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1 **Economic valuation of the vulnerability of world agriculture**
2 **confronted to pollinator decline**

3 **Nicola Gallai*^{1,2}, Jean-Michel Salles³, Josef Settele⁴ & Bernard E. Vaissière¹**

4 ¹INRA, Laboratoire de Pollinisation Entomophile, UMR406 Ecologie des Invertébrés, 84914
5 Avignon Cedex 9, France

6 ²INRA, UMR LAMETA, 2 place Viala, 34060 Montpellier Cedex 1, France

7 ³CNRS, UMR LAMETA, 2 place Viala, 34060 Montpellier Cedex 1, France

8 ⁴UFZ, Helmholtz-Centre for Environmental Research, Dept. of Community Ecology,
9 Theodor-Lieser-Str. 4, 06120 Halle, Germany

10

11 *Corresponding author: Nicola Gallai, INRA, UMR LAMETA, 2 place Viala, 34060
12 Montpellier Cedex 1, France, Tel. (33) [0]4.99.61.29.67, Fax (33) [0]4.67.54.58.05, e-mail:
13 gallai@supagro.inra.fr

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1 Abstract

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

1 Keywords: pollination, valuation, vulnerability, agriculture, ecosystem service, [crop](#)

2 [categories](#)

3

1 1 Introduction

2 The production of 84% of crop species cultivated in Europe depends directly on insect
3 pollinators, especially bees (Williams, 1994). And Klein *et al.* (2007) found that 87 crops, that
4 is 65% of the 134 main crops used directly for human consumption in the world, are
5 dependent on pollinators. Insect pollination is both an ecosystem service and a production
6 practice used extensively by farmers all over the world for crop production. It is an ecosystem
7 service in that wild pollinators, in particular wild bees, contribute significantly to the
8 pollination of a large array of crops (Kremen *et al.*, 2002; Morandin & Winston 2005;
9 Greenleaf & Kremen 2006; Klein *et al.* 2007 ; Winfree *et al.* 2007). And it is also a
10 management tool in that honeybee or bumblebee colonies are rented by farmers in many
11 countries to supplement the local pollinator fauna (McGregor 1976; Robinson *et al.* 1989;
12 Free 1993; Dag *et al.*, 2006). Thus the economic benefit of insect pollination is clear for
13 farmers and the market of colony rental is now well developed and organized for honey bees
14 in the United States of America (Sumner, 2006) and Europe (Carreck *et al.* 1997) as well as
15 for bumble bees all over the world (Velthuis & Van Doorn, 2006). This practice also suggests
16 that there is already not enough wild pollinators to insure adequate pollination of all crops
17 throughout the year in these countries. Yet the abundance and diversity of wild bees as well as
18 the abundance of honeybees are now declining and some species are clearly at risk
19 (Biesmeijer *et al.*, 2006; National Research Council, 2007; Oldroyd 2007; Stokstad 2007).
20 The current decline of insect pollinator populations emphasises the need to better assess the
21 potential loss in terms of economic value that may result from this trend and the possible
22 ultimate disappearance of pollinators, and to estimate the level of vulnerability of the world
23 agriculture to insect pollinators.

24 Two main ways have been used to date to assess the monetary value of pollinators.
25 The first one consists in simply assessing the total value of insect-pollinated crops. This

1 approach has been used at a national scale in the USA (Metcalf, 1992 ; Ware, 1973 ; Martin,
2 1975 ; Levin, 1984) as well as on a world scale (Costanza et al., 1997 ; Pimentel et al., 1997).
3 Since the production of most crops is only partially reduced in the absence of insect
4 pollinators, a second more refined approach to improve the previous estimate has been to
5 introduce a dependence ratio that takes into account the real impact of insect pollinators on
6 crop production (e.g. Klein et al., 2007). This dependence ratio enables the calculation of the
7 production loss in case of a complete disappearance of pollinators, and the economic value of
8 insect pollination service is assimilated with the corresponding loss of crop value. Thus the
9 monetary assessment is directly related to reported values of the dependence of crop
10 production on the level of insect pollination and, in this paper, it will be called a bioeconomic
11 approach. This type of assessment has also been done at national and larger scales (France -
12 Borneck & Bricout, 1984; Hungary - Benedek 1983; Switzerland - Fluri & Frick 2005; United
13 Kingdom - Carreck & Williams 1998; USA - Robinson *et al.* 1989, Morse & Calderone 2000,
14 Losey & Vaughan 2006; 12-member-states European Community - Borneck & Merle 1989).
15 Unfortunately, these studies have used a wide range of dependence ratios for the same crops
16 (Table 1). Indeed, these ratios were estimated based largely on personal communications and
17 interpretation of review material, such as McGregor (1976) and Free (1993), which do not
18 provide dependence ratios. None of the bioeconomic studies to date have evaluated the impact
19 of insect pollinators at the world scale, nor did they make a geographical analysis of the
20 impact of pollinators in terms of the possible vulnerability of agriculture or examined the
21 potential impact of pollinator loss on production compared with the consumption structure.

