *1.05*	**4%** *6.85*
	North Africa	**13%** *3.86*	**16%** *15.73*	**58%** *0.24*	**15%** *1.04*	**4%** *0.14*	– *0*	**13%** *30.45*
	South Africa	**17%** *2.74*	**15%** *7.95*	**45%** *0.08*	**0%** *0.41*	**25%** *0.16*	**16%** *0.16*	**8%** *4.11*
	West Africa	**9%** *23.81*	**11%** *10.88*	**46%** *1.03*	**2%** *0.00*	**3%** *0.25*	**90%** *2.53*	**5%** *17.47*
Asia	Central Asia	**25%** *4.00*	**41%** *2.16*	**35%** *0.03*	**4%** *0.06*	**4%** *0.00*	– *0*	**14%** *8.59*
	East Asia	**17%** *62.76*	**36%** *94.71*	16% *1.70*	**10%** *5.64*	**3%** *0.76*	**2%** *1.08*	**15%** *462.56*
	Middle East Asia	**18%** *5.27*	**24%** *32.97*	**18%** *1.55*	**3%** *2.98*	**1%** *0.23*	**3%** *0.28*	**18%** *49.57*
	Oceania	**24%** *3.69*	**28%** *5.08*	**33%** *0.05*	**6%** *2.14*	**1%** *0.01*	**94%** *0.01*	**8%** *2.86*
	South Asia	**19%** *44.41*	**23%** *56.09*	**23%** *1.00*	**0%** *13.24*	**2%** *3.79*	**11%** *1.51*	**7%** *92.93*
	South East Asia	**11%** *186.07*	**13%** *44.32*	**44%** *1.39*	**3%** *2.22*	**2%** *0.87*	**38%** *2.74*	**7%** *30.90*
Europe	European Union (25 members)	**8%** *31.94*	**30%** *60.05*	**48%** *0.82*	**5%** *5.49*	**1%** *0.13*	– *0*	**7%** *65.35*
	Non EU25	**24%** *17.81*	**51%** *13.31*	**4%** *0.28*	**1%** *2.83*	**3%** *0.12*	**0%** *0.02*	**12%** *35.08*
North America	Bermuda, Canada and USA	**23%** *110.74*	**24%** *27.62*	**46%** *1.31*	**3%** *6.56*	**0%** *0.04*	– *0*	**8%** *39.74*
South & Central America	Central America and Caribbean	**14%** *5.73*	**10%** *29.86*	1% *0.21*	**5%** *1.12*	**2%** *0.16*	**29%** *1.21*	**12%** *19.49*
	South America	**22%** *113.38*	**9%** *71.44*	**25%** *0.30*	**9%** *0.45*	**3%** *0.28*	**30%** *4.55*	**8%** *25.17*
Total		***622.66***	***484.27***	***10.21***	***46.00***	***7.07***	***15.42***	***893.70***

on a global scale for the world production and resulting price structure of these stimulants.

On a global scale, the difference between production and consumption in 2005 was positive for all crop categories that are pollinator-dependent.[1] Looking at these same differences after total pollinator loss, the overall world food supply would not be in jeopardy, but the production drop would create a deficit in three crop categories including fruits and vegetables, two pollinator-dependent categories with a high economic value and low ability for storage from one year to the next (Table 5). Looking at these three categories for which the overall production would no longer meet consumption patterns after total pollinator loss, we examined their change in availability in each geographical region. The deficit resulting from the loss of pollinators appears important in many region and crop category combinations, and it could have some serious consequences in two types of situations. First, in some regions where production was clearly exceeding consumption, the loss of pollinators would result in a deficit such that production would no longer be able to meet consumption. This is the case for fruits in North Africa as well as in Central, East and South Asia (Table 6). A case in point is East Asia where fruit production exceeded consumption by 19% in 2005 and where total pollinator loss would result in a deficit with consumption exceeding production by 26%, which is considerable since this region produces nearly 20% of the world fruit output. Other examples of a similar situation of consumption exceeding production as a consequence of pollinator loss are found (i) for vegetables in North and South Africa, East and Middle East Asia, and South America, and (ii) for stimulant crops in South Africa. A second type of situation where pollinator loss could have serious consequences arises for regions which are already barely meeting their consumption patterns or which are net importers for a given crop category and could therefore be severely impacted by the drop of production following pollinator loss. This is the case for example with fruits in the European Union where consumption exceeded production by 20% in 2005 and this deficit would double following total pollinator loss in Europe. Other examples include fruits in West Africa and North America, vegetables in Central Africa, Oceania, the European

---

[1] This global statement is not in contradiction with the fact that, according with the World Health Organization (WHO) some 3.7 billion people were malnourished in 2005 or, following the Food and Agricultural Organization (FAO) estimates, 850 million, as FAO recorded only the people that are protein/calories malnourished, rather than nutrient deficient.

