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Pollinator Dependence of Argentinean Agriculture: Current Status and Temporal Analysis

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ABSTRACT

A sizable proportion of agricultural production depends directly or indirectly on animal pollination but estimation of the size of this dependence is missing for most countries, even for some of the most important food producers. Here, we evaluate the current status and temporal trends (1961-2007) in pollinator dependency of Argentinean agriculture. We classified crops in categories according to their pollinator dependence, and estimated their harvested area, production, economic and nutritional values. We also estimated the expected production deficit in the absence of pollinators, the extra area needed to cope with this deficit, and trends in honeybee stocks. From a total of 68 crops, animal pollination increased directly production in 37 and indirectly in 13. More than half of the harvested area and total agricultural production corresponded to pollinator dependent crops, a trend highly influenced by the inclusion of soybean as a modestly dependent crop. Highly pollinator-dependent crops produced 2-4 times more income per hectare than any other crop, and modestly dependent crops bear on average the highest protein and fat content. During the study period the production deficit increased three-fold, reaching 12% in 2007, whereas the area needed to compensate for these deficiencies attained 24%. Regarding pollination services, indicators are mixed; whereas Argentinean honey-bee stock triplicates from 1961 to 2007, native forest area, a source of pollinator diversity, shrank to more than half since 1940's. Experiments testing the degree of pollinator dependency on the quality and quantity of crop production for soybean varieties cultivated in Argentina are urgently needed. Our estimations depict an agriculture that is becoming more dependent on pollinators, but native forests and other native terrestrial habitats, which host most of the country's pollinator diversity, are decreasing at an alarming rate.

Keywords: crop pollination, pollination service, productivity, soybean, yield
Abbreviations: Ha, hectare; **Mt**, metric ton; **U$S**, United States Dollars

INTRODUCTION

In the face of current rapid degradation of terrestrial ecosystems worldwide, there is an increasing need for the study, valuation, and conservation of ecosystem services (Constanza *et al.* 1997; Chapin *et al.* 2000; Balvanera *et al.* 2006). Animal pollination is a key ecosystem service because most of the plants rely to some extent on animal pollination for sexual reproduction (Bawa 1995), including many of the crops that feed us (Free 1993; Roubik 1995). A range of animals that includes bees, bats, birds, beetles, butterflies, flies, moths and wasps are the responsible of the service of animal pollination, thus they provide a high economic and ecological benefits to humans. However bees are the world's dominant pollinators, as the approximately 17,000 known bee species (Michener 2000) depend on flowers for their survivor. There is growing evidence and concern that pollination services provided by natural or managed pollinators may increasingly limit crop production (Cane and Tepedino 2001; Biesmeijer *et al.* 2006; Oldroyd 2007; Ricketts *et al.* 2008; Aizen *et al.* 2009a; Aizen and Harder 2009, but see Ghazoul and Koh 2010). Thus, the assessment of the so-called "pollination service" has became a prime topic of applied research in different agro-ecosystems contexts (Aizen *et al.* 2009a). This assessment involves estimations of both agriculture demand for animal pollination and pollinator availability (Kremen *et al.* 2004; Aizen and Harder 2009).

Despite the importance of animal pollination for agriculture, it has not been until recently that researchers started conducting detailed studies on how much crop yield depend on pollinator abundance and diversity including studies on watermelon (Kremen *et al.* 2002), coffee (Roubik 2002; Klein *et al.* 2003a), atemoya (Blanche and Cunningham 2005), canola (Morandin and Winston 2005), macadamia (Blanche *et al.* 2006), grapefruit (Chacoff and Aizen 2007; Chacoff *et al.* 2008), and raspberry (Morales 2009). A recent review reported that pollinating insects increase fruit or seed quantity and/or quality (i.e., fruit or seed weight) of 39 of the 57 major crops worldwide (Klein *et al.* 2007), concluding that 35% of global food production (in metric tons) comes from crops that depend to some degree on pollinators (Klein *et al.* 2007).

The pollinator dependence of specific crops could be particularly critical for national or regional economies (e.g., coffee for Colombia, or cacao for some regions in Brazil), see also Ghazoul and Koh (2010). Recently, an economically-focused study estimated that, on average, 9.5% of the value of the world agricultural production used for human food relies directly on animal pollination (Gallai *et al.* 2009). However, there is large variation in the economical importance of pollinators within and among world regions. Pollinators are particularly important in the agriculture of many countries from Asia, South America and southern Europe (Gallai *et al.* 2009). Particularly, the value of animal pollination represents a sizable percent of the Gross Natio-

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nal Product for major food-producing countries with an agriculture-based economy such us Argentina.

Beyond their importance in agriculture production, animal pollinators may play an important role at increasing food diversity and for the supply of vital nutrients for human health (Ashworth *et al.* 2009; Gallai *et al.* 2009), which is not necessarily reflected in market prizes of crops and food. Although all these potential benefits of animal pollination have been invoked, we are still largely ignorant of the nutritional contribution (proteins, fats and carbohydrates) of pollinator dependent crops for human nourishment (Steffan-Dewenter *et al.* 2005). Despite fragmentary knowledge, all these different aspects should be contemplated in a thorough evaluation of the role of pollinators in agriculture.

Nowadays there are estimations of agriculture dependence on pollinators at a global scale (Klein *et al.* 2007; Gallai *et al.* 2009), but few estimations are at the country scale (Ashworth *et al.* 2009). This is important because the national scale is the one at which most decisions regarding agricultural policies are made. Whereas crop commodities in Argentina account for 56% of the per capita gross domestic product (FAO-Statistics 2007), no estimations of the importance of animal pollination exist for this country. Agriculture in Argentina is represented by a wide diversity of crops (**Appendix 1**). Nevertheless, soybean (*Glycine max*) has become the most important crop in terms of area and total production since the last decade (Paruelo *et al.* 2005). A temporal analysis revealed that total cultivated area increased by about 45% from 1990 to 2006; which reflected the expansion of soybean and resulted in a trend towards homogenization of Argentina's agricultural landscape (Aizen *et al.* 2009b). In addition, vast areas of native forest have been fragmented or directly cut down and converted to agriculture (Zak *et al.* 2004; Gasparri and Grau 2009), probably reducing the abundance and diversity of wild pollinators (Aguilar *et al.* 2006; Winfree *et al.* 2009). Thus, despite the profound changes experienced in the last decades by both agricultural and natural landscapes, we know neither the current level of animal pollination dependence of Argentina's agriculture nor its temporal dynamics.

In this study, we assess the historical and current importance of pollinators for Argentinean agriculture. Our evaluation will help to understand the vulnerability of the country's economy and, more directly, of food provisioning under a potential scenario of pollinators decline. We apply methods proposed by Aizen *et al.* (2009a) that had been used at a global level, and also incorporate other dimensions to evaluate pollinator importance such us nutritional value of pollinator dependent crops. Specifically, we (a) compared crops with varying degrees of pollinator dependence in terms of harvested area (ha), production (Mt), yield (Mt/ha), yield value (U$S/ha), prize (U$S/Mt), and nutritional value (total estimated fat, proteins and total carbohydrates); (b) evaluated the temporal change in pollinator dependence in terms of total harvested area (ha), and yield value (U$S/ha), (c) estimated the potential production deficit in absence of pollinators as well as the area compensation needed to compensate with this deficit and (d) assessed how the pollinator service provided by managed and wild pollinator accommodates to changes in the demand imposed by pollinator-dependent crops.