22 Our first objective was to quantify the economic loss that could result from the total
23 disappearance of insect pollinators on world agricultural output and we based our calculations
24 on the dependence ratios recently published for the crops used directly for human food (Klein
25 et al. 2007). Due to the many crop species and the heterogeneity of the structure of the

1 agricultural production, the vulnerability to pollinator decline is likely to vary widely among
2 the different continents and regions. Our second objective was therefore to provide a measure
3 of the vulnerability of the regional and world agriculture when confronted to the decline, or
4 even the total disappearance, of insect pollinators. Finally our third objective was to compare
5 the production and consumption of insect-pollinated crop categories at the regional and world
6 scale in the face of pollinator loss in order to draw some insight on potential local shortages
7 and impacts on trade. Our calculations were based on the assumption of a total pollinator loss,
8 but our results can be extended to any level of pollinator decline as there is empirical evidence
9 that the yield of entomophilous crops responds linearly to pollinator density (Dedaj &
10 Delaplane , 2003; Steffan-Dewenter, 2003; Clement et al. 2007).

11 2 Methods

12 2.1 Principles

13 Among the main crops that contribute to human food, some, such as most cereals, do not
14 depend on insects for their pollination, while others can be highly or totally dependant on
15 insect pollination, such as many fruits, vegetables and stimulant crops (Klein et al. 2007).
16 Our study is based on the hypothesis that the economic impact of pollinators on agricultural
17 output is measurable through the use of dependence ratios quantifying the impact of a lack of
18 insect pollinators on crop production value. This decrease in the production value could result
19 from a reduction in yield as well as in quality (Free, 1993). Unfortunately, this impact on
20 production value is unknown for most crops as what is usually reported is solely the degree of
21 dependence of the production on insect pollinators (Borneck & Bricout 1989; Robinson et al.
22 1989; Southwick & Southwick 1992; Morse & Calderone 2000; Klein et al. 2007). It is this
23 dependence ratio that we used again in our study to calculate the economic impact of
24 pollinators and the vulnerability of the agricultural output at various scales.

1 Because of the lack of substitution among agricultural produce, the economic impact
 2 and the vulnerability of the agricultural output is not enough to assess the full value of insect
 3 pollinators as, indeed, one ton of rice is not an appropriate substitute for one ton of coffee or
 4 of cantaloupe. Thus, in addition to looking at individual crops, we examined the vulnerability
 5 to pollinator decline of the FAO crop categories to which each crop belonged based upon the
 6 hypothesis that crops within a category could be considered as potential appropriate substitute
 7 for one another while this would not be the case for crops in different categories. We used the
 8 following 9 categories based on FAO: cereals, edible oil crops, stimulant crops, spices, fruits,
 9 vegetables, sugar crops, roots and tuber crops, and nuts.

10 2.2 Indicators and formulae

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

$$23 \quad \text{IPEV} = \sum_{i=1}^I \sum_{x=1}^X (P_{ix} \times Q_{ix} \times D_i) \quad [1]$$

1 Following White (1974), a precise definition of vulnerability was given by Turner *et al.*
 2 (2003) and used by Schröter *et al.* (2005) to assess the vulnerability of Europe faced with
 3 global change. Vulnerability is a function of three elements: exposure, sensitivity and
 4 adaptive capacity. In this context, we used the ratio of the economic value of insect
 5 pollination to the total value of the crop to calculate a level of vulnerability since it provides a
 6 measure of the potential relative production loss attributable solely to the lack of insect
 7 pollination. The ratio of vulnerability (RV) for the world output used for human food was
 8 thus calculated as follow:

$$9 \quad RV = \frac{IPEV}{\sum_{i=1}^I \sum_{x=1}^X (P_{ix} \times Q_{ix})} = \frac{\sum_{i=1}^I \sum_{x=1}^X (P_{ix} \times Q_{ix} \times D_i)}{\sum_{i=1}^I \sum_{x=1}^X (P_{ix} \times Q_{ix})} (\%) \quad [2]$$

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

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

$$16 \quad \frac{\sum_{i=1}^I \sum_{x=1}^X (Q_{ix} - C_{ix})}{\sum_{i=1}^I \sum_{x=1}^X (C_{ix})} \quad [3]$$