Author's personal copy

Table 5 – Effect of pollinator loss on the capacity to provide food at the world scale for the pollinator-dependent crop categories

Crop categories	Relative production surplus before pollinator loss	Relative production surplus after pollinator loss
	% of consumption	
Stimulant crops	18	−24
Fruits	12	−12
Vegetables	19	−6
Spices	11	8
Nuts	29	16
Edible oil crops	75	40
Pulses	60	54

The differences between 2005 production and consumption figures are expressed in relative terms as % of the 2005 consumption figures following FAO (http://faostat.fao.org).

Union and North America, and stimulant crops in the European Union and North America.

4. Discussion

We found a value of about €153 billion as an assessment of the economic value of insect pollination for the world agriculture in 2005. This is the direct result of the calculations based on Eq. (1) using the dependence ratios towards pollinators given by a recent review (Klein et al., 2007) and the production value of the most important crops directly used for human food. It measures the part of the gross value of the world food production attributable to insect pollination and can therefore be considered as a conservative assessment of the gross value of the insect pollination service. Indeed, in an early valuation of the service provided by bees on US agriculture, Martin (1975) stated that the value of beef and dairy products that result from the seed production of forage legumes such as alfalfa accounts for about 80% of the economic value of insect pollinators. At the world scale, such a high value is most unlikely, at least because forage legume are not as important worldwide as in the USA. But this statement nevertheless underlines the fact that the indirect impact of pollinator decline on forage production, though quite difficult to assess, may not be anecdotal. Similarly, our assessment did not take into account the value of pollinators for the seed production necessary to grow the vegetative parts of many species which are consumed by humans (such as many vegetables; see Appendix 1 of Klein et al., 2007, and our supplementary data — Appendix B), nor the seed production for ornamental flowers and other uses not devoted to human food such as biofuels. Soybean and other pollinator-dependent edible oil crops contribute to the supply of biofuels, but current relative prices limit their use and biofuels are mainly produced from non-pollinator dependent crops such as sugar cane and corn (Schubert, 2006; see supplementary data — Appendix B).

In the literature, we found only two studies giving an economic valuation of the pollination service at the world scale (Costanza et al., 1997; Pimentel et al., 1997). Yet the comparison of our results with those of these two studies is

Table 6 – Regional effect of pollinator loss on the capacity to meet consumption before and after (in bold) total pollinator loss for the three crop categories for which the 2005 overall balance was negative following pollinator loss

Geographical region (FAO classification)	Fruits		Stimulant crops		Vegetables	
	% of consumption					
Africa						
Central Africa	22	**16**	633	**102**	−4	**−16**
East Africa	−51	**−54**	369	**297**	9	**5**
North Africa	15	**−4**	−100	**−100**	16	**−13**
South Africa	56	**29**	10	**−5**	2	**−11**
West Africa	−22	**−28**	2982	**169**	21	**16**
Asia						
Central Asia	31	**−22**	−100	**−100**	40	**5**
East Asia	1	**−26**	−30	**−30**	28	**−4**
Middle East Asia	31	**2**	−43	**−43**	31	**−12**
Oceania	60	**21**	−93	**−100**	−4	**−22**
South Asia	20	**−3**	23	**45**	9	**0**
South East Asia	30	**20**	289	**140**	15	**6**
Europe						
European Union (25 members)	−20	**−40**	−100	**−100**	−3	**−16**
Non EU25	−30	**−61**	−98	**−98**	−2	**−23**
North America						
Bermuda. Canada and USA	−30	**−46**	−100	**−100**	−3	**−16**
South and Central America						
Central America and Caribbean	54	**35**	183	**99**	63	**27**
South America	83	**65**	176	**103**	17	**−4**

The differences between 2005 production and consumption figures are expressed in relative terms as % of the 2005 consumption figures following FAO (http://faostat.fao.org).

Author's personal copy

difficult because their methods are so different. Costanza et al. used the findings of Levin (1984) to determine a lower limit of the value of insect pollination service of US$140 million, corresponding to the value of honey and beeswax in 1980, and an upper limit of US$18.9 billion, which was the value of 1980 U.S crops that they considered dependent on insect pollinators (fruits, nuts, vegetables, seeds, fibers, cattle, calve and liquid milk production). Conservatively and without further justification, they chose a value of US$2 billion from this interval and assumed that the U.S. agriculture represented 10% of the world crop value. In this way, they found a value of the insect pollination service to crops worldwide of US$20 billion for 1996 which amounts to about €20 billion when adjusted for inflation (http://data.bls.gov) and 2005 exchange rate (http://fxtop.com). Pimentel et al. (1997) started with the figure of US$8 billion reported by Martin (1975) and quoted in Robinson et al. (1989) for the 1970 value of USA crops dependent on insect pollinators and used for human food. Martin increased this figure to US$ 40 billion when adding the value of beef and dairy products that are derived from insect-pollinated legume forage to the value of crops used directly for humans. Then, Pimentel et al. extrapolated this value to the entire world by assuming that the economic value of insect pollination worldwide was at least five times that of the USA. With appropriate exchange rate and inflation correction, the figures of Pimentel et al. (1997) give an economic value of insect pollination to the world agriculture of US$200 billion in 1996, and gives a 2005 economic value of €200 billion, which takes into account the value of beef and dairy products that are derived from insect-pollinated forage legumes. Interestingly, if we start with the original figure of US$ 8 billion for the crops used for human foods only, the economic value of insect pollination worldwide amounts to US$40 billion (€40 billion in 2005 economic value).