METHODS

Dataset

The Food and Agriculture Organization of the United Nations (FAO) has gathered information on crop cultivation from questionnaires sent annually to member countries from which we extracted the information. However, not all the cultivated crops in Argentina are reported by the FAO. For instance, information on non-traditional crops like raspberries and blueberries was not available despite they have experienced substantial growth during the last years (Bruzone 2004). Crops or varieties cultivated on a local scale (e.g. local races of potatoes and maize), that are irrelevant for the economy at the country scale, are not reported to the FAO either. However, these crops can be important locally, for the welfare and subsistence of local communities. In addition, some agriculture items were discarded from the data set because information on pollinator dependence was not available, or because that item could not be assigned to an identifiable single crop (e.g. groups of crops pooled within a single entry like "vegetable fresh"). Our dataset, therefore, yielded a total of 68 crops that accounted for >99% of the total Argentinean production reported by the FAO.

From the FAO dataset (FAOSTAT 2009), we compiled annual data from 1961 to 2007 on harvested area (ha), production (Mt) and from 1991 to 2006 on producer prize (U$S/Mt). Nutritional values for the cultivated species were obtained from FAO information for Latin America (FAO-LATINFOODS 2002). FAO tables provide information on 24 different nutritional components. Among them we selected proteins, fat, and carbohydrates (all in units of grams per 100 g of edible part), because they constitute the basic components of the daily human consumption (WHO 1990). Minerals, fiber and vitamins are also fundamental in a healthy diet (WHO 1990); however, they were not regularly reported as the components listed above. Nutritional composition of a given food item is reported by each country producing that item, therefore reflecting the actual nutritional value of the food cultivated in that country. When information was not available for an Argentinean product, we used the data reported by the nearest neighbor country in America (Chile, Uruguay, Brazil, Bolivia, Peru or Mexico) producing that crop.

Information on the degree of dependence of animal pollination for fruit or seed production for each crop was obtained from Klein *et al.* (2007). When this information was not available, we further obtained pollination dependence data from other sources (see **Appendix 1**). Crops were classified into two broad pollinator dependence categories, based on whether or not pollinators increase production: (a) "dependent" on animal pollination if pollinators increased to any extent the production of the fruits or seeds for which they are cultivated, (b) "nondependent" if animal pollination does not *directly* increase the production, either because they produce parthenocarpic fruits (e.g. bananas, pineapples), are pollinated abiotically (e.g. cereals), autogamously (e.g. lentils) or because they are cultivated for vegetative parts like leaves, steams, tubers (e.g. tea, potatoes) (see **Fig. 1**). Next, pollinator-dependent crops were further classified in four sub-categories that better reflect the importance of pollination for yield increase. This classification follows Klein *et al.* (2007) and is based on the magnitude of the reduction in production when pollinators are experimentally excluded from flowers: (a) little (>0-10% production reduction), (b) modest (>10-40%), (c) high (>40-90% reduction) and (d) essential (>90% reduction without pollinators) (see **Fig. 1**).

Among nondependent crops (i.e., those for which the magnitude of production reduction in the absence of pollinators is zero), animal pollination might still be important for producing the seeds necessary to cultivation, propagation or for breeding programs; therefore pollinators can *indirectly* increase or improve the production in the mid or long term. Thus, nondependent crops were further classified into three classes also following Klein *et al.* (2007): (a) crops that do not depend on pollinators at all; (b) crops that depend on pollinators only for seed production, and (c) crops that depend on pollinators for breeding (**Appendix 1**, **Fig. 1**). Nevertheless, since this study is focused on the direct contribution of pollinators to crop production, non-dependent crops are treated as a single category in most analyses, regardless of the contribution of pollinators for seed propagation and breeding.

Information on stocks of domestic honey bee (*Apis mellifera*) was also gathered from the FAO database (FAOSTAT 2009). We compiled yearly data on the number of honey bee hives for the period 1961-2006. Finally, official statistics on deforestation in Argentina for the period (1937-2007), were obtained from the Secretariat of Environment and Sustainable Development (Secretaría de Ambiente y Desarrollo Sustentable de Argentina 2007: http://www.ambiente.gov.ar/).

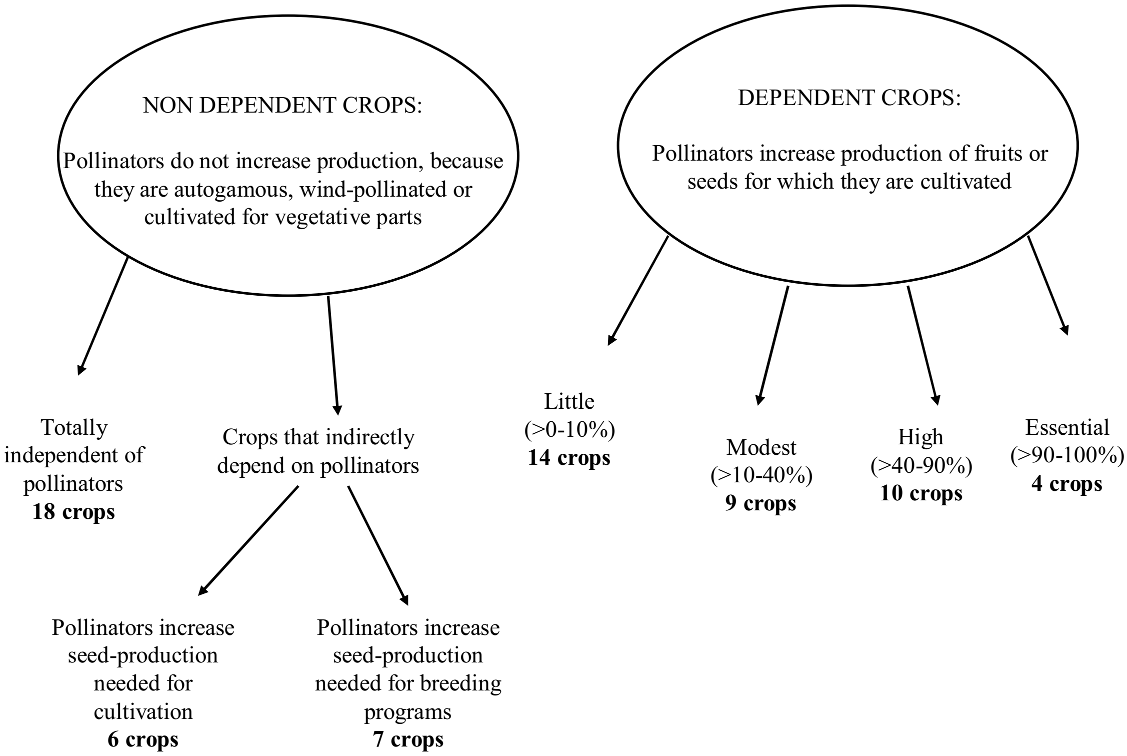

Fig. 1 Pollinator dependence categories used in this study. Between parenthesis, magnitude of reduction of production in the absence of pollinators.