17 The corresponding matrix after total pollinator loss was:

$$18 \quad \frac{\sum_{i=1}^I \sum_{x=1}^X (Q_{ix} (1 - D_i) - C_{ix})}{\sum_{i=1}^I \sum_{x=1}^X (C_{ix})} \quad [4]$$

1 Data collection

2 The geographical scale of our study was the world based upon the 2005 data from the FAO
3 database (<http://www.fao.org>) and thus restricted to the 162 countries that are members of this
4 international organisation. Following FAO definitions, we gathered these countries into 5
5 main regions (Africa, Asia & Oceania, Europe, North America and Caribbean, South and
6 Central America), and, within each region, into sub-regions (see supplementary data –
7 Appendix 1).

8 We limited the scope of our study to the direct crops and commodity crops used
9 directly for human food as reported by FAO see supplementary data – Appendix 2). Direct
10 crops are those listed individually with their production by the FAO while a commodity is an
11 aggregation of different crops for which the production figures are pooled together and most
12 are reported as Not Elsewhere Classified. Commodity production figures are based on a
13 questionnaire that countries fill out to include important crops for the world market that are
14 not listed individually by the FAO. We included the commodity crops in the study because
15 they represent a significant part of the agricultural world output.

16 For Q_{ix} and C_{ix} , we used the 2005 FAO production and consumption data, respectively
17 (<http://www.fao.org>). For P_{ix} , we needed the mean 2005 producer price per unit weight for
18 each crop or commodity and each region as we opted to take into account regional
19 specialization, geographical context, and socio-economic factors. We chose this approach
20 because producer prices vary with many factors such as crop management, climate, varieties
21 and market in such a way that a regional approach should provide more accurate price
22 estimates than a worldwide approach. To fit complex geographical patterns as well as to be
23 able to concentrate on large producing regions without having to go to the level of individual
24 countries for which many price data are not available either, we used the five main world
25 regions defined previously (see supplementary data - Appendix 1). Major world field crops,

1 like most cereals and sugar crops, are produced on a large scale and have a large-enough
2 commercial value to be traded on financial markets. For these crops, we used the “free on
3 board” (FOB) prices, which are future contracts for 2005. These prices are available on the
4 websites of financial market places specialized in commodities such as the Chicago Board of
5 Trade (CBOT) and the New York Board of Trade (NYBOT). For most other crops, prices are
6 not available on the financial market place because of lower interest in their international
7 trading on a large scale. For these crops, we used the 2005 producer prices for each world
8 region that were provided by the European database Eurostat
9 (<http://epp.eurostat.ec.europa.eu>) and by the United States Department of Agriculture
10 (<http://www.fas.usda.gov>). For minor crops, defined as those for which the 2005 producer
11 price was not available in either of these two large databases, as well as for all the
12 commodities, we used the average producer price listed on the FAOSTAT website for the
13 period 1991-2002 for the most important producing country of each world region. We used
14 this method to reduce the effect of year-to-year price variation as well as the biases on prices
15 that might take place in small producing countries. Furthermore, when a country or a world
16 region largely exceeded its expected share of world production for a given crop based on its
17 sole size, we considered it to be specialized in this crop. For example, Asia produced 90% of
18 the rice, so we assumed that the world demand for rice, and thus its world price, would be
19 influenced by the Asian supply. In this example, we took the producer price of Asia rice and
20 applied it on a worldwide basis. In all cases, we used the local currency and the exchange rate
21 of the years of the data collected to calculate the prices and production values in 2005 euros.

22 We calculated the dependence ratios D_i based upon the five levels of the extensive
23 recent review of Klein et al. (2007; see supplementary data - Appendix 2). Starting with the
24 complete set of direct and commodity crops used for human food, we selected the ones which
25 are pollinated by insects and for which we had production and price data. For the individual

1 crops among the 11 commodities, neither the production nor the producer price was available
2 and the crops that composed each of these commodities were not all dependent on insect
3 pollination at a similar level for their production. Consequently we could not calculate the
4 economic value of pollinators for these commodity crops and they were not considered
5 further. For the remaining direct crops, we focused on those reviewed in Appendix 2 of Klein
6 et al. (2007) for which we calculated the average dependence ratio based on the reported
7 range of dependence to animal-mediated pollination (See supplementary data - Appendix 2).