Even after appropriate corrections, the 2005 estimated values from these two studies (€20 billion and €40 billion for Costanza et al., 1997 and Pimentel et al., 1997, respectively) remain considerably smaller than our result (€153 billion; Table 2). Such a difference raises many questions. Since these authors give little explanations on their methods, we might assume that they have integrated in their calculations some more sophisticated – though unformulated – considerations, especially in relation to the behavior of economic actors that will adapt to a pollinator-free context.

These €153 billion stand for about 9.5% of the world value of the crops used directly for human food. This ratio of vulnerability can be interpreted as an indicator of the value of pollination service relative to the other factors that contribute to agricultural production worldwide. The value of the vulnerability ratio is of course contingent upon the relative prices of crops and, especially, the prices of pollinator-dependent crops relative those which are not.[2]

It must be clearly stated that this economic valuation is not a scenario assessment, since all economic agents can change their behavior in order to adapt to a pollinator decline. These changes will have some costs, namely opportunity costs. But one can assume that producers will make efficient trade-offs between the costs of changing crop species, or varieties, or production technologies – namely pollination techniques – and the losses resulting from keeping less profitable practices.[3]

It appears difficult to gauge the real significance of a vulnerability of about 10% on the agricultural industry. In some cases, a small variation may induce large consequences, especially through the impact it might have on the financial equilibrium of farms. The transmission of the price change can have variable effects within the food supply chain (Wu, 2004; Tang, 2005) and the capacity of the food supply chain operators to adapt to new situations and limit the consequences, either through technical change or because of the existence of market power, is poorly known (Hassan and Simioni, 2001).

Furthermore, the decline of pollinators will certainly be heterogeneous among different regions of the world due to differences in land and crop management as well as the abundance and diversity of wild and managed bees. For example, in a reverse scenario Roubik and Wolda (2001) found that the arrival of Africanized honey bees in South and Central America resulted in much higher population densities of bees, and this translated into increased coffee production (Roubik, 2002). On a smaller scale, landscape management is also likely to affect pollinator density (Kremen et al., 2002; Klein et al., 2007).

A first step towards a better understanding of the meaning of a 10% vulnerability ratio could consist in introducing an economic measure of this vulnerability in terms of consumer surplus. Southwick and Southwick (1992) estimated the economic value of honeybees as agricultural pollinators in the USA based upon a measure of the surplus gain resulting from their pollination service. They considered a price reaction to quantity limitation related to the dependence ratio that leads to the following expression of the consumer monetary surplus gain for each crop:

$$\text{Gain} = Q_1(P_1 - P_0) + \int_{Q_1}^{Q_0} [P(Q) - P_0]dQ \tag{5}$$

where P_0 and Q_0 are the price and quantity with honeybee pollination, the price P was estimated as a function of the quantity Q and the income of American households from temporal series, P_1 and Q_1 are the price and quantity without honeybee pollination.

Our assessment is based upon the calculation of the loss in terms of agricultural production for each crop i, that is $P_{i0}(Q_{i0} - Q_{i1})$ (see Fig. 1). This result must be transformed into economic surplus loss for consumers to obtain an assessment of the social cost of pollinator decline. Since there are no appropriate data to find econometrically for each crop at the world scale

---

[2] It must be mentioned that crops vary in the manner in which their prices behave. Tropical fruits and spices also suffer from price volatility, which produce losses or windfall gains. There are high price regimes and low price regimes as in the case of coffee and spices (also bee-pollinated crops) coinciding with crop failures in major producing countries such as Brazil (for coffee) and Guatemala (for cardamom). This might implicitly mean high elasticity of demand in high price regimes and low elasticity in low price regimes.

[3] For orchard crops that are perennial in nature, elasticity of adaptation measures such as shifting to other crops is low. Supply elasticity for perennial crops tends to be low as compared to demand elasticity. As a result, the opportunity costs of taking up new crops would likely be very high.