Data analysis

1. Current dependence

We compared total harvested area (ha), production (Mt), yield (Mt/ha), yield value (U$S/ha), prize (U$S/Mt) and nutritional content (proteins, fat and carbohydrates) between the five different categories of crop pollinator dependence, from essential dependent to the broad nondependent pollinator dependence category (including also as non-dependent those crops that depend indirectly on pollinators). To estimate approximate current dependence, we used values of each variable averaged across the last three years for which data were available (2005-2007). As soybean represents the dominant crop in terms of cultivated area in Argentina (see above), we did all the comparisons with and without soybean, which was classified as a modestly dependent crop (Klein *et al*. 2007). We also estimated the expected nutritional deficit in the absence of pollinators for Argentina. For each year (2005-2007), we calculated the expected percent decrease in nutritional contents (i.e., nutritional deficit of proteins, carbohydrates or fat) in the absence of animal pollination as ND = 100. $(\sum N_{it} - N_{it}') / N_{it}$, where N_{it} is the nutritional content of crop i multiplied by the crop total production during year t, and $N_{it}' = N_{it}(1\text{-}d_i)$. The coefficient d_i ranges from 0 for crops that do not depend on pollinators to 1 for crops that depend fully on pollinators for production.

2. Temporal trends

We used data on total harvested area (ha) and total crop production (Mt) to estimate different indices of agricultural pollinator dependency for Argentina, considering the magnitude of reduction of production in the absence of pollinators. For each year, we estimated the expected percent decrease in agricultural production (i.e., production deficit) in the absence of animal pollination as PD = 100. $(\sum P_{it} - P_{it}') / P_{it}$, where P_{it} is the production (Mt) of crop i during year t, and $P_{it}' = P_{it}(1\text{-}d_i)$. The coefficient d_i ranges from 0 for crops that do not depend on pollinators to 1 for crops that depend fully on pollinators for production. For each year, we also calculated the total percent increase in cultivated area needed to balance the production deficit of each crop (i.e., area compensation) as AC = 100. $(\sum A_{it} - A_{it}') / A_{it}$, where A_{it} is the area (in ha) cultivated with crop i during year t and $A_{it}' = A_{it} / (1\text{-}di)$ (i.e., the area needed to produce P_{it} in the absence of animal pollination). To see more information on the statistical procedure see Aizen *et al.* (2009a) and Aizen and Harder (2009). Again, temporal analyses were done with and without soybean.

RESULTS AND DISCUSSION

The group of 68 crops with known pollinator dependence status reported for Argentina in the FAO database includes crops used directly for human food (i.e., cultivated for their edible parts), indirectly for human food (i.e., to feed livestock) as well as industrial crops (**Appendix 1**). Out of these 68 crops, 50 (73.5%) depended on pollinators, either directly to increase production (37 crops; i.e. 54.5% of the total) or indirectly to increase propagation or improve breeding (13 crops, 19%). Production of the remaining 18 crops (26.5%) was fully independent of pollinators. The percentage of crops cultivated in Argentina that depend either directly or indirectly on pollinators is similar to that reported for the global scale (74%, Klein *et al.* 2007) and slightly lower than that for Mexico (80%, Ashworth *et al.* 2009). However, most pollinator dependent crops are only partially dependent on animal pollination, thus the amount of production directly attributable to animals is much lower than this estimation.

Crops cultivated in Argentina encompassed a variety of categories that includes cereals, pulses (legumes), oil-seed crops, roots and tubers, stimulants, sugar crops, fruits, vegetables, nuts and spices (**Appendix 2**). Most fruits, vegetables and oil-bearing crops, which together represented 58% of the total cultivated crops, depended directly or indirectly on pollinators (**Appendix 2**). At the other extreme, cereals and sugar crops (14.5%) were totally independent on pollinators, while tuber and root crops depended on pollinators for breeding (**Appendix 2**). Crops for which the absence of pollinators might cause more than 40% reduction in the production (i.e., those classified in the "high" and "essential" categories) include pumpkins, peaches, pears, plums, watermelons, almonds, apples, mangos and avocados. Crops with modest dependence include soybean, sunflower and rapeseed, while crops with little dependence included oranges and tangerines (**Appendix 1**).

Table 1 Indicators of the current importance of crops from different pollinator dependence categories for Argentinean agriculture. (A) Total harvested area (ha), production (Mt), net income (U$S) and net nutritional contribution per category. (B) Mean yield (Mt/ha), yield value (U$S/ha), producer prize (U$S/Mt) and average nutritional content of crops used as human food.

	Pollinator dependence categories					
	essentials	**high**	**little**	**modest** (4)	**soybean**	**non-dependent**
A) Total values						
Harvested area (ha 10^3) (1)	67.6	112.5	662.7	2723.6	15078.1	10405.4
Metric tonnes (Mt 10^3)	538.6	2315.2	4639.0	4103.4	41422.4	66273.8
Net income (U$S 10^6) (2)	140.5	2759.0	3128.3	1423.6	12459.0	11485.4
Proteins (Mt 10^3) (3)	2.6	10.8	298.1	924.4	14332.1	3834.1
Fats (Mt 10^3) (3)	1.0	9.2	289.7	1.864.9	10024.2	525.1
Carbohydrates (Mt 10^3) (3)	30.6	338.9	623.6	526.8	11266.8	47538.9
B) Mean values						
Yield (Mt/ha)	11.24 ± 6.81	12.34 ± 11.20	12.23 ± 11.83	4.07 ± 3.56	2.54	10.26 ± 16.42
Prize (U$S/Mt)	271 ± 166	1349 ± 1912	472 ± 237	720 ± 721	301	496 ± 492
Yield value (U$S/ha)	3643 ± 3460	13821 ± 15701	6482 ± 7682	3801 ± 5480	773	3671 ± 5258
Protein content (g)*	0.53 ± 0.06	2.98 ± 7.12	6.49 ± 11.84	8.58 ± 11.53	34.6	6.11 ± 5.68
Fat content (g)*	0.20 ± 0.00	7.42 ± 15.79	5.03 ± 13.82	13.28 ± 25.35	24.2	4.77 ± 14.34
Carbohidrates content (g)*	6.20 ± 0.61	14.28 ± 5.08	15.45 ± 15.87	14.60 ± 4.84	27.2	36.07 ± 30.55

(1) Total values were summed across crops after averaging the reported value of the 2005-2007 years for each crop. (2) Net income was estimated from the metric tones (Mt) and the producer prize (U$S/Mt) reported in FAO Data bases. (3) Total nutritional contributions were estimated from total production (Mt) and (*) mean values per 100 g of edible part, assuming that the whole production is transformed to food. (4) Soybean excluded.

Current dependence (2005-2007)

Crops that do not depend on pollinators for production represented 36% of the harvested area, whereas 64% corresponded to crops with different levels of dependence on animal pollination. However, the harvested area was not homogeneously distributed among the different pollinator-dependence categories. Crops with essential and high dependence occupied together only 0.6% of the total harvested area, crops with modest dependence others than soybean occupied 9.4% whereas soybean alone occupied 52% (**Table 1A**). When taking into account only those crops cultivated for their seeds or fruits, the percent of area with pollinator dependent crops after removing soybean was 27%, which is slightly lower than that reported for Mexico (33%, Ashworth *et al.* 2009, **Table 1**). Finally, the area occupied by non dependent crops mostly reflected the cultivation of cereals like wheat and corn.