8 3 Results

9 We found 89 direct crops and 11 commodities used for human food (100 lines in Appendix
10 2). Among these, 46 direct crops in 7 categories are dependent on insect pollinators for their
11 production and pollinators are essential for 6 of these crops. The contribution of insect
12 pollinators is also reported as great for 13 direct crops, modest for 13 and little for 14
13 (Appendix 2). It is noteworthy that within each crop category, there was considerable
14 variation among the crops as to their level of dependence on pollinators.

15 The 2005 world production value for crops used for human food was €1.618 trillion,
16 and the total value of the 46 insect-pollinated direct crops was €625 billion, that is 39% of the
17 world production value (Table 2 and supplementary data in Appendix 2). The economic value
18 of insect pollination was €153 billion (Table 2). The most pollinator-dependent crop
19 categories ranked by decreasing economic value of insect pollination were vegetables, fruits,
20 and edible oil crops (Table 2). It is noteworthy that the production value of a ton of the crop
21 categories that do not depend on insect pollination – namely cereals, sugar crops, and roots &
22 tubers – averaged 151 € while that of those that are pollinator-dependent averaged 761 €, or
23 five times more, and these values were significantly different ($t = 4.851$; $n = 3$ and 7,
24 respectively; $P = 0.0013$; t test on the Log-transformed values to have similar variance among
25 the two groups).

1 The rate of vulnerability of the world agricultural production used for human food in
2 the face of total pollinator loss was 9.5% (Table 2). This overall value may seem small, but it
3 does not reveal the large range of values among the different crop categories. The stimulant
4 crops with a total production value of only €19 billion had the highest vulnerability ratio
5 (39%). And vegetables, the category with the highest crop production value (€418 billion)
6 still had a vulnerability ratio of 12%. Interestingly, there was a positive correlation between
7 the rate of vulnerability of a crop category to pollinators and its value per production unit ($r =$
8 0.729 , $n = 10$, $P = 0.017$).

9 Looking at the economic vulnerability ratios of the different crop categories among
10 the regions of the world indicates that, in each region, there is a category that is highly
11 vulnerable to pollinator loss with vulnerability ratios ranging from 22% to 94% (Table 4).
12 Interestingly, nuts were the most vulnerable crop category over the largest area (7 sub-
13 regions), followed by fruits and stimulant crops (5 sub-regions each). Furthermore, because
14 some regions are specialized in the production of some pollinator-dependent crop category,
15 the vulnerability of the world production for these categories is much higher than the overall
16 worldwide value indicated on Table 3. For example, East Asia produced nearly 52% of the
17 world vegetables with a vulnerability ratio of 15% while the worldwide value was 12%
18 (Tables 2 and 4). Also North and South Americas produced 36% of the edible oil crops with a
19 vulnerability ratio greater than 22%, while the worldwide value was 16% (Tables 2 and 4).
20 And West Africa, South East Asia and North America together produced 36% of the nuts in
21 the world with a vulnerability ratio $\geq 44\%$ in all three regions. The situation appeared
22 particularly critical for stimulant crops as West Africa produced 56% of the world production
23 with a vulnerability ratio of 90% (Table 4). This region produced a lot of coffee and/or cocoa,
24 both of which are dependent of insect pollinators for their production, and the consequences
25 of a total pollinator loss on these crops could be considerable not only for the revenues that

1 West Africa derives from these crops, but also on a global scale for the world production and
2 resulting price structure of these stimulants.

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

1 the European Union where consumption exceeded production by 20% in 2005 and this deficit
2 would double following total pollinator loss in Europe. Other examples include fruits in West
3 Africa and North America, vegetables in Central Africa, Oceania, the European Union and
4 North America, and stimulant crops in the European Union and North America.

5 4 Discussion

6 We found a value of about €153 billion as an assessment of the economic value of insect
7 pollination for the world agriculture in 2005. This is the direct result of the calculations based
8 on equation [1] using the dependence ratios towards pollinators given by a recent review
9 (Klein et al. 2007) and the production value of the most important crops directly used for
10 human food. It measures the part of the gross value of the world food production attributable
11 to insect pollination and can therefore be considered as a conservative assessment of the gross
12 value of the insect pollination service. Indeed, in an early valuation of the service provided by
13 bees on US agriculture, Martin (1975) stated that the value of beef and dairy products that
14 result from the seed production of forage legumes such as alfalfa accounts for about 80% of
15 the economic value of insect pollinators. At the world scale, such a high value is most
16 unlikely, at least because forage legume are not as important worldwide as in the USA. But
17 this statement nevertheless underlines the fact that the indirect impact of pollinator decline on
18 forage production, though quite difficult to assess, may not be anecdotal. Similarly, our
19 assessment did not take into account the value of pollinators for the seed production necessary
20 to grow the vegetative parts of many species which are consumed by humans (such as many
21 vegetables; see Appendix 1 in Klein et al. 2007, and our supplementary data - Appendix 2),
22 nor the seed production for ornamental flowers and other uses not devoted to human food
23 such as biofuels. Soybean and other pollinator-dependent edible oil crops contribute to the
24 supply of biofuels, but current relative prices limit their use and biofuels are mainly produced

1 from non-pollinator dependent crops such as sugar cane and corn (Schubert, 2006; Appendix
2 2).