Author's personal copy

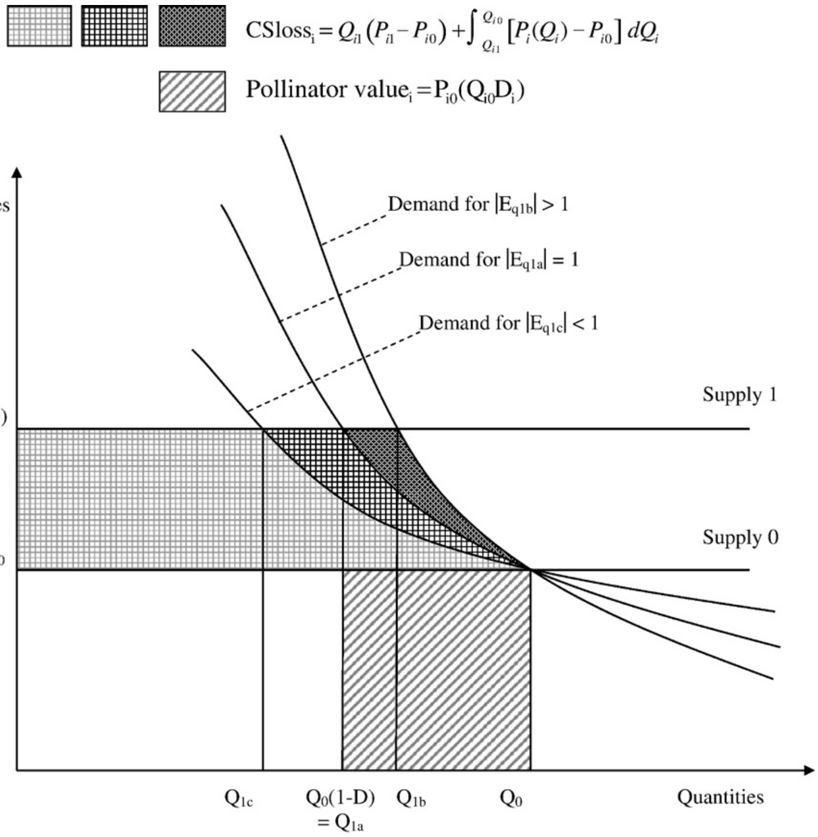


Fig. 1 – Estimates of the consumer surplus loss for different values of price elasticity.

the price elasticities, assumptions must be made on the shape and value of P(Q). A simple idea is to assume that for all crops the price elasticities (E) are constant. Inverse demand functions can then easily be expressed and consumer surplus variations analytically calculated.

The choice of a constant elasticity price is acceptable for most crops as long as the price range remains in the neighborhood of current prices. The neighborhood wideness is variable with the crop and its economic status as primary good or luxury good. It is probably unacceptable when the ratio of dependence is very high, since the price should then rise considerably (e.g. for the 6 crops with a dependence ratio of 95%, which means that for a price elasticity value of – 1, the price following total pollinator loss would be multiplied by 20).

Given a constant elasticity price, the mathematical representation of the demand function comes from the definition of the price-elasticity $E = \frac{\delta Q/Q}{\delta P/P}$, which leads to $P(Q) - EQP'(Q) = 0$ and, assuming $E \neq 0$, gives the inverse demand function:

$$P(Q) = P_0 \left(\frac{Q}{Q_0}\right)^{\frac{1}{E}} \qquad (6)$$

We will also assume, following Southwick and Southwick (1992), that the long-term supply curve is perfectly elastic, which means that farmers can switch from one crop to another without increasing production cost and without constraint of arable land availability. It means that there is no producer surplus variation and then the consumer surplus variation is actually the social surplus variation.

We used the large matrix that was built to measure the economic value of insect pollination (Appendices B and C) to calculate what would be the consumer surplus loss according to several price elasticity values. For each value, we applied our hypotheses to each crop with its specific dependence ratio to pollinators.

The choice of a unique value for E may seem like an oversimplification. But choosing different values of E for each crop in each region would be equally arbitrary since these values could not be determined from appropriate econometric data. Some crops, like cereals, are generally associated with low price elasticities, usually estimated to be $|E| < 0.5$ in the literature. Other crops, such as fruits, appear to have higher price-elasticities, $|E| > 1$ and possibly much more in some cases (Southwick and Southwick, 1992).

The choice of the unique value of E for all crops must take into account the relative importance of crops with high and low elasticities, which are used to calculate the total consumer surplus loss. Fruits, vegetables, nuts, edible oil crops, stimulant crops, and spices are the most pollinator-dependent crop categories and they are also those that will make the largest part of the total loss. Yet they are also those that appear most likely to have the highest elasticities in absolute terms. So the overall appropriate figure for E is likely to be in the neighborhood of – 1. Furthermore, a distinction must be made between short-term and long-term elasticities, the latter being traditionally higher ($|E| > 1$). Since we consider a hypothetical situation of total pollinator loss, long-term elasticities appear more appropriate.

Author's personal copy

We have to assess now what will happen to the food production and markets after insect pollinators decline to a complete loss. The first consequence is a loss in production from Q_0 to $Q_0(1-D)$ for a similar production effort (i.e. without change in the total production costs). If a smaller production is obtained for the same total cost, we can assume that the unitary production cost will grow from P_0 to $P_0/(1-D) = P_1$. We will then consider that P_{i1} is the new price of the crop i on the market of our pollinator-free economy. At this price, the effective demand will be $Q_i(P_{i1}) = Q_{i1}$. This assumption allowed us to calculate the consequent surplus loss (CSloss; Fig. 1) according to the value of E.

$$\mathrm{CSloss}_i = Q_{i1}(P_{i1} - P_{i0}) + \int_{Q_{i1}}^{Q_{i0}} [P_i(Q_i) - P_{i0}]dQ \tag{7}$$