Considering production, we observed the opposite pattern. More than half (55.5%) of the total country's production (Mt) came from nondependent crops. Only 6.3% belonged to crops with high, essential and little dependency, and 38.2% corresponded to modest dependent crops (**Table 1A**), which was mainly the result of soybean production (34.7%). Despite essential, high and little dependent crops were on average slightly more productive (in Mt/ha) than nondependent crops (**Table 1B**), and almost five times more productive than soybean (i.e., one hectare cultivated with a essential, highly or little dependent crops produce almost five times the yield of an hectare cultivated with soybean) they contribute very little to the total production, because the area they occupy was orders of magnitude lower than that devoted to non-dependent crops or soybean.

Economically, pollinator dependent crops contributed together with 63% of the economic income derived from agriculture (**Table 1A**). Soybean alone represented the most valuable crop (39.7%), which was associated to the vast area occupied by this crop (**Table 1A**). Interestingly, high dependent crops had the highest production value (U$S/Mt), and yield value (U$S/ha) of all crop categories, either considering or not soybean (**Table 1B**). One hectare cultivated with a high pollinator dependent crop generated 2-4 times the income of one hectare cultivated with any other crop. These results agree with a recent economic valuation of pollination service to global agriculture that reported that on average, the value of a Mt of pollinator dependent crops was five times higher than a Mt of nondependent crops (Gallai *et al.* 2009).

In terms of nutritional contents, dependent crops had aggregately a larger nutritional content, in terms of proteins (80.2%) and fats (95.8%), while nondependent crops attained the majority of the carbohydrates (78.8%, **Table 1A**). When soybean is excluded, however, nondependent crops (in particular maize and wheat) followed by modestly dependent crops (specifically sunflower) are the major protein sources (75.6 and 18%, respectively). The exclusion of soybean for the fat sources, lead that modestly dependent crops accounted for 69.3% (mainly due to sunflower), followed 19.5% from non dependent crops (wheat, maize and oats, **Table 1A**, **Appendix 1**). Thus, because of the strong area dominance of two modestly dependent crops (soybean and sunflower) with high protein and fat contents, our results only partly agree with the generalization that the major caloric inputs in the human diet comes from a few staple foods with large world production for which animal pollination is irrelevant (Ghazoul 2005). This study represents a first step toward quantifying the quantitative contribution of pollinator dependent crops to nutrients provisioning. Future studies should refine this estimation by taking into account the proportion of total production that is converted to food for each crop.

On average, modestly dependent crops, including soybean bear the highest protein and fat content (**Table 1B**). The five top crops in terms of protein content were dependent crops (modestly dependent soybean and sunflower, little dependent groundnut and dry bean, and highly dependent almond). The crop with the highest fat content was the non dependent walnut, followed by five dependent crops (modestly dependent soybean and sunflower, little dependent ground nut, and highly dependent almond and avocado). Accordingly, the expected nutritional deficit in the absence of pollinators was higher for fat production (25%), followed by proteins (20%). Thus pollinators seem to be important to human nutrition (Steffan-Dewenter *et al.* 2005) by contributing to crops that in the case of Argentina are high in fat and protein content. Although our analysis is missing many other nutritional components like minerals, fiber and vitamins, to our knowledge this work represents the first attempt to take into account the nutritional quality of crops that rely in some extent on pollinators.

Temporal trend analysis

Overall, the total harvested area in Argentina has increased 2.2 times between 1961 and 2007. This increase has occurred mostly due to cultivation of crops with modest dependence on pollinators (**Fig. 2A**), whose expansion accelerated since the early nineties. This increase in relative and absolute harvested area of crops with modest pollinator dependence can be explained by the rapid expansion of the area devoted to soybean cultivation, whereas other crops did not change substantially during the same period (**Fig.**

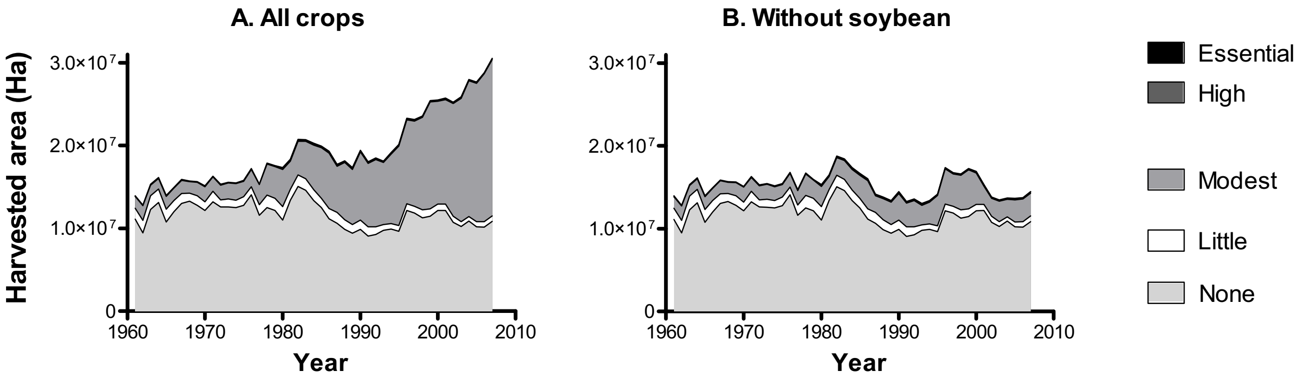

Fig. 2 Temporal trends in harvested area from 1961 to 2007 in Argentina, as reported by the FAO. Trends consider all crops (**A**) and excluding soybean, the crop that currently occupies the greatest area (**B**). Crops were grouped according to its pollinator dependence level (gray scale), based on the magnitude of the reduction in yield in the absence of pollinators.

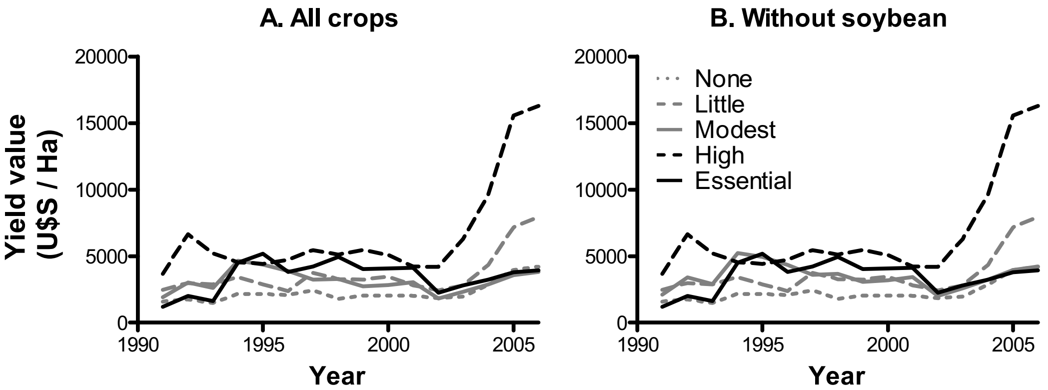

Fig. 3 Temporal trends in yield value (U$S/ha) from 1991 to 2006. Yield values are averaged among crops within each pollinator dependence category, considering all crops (**A**) and without soybean (**B**).