3 In the literature, we found only two studies giving an economic valuation of the
4 pollination service at the world scale (Costanza et al, 1997; Pimentel et al, 1997). Yet the
5 comparison of our results with those of these two studies is difficult because their methods are
6 so different. Costanza et al. used the findings of Levin (1984) to determine a lower limit of
7 the value of insect pollination service of US\$140 million, corresponding to the value of honey
8 and beeswax in 1980, and an upper limit of US\$18.9 billion, which was the value of 1980 U.S
9 crops that they considered dependent on insect pollinators (fruits, nuts, vegetables, seeds,
10 fibbers, cattle, calve and liquid milk production). Conservatively and without further
11 justification, they chose a value of US\$2 billion from this interval and assumed that the U.S.
12 agriculture represented 10% of the world crop value. In this way, they found a value of the
13 insect pollination service to crops worldwide of US\$20 billion for 1996 which amounts to
14 about €20 billion when adjusted for inflation (<http://www.westegg.com/inflation>) and 2005
15 exchange rate (<http://fxtop.com>). Pimentel et al. (1997) started with the figure of US\$8 billion
16 reported by Martin (1975) and quoted in Robinson et al. (1989) for the 1970 value of USA
17 crops dependent on insect pollinators and used for human food. Martin increased this figure to
18 US\$ 40 billion when adding the value of beef and dairy products that are derived from insect-
19 pollinated legume forage to the value of crops used directly for humans. Then, Pimentel et al.
20 extrapolated this value to the entire world by assuming that the economic value of insect
21 pollination worldwide was at least five times that of the USA. With appropriate exchange rate
22 and inflation correction, the figures of Pimentel et al. give an economic value of insect
23 pollination to the world agriculture of US\$200 billion in 1996, and gives a 2005 economic
24 value of €200 billion, which takes into account the value of beef and dairy products that are
25 derived from insect-pollinated forage legumes. Interestingly, if we start with the original

1 figure of US\$ 8 billion for the crops used for human foods only, the economic value of insect
2 pollination worldwide amounts to US\$40 billion (€40 billion in 2005 economic value).

3 Even after appropriate corrections, the 2005 estimated values from these two studies
4 (€20 billion and €40 billion for Costanza et al. 1997 and Pimentel et al. 1997, respectively)
5 remain considerably smaller than our result (€153 billion; Table 2). Such a difference raises
6 many questions. Since these authors give little explanations on their methods, we might
7 assume that they have integrated in their calculations some more sophisticated - though
8 unformulated - considerations, especially in relation to the behaviour of economic actors that
9 will adapt to a pollinator-free context.

10 These €153 billion **stand for** about 9.5% of the world value of the crops used directly
11 for human food. This ratio **of vulnerability** can be interpreted as an indicator of the value of
12 pollination service relatively to the other factors that contribute to agricultural production
13 worldwide. The value of the vulnerability ratio is of course contingent of the relative prices of
14 crops and, especially, of the prices of pollinator-dependent crops relative those which are not¹.

15 It must be clearly stated that this economic valuation is not a scenario assessment,
16 since all economic agents can change their behaviour in order to adapt to a pollinator decline.
17 These changes will have some costs, namely opportunity costs. But one can assume that
18 producers will make efficient trade-offs between the costs of changing crop species, or
19 varieties, or production technologies – namely pollination techniques – and the losses
20 resulting from keeping less profitable practices².

20

¹ 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.

² For horticulture 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. The opportunity costs of taking up new crops are very high as a result.

1 It appears difficult to gauge the real significance of a vulnerability of about 10% on
2 the agricultural industry. In some cases, a small variation may induce large consequences,
3 especially through the impact it might have on the financial equilibrium of farms. The
4 transmission of the price change can have variable effects within the food supply chain (Wu,
5 2004 ; Tang, 2005) and the capacity of the food supply chain operators to adapt to new
6 situations and limit the consequences, either through technical change or because of the
7 existence of market power, is poorly known (Hassan and Simioni, 2001).