For the value $E = -1$, it comes from Eq. (6) that $P(Q) = P_0 \times Q_0/Q$, and $Q_1(P_1 - P_0) = P_0(Q_0 - Q_1)$. The consumer surplus loss is then:

$$\mathrm{CSloss} = \int_{Q_1}^{Q_0} [P(Q)]dQ = \int_{Q_0}^{Q_1} \frac{P_0Q_0}{Q}\delta Q = P_0Q_0 \cdot \log\frac{Q_1}{Q_0} \tag{8}$$

where P_1 and Q_1 are the price and quantity without insect pollination, P_0 and Q_0 are the price and quantity with insect pollination. If we apply this expression to a quantity reduction related to a total pollinator loss for a crop with a ratio of dependence D, $Q_1 = Q_0(1-D)$ and it comes: CSloss = $P_0 \cdot Q_0 \cdot \log(1-D)$. This value is easy to calculate using the matrix of prices and quantities in Appendices B and C. Applying this formula to all crops used directly for human food on a worldwide basis gives a total loss of consumer surplus of about €260 billion for 2005.

For any price-elasticity $E \neq -1$, it comes:

$$\mathrm{CSloss} = \frac{P_0Q_0}{1+E}\left(\left(\frac{1}{1-D}\right)^{1+E} - 1\right). \tag{9}$$

This value can be calculated for any value of E using the database of all crops in each world region (See supplementary data — Appendices B and C):

$$\sum_{i=1}^{I}\sum_{x=1}^{X} \frac{P_{ix0}Q_{ix0}}{1+E}\left(\left(\frac{1}{1-D_i}\right)^{1+E} - 1\right). \tag{10}$$

For $E = -0.8$, we find €310 billions; and for $E = -1.5$, about €191 billion (see Table 7).

Though a more refined analysis remains to be done, it is possible to suggest some changes that are likely to take place in the behavior of producers, agro food supply chains, and consumers, if the decline in insect pollination services is further confirmed. Farmers would at least to some extent switch from pollinator-dependent crops to less dependent species or, when available, varieties. But a first reaction would probably be in many cases, as it is widely done for fruit production in the USA, to try to improve insect pollination through the management of selected species and the development of artificial pollination techniques.

For the rare pollinator-dependent crops with low price elasticity ($|E| < 1$; i.e. apples with $E = -0.59$, (Southwick and Southwick, 1992) the farmers' income will increase when yields decrease since prices will rise faster ('King effect'). This effect should nevertheless be limited by competition among farmers and resulting production enhancing investment.

Table 7 – Consumer surplus loss at the world scale for 2005 in relation with price elasticity

Price elasticity parameter	Consumer surplus loss (10^9€)
−0.50	422
−0.60	378
−0.70	341
−0.80	310
−0.90	285
−1.00	263
−1.10	244
−1.20	228
−1.30	214
−1.40	202
−1.50	191
−1.60	182
−1.70	173
−1.80	166
−1.90	159
−2.00	153

Following the agro food supply chains, it can be assumed that optimization tuning will aim at reducing the impact of pollinator decline onto consumers, through substitution both in the nature of the good and the processing formula. Finally, consumers would modify their choices according to the relative prices of food items and, in the case of strong changes; the food budget might compete with other parts of the consumption patterns.[4]

The potential loss in some food production may not have measurable consequences in economic terms only, as it might also have serious consequences on human health. In particular, the decrease of fruit and vegetable availability could impact the health of consumers worldwide. The World Health Organisation (WHO) has set a lower limit of 400 grams per capita and per day for fruit and vegetable consumption (WHO Report, 1990). Naska et al. (2000) studied fruit and vegetable consumption among ten European countries and found that more than 50% of the households were below this recommendation. In the case of a total disappearance of pollinators, this situation is very likely to worsen.

5. Conclusions

The aim of our work was to assess the vulnerability of the food production worldwide faced to the decline of insect pollinators. Non-food agricultural production, cattle raising, and natural vegetation will also be impacted but are not studied in this paper. Using a bioeconomic approach, we calculated a world value for the contribution of pollinators to the production of crops used directly for human food of €153 billion, which is about 9.5% of the total value of the production of human food worldwide.

---

[4] The emergence of organic foods and widespread concerns about GM foods has reduced elasticity of substitution for health foods (organic and non GM traditional foods) despite health foods carrying higher prices. Finally, the loss in output of conventional pollinated crops due to inadequate pollination forms a deadweight loss, net loss to producer and consumers and hence to society.

Author's personal copy

Since this first result was obtained through multiples sums, we extracted partial results such as the most vulnerable crop categories (stimulant crops, nuts and fruits) or the categories that stood for the largest part of the economic vulnerability (fruits, edible oil crops, vegetables). Related to their agricultural orientations, some regions appeared more vulnerable like Middle East Asia (15%), Central Asia (14%), East Asia (12%) and non European Union countries (12%). At the global scale, the vulnerability of the Northern countries appeared higher than the southern ones, which suggests that the decline of insect pollinators might have heavy consequences for the North–South agro-food trade. To complete these data, we calculated the capacity to nourish world population after pollinator loss and found that the production of 3 crop categories will be clearly below the current consumption at the world scale and even more so for certain regions like Europe.