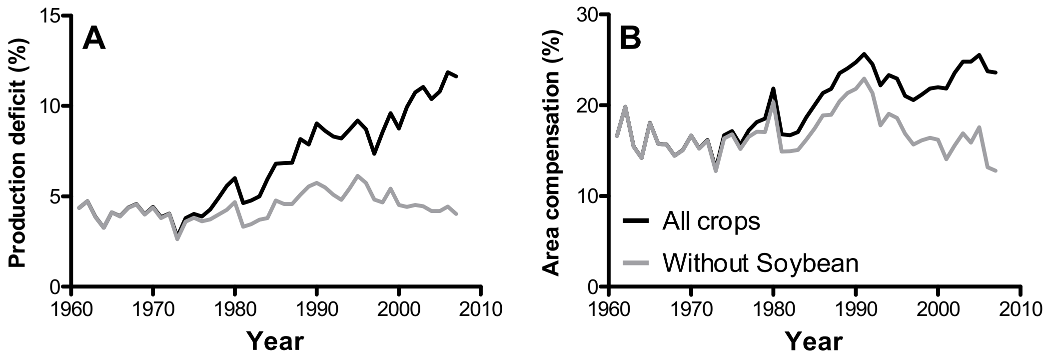

Fig. 4 Temporal trends in pollinator dependence of Argentinean agriculture. Trends estimated as production deficits in the absence of animal pollination (**A**), and surplus cultivated land required to compensate the deficits in crop production (**B**) for Argentina during 1961-2007. Area compensation was estimated assuming that the pollinator dependence of individual crops was represented by the mid-value of the range defining its dependence class (average-area compensation) and by the lower limit of the range (minimum-area compensation). Black lines show all crops, while gray lines represent all crops excluding soybean and considering soybean as non dependent (ND).

2B).

Crops in all dependence categories showed fluctuations in yield value since 1991; however, there is a constant increase in yield value since 2001-2002. This increase is considerable stronger for highly dependent crops than for the remaining categories (**Fig. 3A, 3B**). On the other hand, nondependent crops had low and stable yield values, which can be attributed to stable prizes for cereals (**Appendix 1**). The greatest value, among highly dependent crops, was achieved by pears, cherries and apples (**Appendix 1**).

During the study period the production deficit increased by a factor of three, from nearly 4% in 1961 to 12% in 2007 (**Fig. 4A**), which follows a more global trend of increasing pollinator dependency in agriculture. This figure is in accordance to the predicted production deficit for the developing countries for the last years of the first decade of the 2000, which was nearly 8% (Aizen *et al.* 2009a). This trend, however, can be mostly attributed to the soybean expansion because the exclusion of soybean resulted in a more or less constant mean of 4% of production deficit over the entire period (**Fig. 4A**).

The area to compensate for this production deficit also increased since 1970 (from 16 to 24%) albeit fluctuations (**Fig. 4B**). However, when soybean was excluded from the analysis, the opposite temporal trend emerges; between 1980 and 1990 the area of compensation increases from 16 to 20%, falling since then onward. Beyond the soybean effect, our results show that crop production will suffer substantial deficits in case of pollination shortage as a consequence of increasing dependence of Argentinean agriculture on pollinators, which, as proposed by Aizen *et al.* (2009a) will intensify the demand for agricultural land.

Regarding domesticated pollinators, the Argentinean stock of honey bees triplicated since 1961. Despite the per-

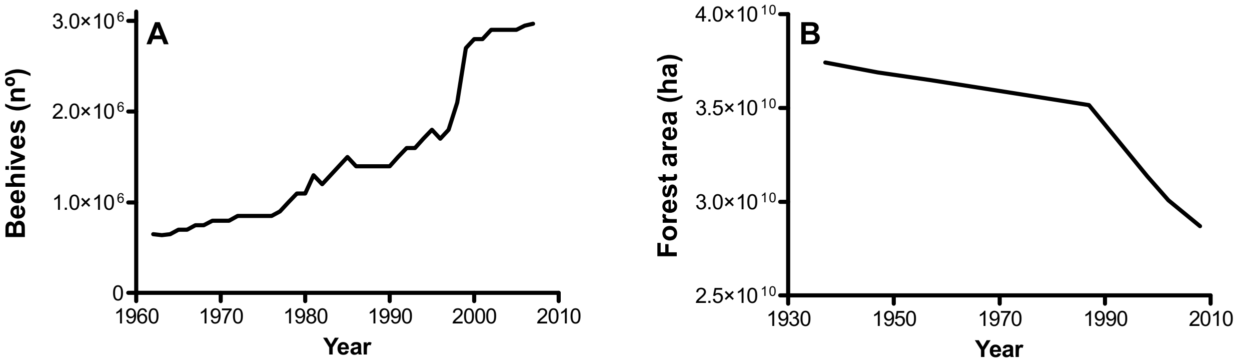

Fig. 5 Commercial beehives and deforestation trends in Argentina. (**A**) Number of commercial beehives in Argentina from 1961 to 2007, as reported by the FAO. (**B**) Deforestation levels from 1937 to 2008, adapted from the *2007 Report on Deforestation in Argentina*. Source: Secretariat of Environment and Sustainable Development of Argentina.

manent growth of the honeybee stock, which suffered only three minor drops (1982, 1986 and 1997), the more pronounced increase occurred between 1998 and 2001 (**Fig. 5A**). This exponential increase can not be interpreted as a response to an increasing demand of pollination services, because the only crop that increased in harvested area in a similar way during that time period was soybean, which in Argentina is produced without the use of managed honeybee colonies. The constant increase in the number of honey bees may be associated with an increase in the world-demand for honey (Aizen and Harder 2009). Argentina is today the second world honey producer (Bradbear 2008), and most of its honey production is exported. Additionally, honey-bee managing for pollination is not a common practice in the country.

On the other hand, at the country scale, native forests have retracted nearly $9 \cdot 10^9$ hectares from 1937 to 2007 (**Fig. 5B**). Native forests are the habitat of many pollinator species important for crops, as reflected by the augmented pollination of grapefruits in proximity of forest in NW Argentina (Chacoff *et al.* 2008). Therefore, this reduction might indicate a decline in wild pollinators population and in the availability of free pollinator services, in particular in subtropical regions of Argentina, where deforestation has been more pronounced (Gasparri and Grau 2009), in parallel with the expansion of soybean cultivation. These results support the findings of studies in several world regions reporting declines in the abundance and diversity of wild pollinators due to habitat destruction and environmental degradation (Ricketts *et al.* 2008; Winfree *et al.* 2009).