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

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

$$22 \quad \text{Gain} = Q_1(P_1 - P_0) + \int_{Q_1}^{Q_0} [P(Q) - P_0] dQ \quad [5]$$

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

4 Our assessment is based upon the calculation of the loss in terms of agricultural
 5 production for each crop i , that is $P_{i0}(Q_{i0} - Q_{i1})$ (see Figure 2). This result must be
 6 transformed into economic surplus loss for consumers to obtain an assessment of the social
 7 cost of pollinator decline. Since there are no appropriate data to find econometrically for each
 8 crop at the world scale the price elasticities, assumptions must be made on the shape and
 9 value of $P(Q)$. A simple idea is to assume that for all crops the price elasticities (E) are
 10 constant. Inverse demand functions can then easily be expressed and consumer surplus
 11 variations analytically calculated.

12 The choice of a constant elasticity price is acceptable for most crops as long as the
 13 price range remains in the neighbourhood of current prices. The neighbourhood wideness is
 14 variable with the crop and its economic status as primary good or luxury good. It is probably
 15 unacceptable when the ratio of dependence is very high, since the price should then rise
 16 considerably (e.g. for the 6 crops with a dependence ratio of 95%, which means that for a
 17 price elasticity value of -1 , the price following total pollinator loss would be multiplied by
 18 20).

19 Given a constant elasticity price, the mathematical representation of the demand
 20 function comes from the definition of the price-elasticity $E = \frac{\delta Q/Q}{\delta P/P}$, which leads to

21 $P(Q) - EQP'(Q) = 0$ and, assuming $E \neq 0$, gives the inverse demand function:

$$22 \quad P(Q) = P_0 \left(\frac{Q}{Q_0} \right)^{\frac{1}{E}} \quad [6]$$

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

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

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

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

1 We have to come here at what will happen on the food production and markets after
 2 the insect pollinator decline. The first consequence is a loss in production from Q_0 to $Q_0(1-D)$
 3 for a similar production effort (i.e. without change in the total production costs). If a smaller
 4 production is obtained for the same total cost, we can assume that the unitary production cost
 5 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
 6 i on the market of our pollinator-free economy. At this price, the effective demand will be
 7 $Q_i(P_{i1}) = Q_{i1}$. This assumption allowed us to calculate the consequent surplus loss according
 8 to the value of E .

9 For the value $E = -1$, it comes from [6] that $P(Q) = P_0 \cdot Q_0/Q$. The consumer surplus
 10 loss (CSloss ; Figure 2) is then:

$$11 \quad CS_{\text{loss}} = \int_{Q_1}^{Q_0} [P(Q)] dQ = \int_{Q_1}^{Q_0} \frac{P_0 Q_0}{Q} dQ = P_0 Q_0 \cdot \text{Log} \frac{Q_1}{Q_0} \quad [7]$$

12 where P_1 and Q_1 are the price and quantity without insect pollination, P_0 and Q_0 are the price
 13 and quantity with insect pollination. If we apply this expression to a quantity reduction related
 14 to a total pollinator loss for a crop with a ratio of dependence D , it comes:
 15 $CS_{\text{loss}} = P_0 \cdot Q_0 \cdot \text{Log}(1 - D)$. This value is easy to calculate using the matrix of prices and
 16 quantities in Appendices 2 and 3. Applying this formula to all crops used directly for human
 17 food on a worldwide basis gives a total loss of consumer surplus of about €260 billion for
 18 2005.

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

$$20 \quad CS_{\text{loss}} = \frac{P_0 Q_0}{1+E} \left(\left(\frac{1}{1-D} \right)^E - 1 \right). \quad [8]$$

21 This value can be calculated for any value of E using the database of all crops in each world
 22 region (Appendices 2 and 3) :

$$1 \quad \sum_{i=1}^I \sum_{x=1}^X P_{ix0} Q_{ix0} \left(\frac{(1 - D_i)^{\frac{1+E}{E}} - 1}{1 + E} \right) \quad [9]$$

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

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

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

14 Following the agro food supply chains, it can be assumed that optimisation tuning will
 15 aim at reducing the impact of pollinator decline onto consumers, through substitution both in
 16 the nature of the good and the processing formula. Finally, consumers would modify their
 17 choices according to the relative prices of food items and, in the case of strong change, the
 18 food budget might compete with other parts of the consumption patterns³.

19 The potential loss in some food production may not only have measurable
 20 consequences in economic terms, as it might also have serious consequences on human
 21 health. In particular, the decrease of fruit and vegetable availability could impact the health of

21

³ 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 low pollination forms a deadweight loss, net loss to producer and consumers and hence to society.