Although we created a complete database of prices and production quantities for each crop in each region of the world and we used a very recent review to get the dependence ratio of each crop on insect pollination, the uncertainties are probably large but difficult to assess, especially since ecological responses to pollinator decline on large scales remain poorly known (National Research Council, 2007). More specifically, there is an ongoing debate on the existence of a “pollinator paradox” meaning that though crops depend on pollinators, the overall crop yield may not necessarily be as dependent because farmers will take into account pollinator decline in their production management and strategies (Ghazoul, 2007).

Despite these uncertainties, we discussed these results in terms of consumer surplus loss, which is a more appropriate indicator of the economic valuation of these vulnerabilities. Since it was not possible to rely on econometrically estimated price elasticities for each crop in each region, our calculations relied on the assumption of an average sensitivity of prices to quantity shortage. Stating that the most vulnerable crops appear to be more sensitive to price variation, the more realistic elasticity parameter is likely to be $|E| > 1$. Furthermore, since we considered the evolution over the long term, we can make the optimistic assumption that farmers would adapt without significant cost, and the social surplus losses would be in the range of €310–191 billions for elasticity parameters ranging from − 0.8 down to − 1.5.

Although our results demonstrate the economic importance of insect pollinators, it cannot be considered as a scenario since it does not take into account the strategic response of the market. Producers might have several levels of response strategies in interaction with the intermediate demands of the food supply chain. Moreover, the response of consumers faced to dramatic changes of relative prices would probably be more elaborate than the simple price-elasticity can summarize. Short and long term reaction for each crop and in each region would probably be quite different and should be studied specifically in further work.

Acknowledgements

This research was funded by the EC within the FP6 Integrated Project “ALARM” (Assessing LArge scale environmental Risks for biodiversity with tested Methods; GOCE-CT-2003-506675; http://www.alarmproject.net; Settele et al., 2005). The authors thank Joshua Bishop, Jean-Marie Boisson, Gabriel Carré, Charles Figuières, Ghislain Géniaux, Mabel Tidball and three anonymous referees for valuable comments on an early version of this text.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecolecon.2008.06.014.

REFERENCES

Benedek, P., 1983. Economic importance of honey bee pollination of props at the national level of Hungary. 29th International Apiculture Congress. Apimondia, pp. 286–289.

Biesmeijer, J.C., Roberts, S.P.M., Reemer, M., Ohlemüller, R., Edwards, M., Peeters, T., Schaffers, A.P., Potts, S.G., Kleukers, R., Thomas, C.D., Settele, J., Kunin, W.E., 2006. Parallel declines in pollinators and insect-pollinated plants in Britain and the Netherlands. Science 313, 251–353.

Borneck, R., Bricout, J.P., 1984. Evaluation de l’incidence économique de l’entomofaune pollinisatrice en agriculture. Bulletin Technique Apicole 11 (2), 117–124.

Borneck, R., Merle, B., 1989. Essai d’une évaluation de l’incidence économique de l’abeille pollinisatrice dans l’agriculture européenne. Apiacta 24, 33–38.

Carreck, N., Williams, I., 1998. The economic value of bees in the UK. Bee World 79, 115–123.

Carreck, N.L., Williams, I.H., Little, D.J., 1997. The movement of honey bee colonies for crop pollination and honey production by beekeepers in Great Britain. Bee World 78, 67–77.

Clement, S.L., Hellier, B.C., Elberson, L.R., Staska, R.T., Evans, M.A., 2007. Flies (Diptera: Muscidae: Calliphoridae) are efficient pollinators of *Allium ampeloprasum* L. (Alliaceae) in field cages. Journal of Economic Entomology 100, 131–135.

Costanza, R., D’Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O’Neill, R.V., Paruelo, J., Raskin, P., van den Belt, M., 1997. The Value of the world’s ecosystem services. Nature 387, 253–260.

Dag, A., Zipori, I., Pleser, Y., 2006. Using bumblebees to improve almond pollination by the honeybee. Journal of Apicultural Research 45, 215–216.

Dedej, S., Delaplane, K.S., 2003. Honey bee (Hymenoptera: Apidae) pollination of rabbiteye blueberry *Vaccinium ashei* var. ‘Climax’ is pollinator density-dependent. Journal of Economic Entomology 96, 1215–1220.

Eurostat. Statistical Database. Available at http://epp.eurostat.ec.europa.eu ; Agriculture, forestry and fisheries themes/Agriculture/Agricultural prices and price indices. Last accessed in October 2006.

Food and Agriculture Organization, 2007. Statistical Database. Available at http://faostat.fao.org ; Agricultural data/Agricultural production/Crops primary. Last accessed in July.