CONCLUSIONS

In Argentina, where agriculture represents the main income source for the country, there are many crops that benefit to different extent from animal pollination. Animal pollination is expected to improve yield of 72.5% of all cultivated crops. In terms of area, pollinator dependent crops occupy 64% of the total cultivated area and 45% of total production measured in metric tons. However, because most crops are not entirely dependent on animal pollination, the amount of production directly attributable to pollinators is smaller than the total estimations (**Fig. 4A**). In addition, these patterns are mostly driven by the strong dominance of soybean in Argentine agriculture.

On the other hand, the proportion of land occupied by high dependent crops in Argentina is remarkable low. An economic valuation of this situation would make us revise our policies, since these type of crops are, by far, those which produce the highest income per area. Given the high environmental heterogeneity existing in Argentina, active policies promoting cultivation of a diversity of valuable pollinator dependent crops is not only feasible but also desirable, particularly considering the pervasive expansion and increasing reliance on soybean.

Our current trend analysis suggests that agriculture is becoming more dependent on animal pollination, which implies that in the absence of pollinators there would be a 12% of deficit in production and an increase in 25% more cultivated area to cope with this deficit. This would probably increase the pressure to transform vast areas of forest, to produce crops, or import them from other areas (Deutsch and Folke 2005). The absence of pollinators might also change the composition of different nutrients in our diets, represented by a deficit of 20% in protein and 25% in fat; however, since a significant proportion of agriculture production is exported, or is not directly used as human food, it is difficult to estimate a realistic nutritional deficit.

Given the overall dominance of soybean for all study variables, many of the results, are highly influenced by the category of pollinator dependence assigned to soybean. Since the pollinator dependence might vary among different varieties cultivated in Argentina, we need more detailed estimations on the actual area cultivated and the degree of pollinator dependence of each variety to better understand the importance of pollinators for this currently dominant crop, to obtain a more accurate picture of the pollinator dependence of Argentinean agriculture.

Argentina has been losing original native forests at an alarming high rate, reaching one of the highest deforestation rates in South America (PNUMA-GEO 2003; Montenegro *et al.* 2004), mostly possibly due to the soybean crop expansion during the last decades. A recent National Forestry Law (Law 26331 Ley de Presupuestos mínimos de protectción ambiental de los Bosques Nativos) is precisely aimed at restricting deforestation in the long run. Therefore, management strategies for maintaining and/or enhancing crop yield should be oriented to ensure efficient and predictable pollination services. Several studies have demonstrated that the efficiency and stability of pollination services are directly related to pollinator diversity (Klein *et al.* 2003b; Kremen 2004; Greenleaf and Kremen 2006) and, thus, are indirectly related to preserving the area, structure, and composition of natural habitats.

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Appendix 1 List of crops classified according to pollinator dependency and FAO category. For each crop we reported the nutritional content, harvested area (ha), production (Mt), yield (Mt/ha), producer prize (U$S/Mt) and income (U$S/ha).

Crop species	Commodity FAO	Pollinator dependence	Dependence level	FAO crop categories	mean harvested area (ha 10^3, 2005-2007)	mean Mt/ha (2005-2007)
Aleurites fordii (1)	Tung nuts	increase	essential	oil bearing crop	33.00	1.09
Amygdalus communis (syn. *P. dulcis*)	Almonds, with shell	increase	high	nut	0.26	1.85
Arachis hypogaea	Groundnuts, with shell	increase	little	pulses	195.23	3.04
Brassica napus	Oilseeds, Nes	increase	modest	oil bearing crop		
Brassica napus	Rapeseed	increase	modest	oil bearing crop	10.72	2.43
Capsicum annuum, *C. fructescens*, *Pimenta dioica* (syn. *P. officinalis*, *P. dioica*)	Chillies and peppers, green	increase	little	spice	7.00	17.86
Carica papaya	Papayas	increase	little	fruit	0.16	13.21
Carthamus tinctorius	Safflower seed	increase	little	oil bearing crop	33.18	1.54
Citrullus lanatus	Watermelons	increase	essential	vegetable	9.16	13.72
Citrus aurantifolia, *C. aurantium*, *C. bergamia*, *C. grandis*, *C. limetta*, *C. limon*, *C. maxima*, *C. medica* (var. cedrata), *C. myrtifolia*, *C. paradisi*, *C. reticulata*, *C. sinensis*, *C. unshiu*, *Fortunella japonica*	Grapefruit (incl. pomelos)	increase	little	fruit	14.23	19.16
Citrus aurantifolia, *C. aurantium*, *C. bergamia*, *C. grandis*, *C. limetta*, *C. limon*, *C. maxima*, *C. medica* (var. cedrata), *C. myrtifolia*, *C. paradisi*, *C. reticulata*, *C. sinensis*, *C. unshiu*, *Fortunella japonica*	Lemons and limes	increase	little	fruit	47.00	31.88
Citrus aurantifolia, *C. aurantium*, *C. bergamia*, *C. grandis*, *C. limetta*, *C. limon*, *C. maxima*, *C. medica* (var. cedrata), *C. myrtifolia*, *C. paradisi*, *C. reticulata*, *C. sinensis*, *C. unshiu*, *Fortunella japonica*	Oranges	increase	little	fruit	61.33	14.44
Citrus aurantifolia, *C. aurantium*, *C. bergamia*, *C. grandis*, *C. limetta*, *C. limon*, *C. maxima*, *C. medica* (var. cedrata), *C. myrtifolia*, *C. paradisi*, *C. reticulata*, *C. sinensis*, *C. unshiu*, *Fortunella japonica*	Tangerines, mandarins, clementines	increase	little	fruit	31.00	14.52
Cucumis melo	Other melons (incl. cantaloupes)	increase	essential	vegetable	5.10	15.59
Cucurbita maxima, *C. mixta*, *C. moschata*, *C. pepo*	Pumpkins, squash and gourds	increase	essential	vegetable	20.33	14.56
Cydonia oblonga (2)	Quinces	increase	high	fruit	3.16	8.12
Ficus carica	Figs	increase	modest	fruit	0.26	3.30
Fragaria ssp.	Strawberries	increase	modest	fruit	0.94	9.38
Glycine max, *G. soja*	Soybeans	increase	modest	pulses	15,078.13	2.54
Gossypium hirsutum, *G. barbadense*, *G. arboreum*, *G. herbaceum*	Seed cotton	increase	modest	oil bearing crop	327.63	1.37
Helianthus annuus	Sunflower seed	increase	modest	oil bearing crop	2,382.33	1.60
Linum usitatissimum	Flax fibre and tow	increase	little	oil bearing crop	2.80	0.68
Linum usitatissimum	Linseed	increase	little	oil bearing crop	37.56	0.96
Lupinus angustifolius (3)	Lupins	increase	modest	pulses	0.09	1.41
Lycopersicon esculentum	Tomatoes	increase	little	vegetable	17.44	38.69
Malus domestica	Apples	increase	high	fruit	43.67	27.62
Mangifera indica	Mangoes, mangosteens, guavas	increase	high	fruit	0.25	7.44
Persea americana	Avocados	increase	high	fruit	0.55	6.23
Phaseolus spp. (*P. vulgaris*, *P. lunatus*, *P. angularis*, *P. aureus*, *P. mungo*, *P. coccineus*, *P. calcaratus*, *P. aconitifolius*, *P. acutifolius*	String beans	increase	little	vegetable	5.43	8.28
Prunus armeniaca	Apricots	increase	high	fruit	2.30	10.87
Prunus avium, *Prunus cerasus*	Cherries	increase	high	fruit	1.36	4.92
Prunus domestica, *P. spinosa*	Plums and sloes	increase	high	fruit	15.29	8.34
Prunus persica, *Persica laevis*	Peaches and nectarines	increase	high	fruit	25.67	10.62
Pyrus communis	Pears	increase	high	fruit	20.00	37.44
Vicia faba	Broad beans, horse beans, dry	increase	modest	pulses	1.67	8.98
Vigna spp., *V. unguiculata*, *V. subterranea* (syn. *Voandzeia subterranea*), *Phaseolus* spp.	Beans, green	increase	little	vegetable	0.66	6.20
Allium cepa, *A. ascalonicum*, *A. fistulosum*	Onions, dry	increase - seed production	no increase	vegetable	24.67	31.00
Allium sativum	Garlic	increase - breeding	no increase	vegetable	15.03	7.75
Ananas comosus	Pineapples	increase - breeding	no increase	fruit	0.17	18.61
Asparagus officinalis	Asparagus	increase - seed production	no increase	vegetable	1.79	3.91