1 consumers worldwide. The World Health Organisation (WHO) has set a lower limit of 400
2 grams per capita per day for fruit and vegetable consumption (WHO Report, 1990). Naska et
3 al. (2000) studied fruit and vegetable consumption among ten European countries and found
4 that more than 50% of the households did not follow this recommendation. In the case of a
5 total disappearance of pollinator, this situation is very likely to worsen.

6 5 Conclusions

7 The aim of our work was to assess the vulnerability of the world agriculture faced to the
8 decline of insect pollinators. Using a bioeconomic approach, we calculated a world value of
9 the contribution of pollinators to the production of crops used directly for human food of €153
10 billion, which is about 9.5% of the total value of the production of human food worldwide.

11 Since this first result was obtained through multiples sums, we extracted partial results
12 such as the most vulnerable crop categories (stimulant, nuts and fruits) or the categories that
13 stood for the largest part of the economic vulnerability (fruits, edible oil crops, vegetables).
14 Related to their agricultural orientations, some regions appeared more vulnerable like Middle
15 East Asia (15%), Central Asia (14%), East Asia (12%) and non European Union countries
16 (12%). At the global scale, the vulnerability of the Northern countries appeared higher than
17 the southern ones, which suggests that the decline of insect pollinators might have heavy
18 consequences for the North-South agro-food trade. In order to complete these data, we
19 calculated the capacity to nourish world population after pollinator loss and found that the
20 production of 3 crop categories will clearly be below the current consumption at the world
21 scale and even more so for certain regions like Europe.

22 Although we created a complete database of prices and production quantities for each
23 crop in each region of the world and we used a very recent review to get the dependence ratio
24 of each crop on insect pollination, the uncertainties are probably large but difficult to assess,

1 especially since ecological responses to pollinator decline on large scales remain poorly
2 known (National Research Council, 2007). More specifically, there is an ongoing debate on
3 the existence of a “pollinator paradox” meaning that though crops depend on pollinators, the
4 overall crop yield may not necessarily be as dependent because farmers will take into account
5 pollinator decline in their production management and strategies (Ghazoul, 2007).

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

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

22

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Tables and figures

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

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

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

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 regions of the world defined following FAO (<http://faostat.fao.org>). **X%** highest value of the economic vulnerability ratio for the sub-region.

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

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 overall balance was negative following pollinator loss. The difference between consumption and production is expressed in relative terms as % of the consumption figures following FAO (<http://faostat.fao.org>).

Table 7 – 2005 consumer surplus loss at the world scale in 10^9€ various different level of price-elasticities

Figure 1 – Estimates of the consumer surplus loss for various price-elasticities

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 & Bricout, 1989			Robinson et al., 1989	Southwick & Southwick, 1992	Morse & Calderone, 2000	Klein et al., 2007		
		<u>Min</u>	<u>Max</u>	<u>Mean</u>				<u>Min</u>	<u>Max</u>	<u>Mean</u>
<u>FRUITS</u>										
<i>Fragaria x ananassa</i>	Strawberry	0.100	0.200	<u>0.150</u>	<u>0.4</u>	0.30	0.2	0.1	0.4	0.25
<i>Malus domestica</i>	Apple	0.100	0.200	<u>0.150</u>	<u>1.0</u>	0.80	1.0	0.4	0.9	0.65
<i>Vitis vinifera</i>	Grape	0.001	0.010	0.006	0.1	<u>0.15</u>	0.1	0.0	0.0	<u>0.00</u>
<u>NUTS</u>										
<i>Amygdalus communis</i>	Almond	0.100	0.200	<u>0.150</u>	<u>1.0</u>	0.90	1.0	0.4	0.9	0.65
<u>VEGETABLES</u>										
<i>Cucumis melo</i>	Melon (incl. cantaloupe)	0.100	0.200	<u>0.150</u>	0.8	0.70	0.9	0.9	1.0	<u>0.95</u>
Mean				0.120	0.66	0.57	0.64			0.50

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 & tubers	137	98	0.0	0.0
All categories pooled together		1 618	152.9	9.5

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 ($\geq 10\%$) are in bold.