Fluri, P., Frick, R., 2005. L’apiculture en Suisse: état et perspectives. Revue Suisse d’Agriculture 37 (2), 81–86.

Free, J.B., 1993. Insect pollination of crops. Academic Press, London, UK. 544 pp.

Ghazoul, J., 2007. Recognizing the complexities of ecosystem management and the ecosystem service concept. GAIA 16, 215–221.

Author's personal copy

Greenleaf, S.S., Kremen, C., 2006. Wild bees enhance honey bees' pollination of hybrid sunflower. Proceedings of the National Academy of Sciences USA 103, 13890–13895.

Hassan, D., Simioni, M., 2001. Price Linkage and Transmission between Shippers and Retailers in the French Fresh Vegetable Channel. Working paper, INRA-ESR, Toulouse.

Klein, A.M., Vaissière, B.E., Cane, J.H., Steffan-Dewenter, I., Cunnigham, S.A., Kremen, C., Tscharntke, T., 2007. Importance of pollinators in changing landscapes for world crops. Proceedings of the Royal Society 274, 303–313.

Kremen, C., Williams, N.M., Thorp, R.W., 2002. Crop pollination from native bees at risk from agricultural intensification. Proceedings of the National Academy of Sciences USA 99, 16812–16816.

Levin, M.D., 1984. Value of bee pollination to United State agriculture. American Bee Journal 124, 184–186.

Losey, J.E., Vaughan, M., 2006. The economic value of ecological services provided by insects. BioScience 56, 311–323.

Martin, E.C., 1975. The use of bees for crop pollination. In: Dadant & Sons (Ed.), The hive and the honey bee. Hamilton, Illinois, pp. 579–614.

McGregor, S.E., 1976. Insect pollination of cultivated crop plants. Agriculture Handbook. United States Department of Agriculture, Washington DC. (available at http://gears.tucson.ars.ag.gov/book/).

Metcalf, R.L., Metcalf, R.A., 1992. The value of insects to humans. In: KotowskiJr. Jr., Frank J. (Ed.), Destructive and Useful Insects: Their Habits and Control. McGraw-Hill Book Company, Inc., New York.

Morandin, L.A., Winston, M.L., 2005. Wild bee abundance and seed production in conventional, organic, and genetically modified canola. Ecological Applications 15, 871–881.

Morse, R.A., Calderone, N.W., 2000. The value of honey bees as pollinators of U.S. crops in 2000. Bee Culture 1–15.

Naska, A., Vasdekis, V.G.S., Trichopoulou, A., Friel, S., Leonhäuser, I.U., Moreiras, O., Nelson, M., Remault, A.M., Schmitt, A., Sekula, W., Trygg, K.U., Zajkas, G., 2000. Fruit and vegetable availability among ten European countries: how does it compare with the 'five-a-day' recommendation? British Journal of Nutrition 84, 549–556.

National Research Council of the National Academies, 2007. Status of Pollinators in North America. National Academy of Science, Washington, D.C. 303 pp.

Olmstead, A.L., Wooten, D.W., 1987. Bee pollination and productivity growth: the case of alfalfa. American Journal of Agricultural Economics, 69, 56–63.

Olroyd, B.P., 2007. What's killing American honey bee? PLoS Biology 5 (6), e168.

Pimentel, D., Wilson, C., McCullum, C., Huang, R., Dwen, P., Flack, J., Tran, Q., Saltman, T., Cliff, B., 1997. Economic and environmental benefits of biodiversity. BioScience 47, 747–757.

Robinson, W.S., Nowogrodzki, R., Morse, R.A., 1989. The value of honey bees as pollinators of U.S. crops: Part II. American Bee Journal 129, 477–487.

Roubik, D.W., 2002. Tropical agriculture: The value of bees to the coffee harvest. Nature 417, 708.

Roubik, D.W., Wolda, H., 2001. Do competing honey bees matter? Dynamics and abundance of native bees before and after honey bee invasion. Population Ecology 43, 53–62.

Schubert, C., 2006. Can biofuels finally take center stage? Nature Biotechnology 24, 777–784.

Schröter, D., Polsky, C., Patt, A.G., 2005. Assessing vulnerabilities to the effects of global change: An eight step approach. Mitigation and Adaptation Strategies for Global Change 10, 573–596.

Settele, J., Hammen, V., Hulme, P., Karlson, U., Klotz, S., Kotarac, M., Kunin, W., Marion, G., O'Connor, M., Petanidou, T., Peterson, K., Potts, S., Pritchard, H., Pysek, P., Rounsevell, M., Spangenberg, J., Steffan-Dewenter, I., Sykes, M., Vighi, M., Zobel, M., Kühn, I., 2005. ALARM: assessing large-scale environmental risks for biodiversity with tested methods. GAIA 14, 69–72.

Southwick, E.E., Southwick, L., 1992. Estimating the economic value of honey-bees (Hymenoptera, Apidae) as agricultural pollinators in the United States. Journal of Economic Entomology 85, 621–633.