Appendix 1 (Cont.)

Crop species	**Commodity FAO**	**Pollinator dependence**	**Dependence level**	**FAO crop categories**	**mean harvested area (ha 10^3, 2005-2007)**	**mean Mt/ha (2005-2007)**
Avena spp., mainly *Avena sativa*	Oats	no increase	no increase	cereal	171.75	1.32
Camellia sinensis (1)	Tea	increase - seed production	no increase	stimulant	37.45	1.81
Cicer arietinum	Chick peas	no increase	no increase	pulses	1.47	1.02
Cynara sp. (1)	Artichokes	increase - breeding	no increase	vegetable	4.63	18.99
Daucus carota	Carrots and turnips	increase -seed production	no increase	vegetable	9.60	23.96
Eleusine coracana, *Eragrostis abyssinica*, *Panicum miliaceum*, *Paspalum scrobiculatum*, *Pennisetum glaucum*, *Setaria italica*	Millet	no increase	no increase	cereal	9.79	1.66
Hordeum distichon, *H. hexastichon*, *H. vulgare*	Barley	no increase	no increase	cereal	347.86	2.57
Humulus lupulus (1)	Hops	no increase	no increase	stimulant	0.24	1.20
Ilex paraguayensis (4)	Mate	increase - seed production	no increase	stimulant	154.00	1.72
Ipomoea batatas	Sweet potatoes	increase - breeding	no increase	roots and tuber	23.87	15.92
Juglans regia (1)	Walnuts, with shell	no increase	no increase	nut	3.65	2.47
Lens esculenta	Lentils	no increase	no increase	pulses	1.60	1.56
Manihot esculenta, syn. *M. utilissima*, *M. palmata*	Cassava	increase - breeding	no increase	roots and tuber	71.57	2.52
Musa sapientum, *M. cavendishii*, *M. nana*, *M. paradisiaca*	Bananas	increase - breeding	no increase	fruit	8.60	20.93
Nicotiana tabacum (1)	Tobacco leaves	increase - seed production	no increase	stimulant	90.67	1.80
Olea europaea	Olives	no increase	no increase	oil bearing crop	39.00	3.97
Oryza ssp. (mainly *O. sativa*)	Rice, paddy	no increase	no increase	cereal	164.00	5.83
Phalaris canariensis (*)	Canary seed	no increase	no increase	cereal	12.41	1.33
Pisum sativum, *P. arvense*	Peas, dry	no increase	no increase	pulses	24.67	1.26
Pisum sativum, *P. arvense*	Peas, green	no increase	no increase	vegetable	12.61	2.02
Saccharum officinarum	Sugar cane	no increase	no increase	sugar crop	286.55	85.15
Secale cereale	Rye	no increase	no increase	cereal	35.48	2.59
Solanum tuberosum	Potatoes	increase - breeding	no increase	roots and tuber	66.33	26.96
Sorghum guineense, *S. vulgare*, *S. durra*	Sorghum	no increase	no increase	cereal	555.20	5.21
Triticum spp. (mainly *T. aestivum*, *T. durum*, *T. spelta*)	Wheat	no increase	no increase	cereal	5,324.24	2.36
Vitis vinifera	Grapes	no increase	no increase	fruit	216.94	13.04
Zea mays	Maize	no increase	no increase	cereal	2,689.56	7.62

* Wind pollinated cereal
* average values per 100 g of edible part
Sources of pollinator dependence data:
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Appendix 1 (Cont.)