Geographical region and sub-region	Total production economic value (EV) 10 ⁹ €	Insect pollination economic value (IPEV) 10 ⁹ €	Rate of vulnerability for the region (IPEV/EV) %
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 & USA	125.7	14.4	11
SOUTH & CENTRAL AMERICA			
Central America & Caribbean	51.1	3.5	7
South America	187.7	11.6	6

Table 4 – Economic vulnerability ratio (in bold) and 2005 production figures in 10⁶ 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 and sub-region	Edible oil crops	Fruits	Nuts	Pulse	Spices	Stimulant crops	Vegetables
AFRICA							
Central Africa	8% <i>4.37</i>	4% <i>5.71</i>	0% <i>0.04</i>	1% <i>0.12</i>	5% <i>0.05</i>	69% <i>0.28</i>	10% <i>2.58</i>
East Africa	18% <i>2.08</i>	4% <i>6.39</i>	22% <i>0.18</i>	10% <i>1.70</i>	3% <i>0.18</i>	17% <i>1.05</i>	4% <i>6.85</i>
North Africa	13% <i>3.86</i>	16% <i>15.73</i>	58% <i>0.24</i>	15% <i>1.04</i>	4% <i>0.14</i>	- <i>0</i>	13% <i>30.45</i>
South Africa	17% <i>2.74</i>	15% <i>7.95</i>	45% <i>0.08</i>	0% <i>0.41</i>	25% <i>0.06</i>	16% <i>0.16</i>	8% <i>4.11</i>
West Africa	9% <i>23.81</i>	11% <i>10.88</i>	46% <i>1.03</i>	2% <i>0.00</i>	3% <i>0.25</i>	90% <i>2.53</i>	5% <i>17.47</i>
ASIA							
Central Asia	25% <i>4.00</i>	41% <i>2.16</i>	35% <i>0.03</i>	4% <i>0.06</i>	4% <i>0.00</i>	- <i>0</i>	14% <i>8.59</i>
East Asia	17% <i>62.76</i>	36% <i>94.71</i>	16% <i>1.70</i>	10% <i>5.64</i>	3% <i>0.76</i>	2% <i>1.08</i>	15% <i>462.56</i>
Middle East Asia	18% <i>5.27</i>	24% <i>32.97</i>	18% <i>1.55</i>	3% <i>2.98</i>	1% <i>0.23</i>	3% <i>0.28</i>	18% <i>49.57</i>
Oceania	24% <i>3.69</i>	28% <i>5.08</i>	33% <i>0.05</i>	6% <i>2.14</i>	1% <i>0.01</i>	94% <i>0.01</i>	8% <i>2.86</i>
South Asia	19% <i>44.41</i>	23% <i>56.09</i>	23% <i>1.00</i>	0% <i>13.24</i>	2% <i>3.79</i>	11% <i>1.51</i>	7% <i>92.93</i>
South East Asia	11% <i>186.07</i>	13% <i>44.32</i>	44% <i>1.39</i>	3% <i>2.22</i>	2% <i>0.87</i>	38% <i>2.74</i>	7% <i>30.90</i>
EUROPE							
European Union (25 members)	8% <i>31.94</i>	30% <i>60.05</i>	48% <i>0.82</i>	5% <i>5.49</i>	1% <i>0.13</i>	- <i>0</i>	7% <i>65.35</i>
Non EU25	24% <i>17.81</i>	51% <i>13.31</i>	4% <i>0.28</i>	1% <i>2.83</i>	3% <i>0.12</i>	0% <i>0.02</i>	12% <i>35.08</i>
NORTH AMERICA							
Bermuda, Canada & USA	23% <i>110.74</i>	24% <i>27.62</i>	46% <i>1.31</i>	3% <i>6.56</i>	0% <i>0.04</i>	- <i>0</i>	8% <i>39.74</i>
SOUTH & CENTRAL AMERICA							
Central America & Caribbean	14% <i>5.73</i>	10% <i>29.86</i>	1% <i>0.21</i>	5% <i>1.12</i>	2% <i>0.16</i>	29% <i>1.21</i>	12% <i>19.49</i>
South America	22% <i>113.38</i>	9% <i>71.44</i>	25% <i>0.30</i>	9% <i>0.45</i>	3% <i>0.28</i>	30% <i>4.55</i>	8% <i>25.17</i>
TOTAL	622.66	484.27	10.21	46.00	7.07	15.42	893.70

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	% 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

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 overall balance was negative following pollinator loss. The difference between production and consumption is expressed in relative terms as % of the consumption figures following FAO (<http://faostat.fao.org>).

Geographical region (FAO classification)	Fruits		Stimulant crops		Vegetables	
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 & USA	-30	-46	-100	-100	-3	-16
SOUTH & CENTRAL AMERICA						
Central America & Caribbean	54	35	183	99	63	27
South America	83	65	176	103	17	-4

Table 7 – 2005 consumer surplus loss at the world scale in 10^9€ following various level of price-elasticities

Price-elasticities	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

Figure 1 – Estimates of the consumer surplus loss for various price-elasticities