Steffan-Dewenter, 2003. Seed set of male–sterile an male–fertile oilseed rape (*Brassica napus*) in relation to pollinator density. Apidologie 34, 227–235.

Stokstad, E., 2007. The case of the empty hives. Science 316, 970–972.

Sumner, D.A., Boriss, H., 2006. Bee-conomics and the leap in pollination fees. ARE update, Univ. California, Giannini Foundation 9(3) Jan/Feb. 2006. http://www.agecon.ucdavis.edu/uploads/update_articles/v9n3_3.pdf).

Tang, K., 2005. Multi-agent and market based dynamic optimisation and its extensions to distributed supply chain procurement planning problems. PhD thesis, Pennsylvania State University, May 2005, 197 pp.

Turner, B.L., Kasperson, R.E., Matson, P., McCarthy, J.J., Corell, R.W., Christensen, L., Eckley, N., Kasperson, J.X., Luers, A., Martello, M.L., Mathiesen, S., Polsky, C., Pulsipher, A., Schiller, A., Tyler, N., 2003. A framework for vulnerability analysis in sustainability science. Proceedings of the National Academy of Sciences USA 100, 8074–8079.

United States Department of Agriculture. Statistical Database. Available at http://www.fas.usda.gov, Commodities and Products. Last accessed in October 2006.

Velthuis, H.H.W., van Doorn, A., 2006. A century of advances in bumblebee domestication and the economic and environmental aspects of its commercialization for pollination. Apidologie 37, 421–451.

White, G.F., 1974. Natural Hazards: Local, National and Global. Oxford University Press, New York. 304 pp.

Williams, I.H., 1994. The dependence of crop production within the European Union on pollination by honey bees. Agricultural Zoology Reviews 6, 229–257.

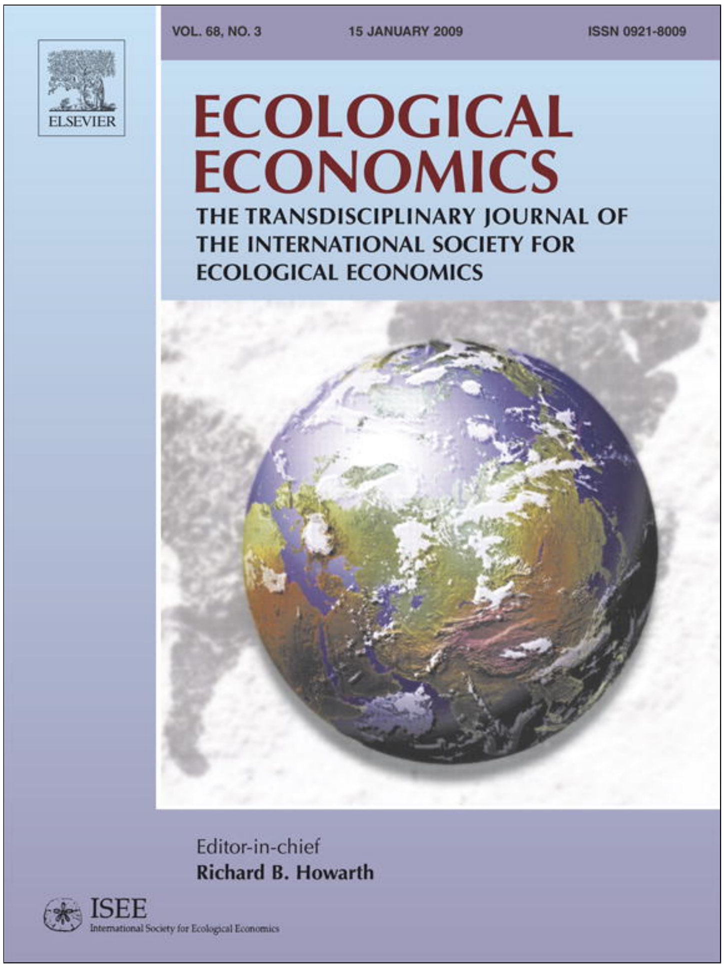
Winfree, R., Williams, N.M., Dushoff, J., Kremen, C., 2007. Native bees provide insurance against ongoing honey bee losses. Ecology Letters 10, 1105–1113.

Winfree, R., Williams, N.M., Gaines, H., Ascher, J.S., Kremen, C., 2008. Wild bee pollinators provide the majority of crop visitation across land-use gradients in New Jersey and Pennsylvania, USA. Journal of Applied Ecology 45, 793–802.

World Health Organization, 1990. Diet, Nutrition and the Prevention of Chronic diseases. Technical Report Series no. 797. WHO, Geneva.

Wu, S.D., 2004. Supply chain intermediation: A bargaining theoretical framework. In: Simchi-Levi, D., Wu, S.D., Shen, Z.M. (Eds.), Handbook of Quantitative Supply Chain Analysis. Kluwer Academic Publishers, pp. 67–115.

Provided for non-commercial research and education use.
Not for reproduction, distribution or commercial use.



This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

http://www.elsevier.com/copyright