Crop species	**mean Mt 10^3 (2005-2007)**	**mean U$S/Mt (2004-2006)**	**mean U$S/ha (2004-2006)**	**Net income (U$S)**	**Proteins (g)****	**Fats (g)****	**Carbo-hydrates (g)****
Aleurites fordii (1)	36.00	144.12	96.22	5.19			
Amygdalus communis (syn. *P. dulcis*)	0.49	914.76	1,743.97	0.45	23.20	45.8	22.8
Arachis hypogaea	601.15	528.09	1,484.84	317.46	33.20	44.3	11.1
Brassica napus	0.00	135.45					
Brassica napus	15.46	315.57	453.69	4.88			
Capsicum annuum, *C. fructescens*, *Pimenta dioica* (syn. *P. officinalis*, *P. dioica*)	126.00	516.72	8,702.83	65.11	1.50	0.5	7.7
Carica papaya	2.20	471.48	6,398.61	1.04	0.50	0.1	12.8
Carthamus tinctorius	28.90	300.94	239.49	8.70			
Citrullus lanatus	125.79	193.94	2,667.03	24.40	0.50	0.2	6.9
Citrus aurantifolia, *C. aurantium*, *C. bergamia*, *C. grandis*, *C. limetta*, *C. limon*, *C. maxima*, *C. medica* (var. cedrata), *C. myrtifolia*, *C. paradisi*, *C. reticulata*, *C. sinensis*, *C. unshiu*, *Fortunella japonica*	207.90	318.11	4,699.66	66.14	0.80	0.2	12.2
Citrus aurantifolia, *C. aurantium*, *C. bergamia*, *C. grandis*, *C. limetta*, *C. limon*, *C. maxima*, *C. medica* (var. cedrata), *C. myrtifolia*, *C. paradisi*, *C. reticulata*, *C. sinensis*, *C. unshiu*, *Fortunella japonica*	1,336.14	781.03	22,500.05	1,043.56	0.90	0.6	8.7
Citrus aurantifolia, *C. aurantium*, *C. bergamia*, *C. grandis*, *C. limetta*, *C. limon*, *C. maxima*, *C. medica* (var. cedrata), *C. myrtifolia*, *C. paradisi*, *C. reticulata*, *C. sinensis*, *C. unshiu*, *Fortunella japonica*	805.62	981.96	12,978.22	791.09	0.80	0.2	13.5
Citrus aurantifolia, *C. aurantium*, *C. bergamia*, *C. grandis*, *C. limetta*, *C. limon*, *C. maxima*, *C. medica* (var. cedrata), *C. myrtifolia*, *C. paradisi*, *C. reticulata*, *C. sinensis*, *C. unshiu*, *Fortunella japonica*	490.00	481.61	7,446.60	235.99	0.90	0.4	21.2
Cucumis melo	81.50	511.71	8,369.28	41.70	0.60	0.2	5.9
Cucurbita maxima, *C. mixta*, *C. moschata*, *C. pepo*	295.33	234.20	3,440.50	69.17	0.50	0.2	5.8
Cydonia oblonga (2)	26.22	313.65	2,576.99	8.22	0.30	0.1	13.9
Ficus carica	0.87	2,078.03	6,988.20	1.81	1.40	0.4	19.6
Fragaria ssp.	8.84	1,598.42	15,044.37	14.13	0.80	0.6	8.1
Glycine max, *G. soja*	41,422.37	300.78	772.75	12,458.88	34.60	24.2	27.2
Gossypium hirsutum, *G. barbadense*, *G. arboreum*, *G. herbaceum*	427.86	712.34	933.88	304.78			
Helianthus annuus	3,635.00	301.08	484.01	1,094.44	25.40	51.3	14.4
Linum usitatissimum	2.00	223.17	157.95	0.45			
Linum usitatissimum	41.26	361.06	378.44	14.90			
Lupinus angustifolius (3)	0.14	391.69	586.13	0.05			
Lycopersicon esculentum	675.00	558.10	21,834.38	376.72	0.90	0.4	4.6
Malus domestica	1,262.07	1,590.67	47,197.88	2,007.54	0.30	0.4	14.9
Mangifera indica	2.02	509.85	4,082.80	1.03	0.30	0.2	19.5
Persea americana	3.49	509.85	3,250.69	1.78	1.70	26.4	3.3
Phaseolus spp. (*P. vulgaris*, *P. lunatus*, *P. angularis*, *P. aureus*, *P. mungo*, *P. coccineus*, *P. calcaratus*, *P. aconitifolius*, *P. acutifolius*	45.25	299.91	2,501.86	13.57	1.50	0.8	4.3
Prunus armeniaca	25.23	1,149.76	12,884.22	29.01	1.00	0.1	12.9
Prunus avium, *Prunus cerasus*	6.75	6,682.54	33,519.99	45.11	1.10	0.5	14.8
Prunus domestica, *P. spinosa*	128.50	490.27	4,196.07	63.00	0.70	0.2	12.9
Prunus persica, *Persica laevis*	267.50	565.16	5,906.16	151.18	0.50	0.1	12
Pyrus communis	592.91	761.90	22,856.08	451.74	0.70	0.4	15.8
Vicia faba	15.23	232.52	2,119.39	3.54	6.70	0.8	16.3
Vigna spp., *V. unguiculata*, *V. subterranea* (syn. *Voandzeia subterranea*), *Phaseolus* spp.	4.15	81.32	523.86	0.34			
Allium cepa, *A. ascalonicum*, *A. fistulosum*	720.77	186.39	5,388.87	134.35	0.70	0.2	12.4
Allium sativum	130.65	1,410.03	12,621.39	184.22	4.40	0.2	20
Ananas comosus	3.23	471.48	9,078.32	1.52	0.40	0.2	13.7
Asparagus officinalis	7.10	1,732.11	6,826.60	12.30	2.20	0.2	3.9
Avena spp., mainly *Avena sativa*	281.62	325.18	552.37	91.58	15.60	7.8	62.5
Camellia sinensis (1)	70.67	77.44	146.59	5.47	8.00	4	71.4
Cicer arietinum	1.47	181.75	181.75	0.27	6.10	2.2	20.2
Cynara sp. (1)	88.67	1,270.79	24,310.66	112.68	2.80	0.2	12.4
Daucus carota	230.37	137.21	3,309.86	31.61	0.60	0.5	9.2
Eleusine coracana, *Eragrostis abyssinica*, *Panicum miliaceum*, *Paspalum scrobiculatum*, *Pennisetum glaucum*, *Setaria italica*	15.43	186.55	305.31	2.88			
Hordeum distichon, *H. hexastichon*, *H. vulgare*	1,187.40	194.85	657.68	231.36	10.20	1.5	74.9
Humulus lupulus (1)	0.29	275.98	332.57	0.08			
Ilex paraguayensis (4)	265.06	63.48	108.70	16.83			
Ipomoea batatas	350.00	253.74	3,818.99	88.81	1.10		19.8
Juglans regia (1)	9.50	967.49	2,493.57	9.19	13.90	67.4	13.2
Lens esculenta	2.32	859.28	1,326.18	1.99	20.80	0.8	64.8
Manihot esculenta, syn. *M. utilissima*, *M. palmata*	175.67				0.50	0.1	27.7
Musa sapientum, *M. cavendishii*, *M. nana*, *M. paradisiaca*	181.00	341.52	7,191.45	61.82	1.20	0.2	23
Nicotiana tabacum (1)	166.18	1,649.98	2,996.07	274.19			
Olea europaea	121.67	942.98	2,943.58	114.73	1.50	13.5	4
Oryza ssp. (mainly *O. sativa*)	1,074.84	234.94	1,523.14	252.53	6.90	0.2	79.2
Phalaris canariensis (*)	13.38	689.10	750.28	9.22			

Appendix 1 (Cont.)

Crop species	**mean Mt 10^3 (2005-2007)**	**mean U$S/Mt (2004-2006)**	**mean U$S/ha (2004-2006)**	**Net income (U$S)**	**Proteins (g)****	**Fats (g)****	**Carbohydrates (g)****
Pisum sativum, *P. arvense*	28.67	181.15	208.21	5.19	6.40	0.4	11.2
Pisum sativum, *P. arvense*	25.90	294.60	607.82	7.63	6.40	0.4	11.2
Saccharum officinarum	20,866.67	33.16	2,500.48	691.87			99.9
Secale cereale	47.50	323.23	391.25	15.35	12.10	1.7	73.4
Solanum tuberosum	1,894.10	174.61	4,993.59	330.74	2.70		18.8
Sorghum guineense, *S. vulgare*, *S. durra*	2,840.71	109.07	526.20	309.85			
Triticum spp. (mainly *T. aestivum*, *T. durum*, *T. spelta*)	13,708.22	236.18	613.99	3,237.61	12.40	2	69.8
Vitis vinifera	2,870.21	954.54	12,569.68	2,739.74	0.30	0.3	10.2
Zea mays	18,894.49	132.83	869.74	2,509.82	9.50	0.9	74.9

* Wind pollinated cereal
* average values per 100 g of edible part
Sources of pollinator dependence data:
(1) **Crane E, Walker P** (1984) Pollination directory of World crops. International Bee Research Association. UK.
(2) **Benedek P, Szabó T, Nyéki J** (2001) New results on the bee pollination of quince (*Cydonia oblonga* Mill.). *Acta Horticulturae* **561**, 243-248.
(3) **Manning R** (2006) Honeybee pollination: Technical data for potential honeybee-pollinated crops and orchards in Western Australia. In *Dept. of Agriculture of West Australia*, http://www.agric.wa.gov.au/content/aap/hbh/bulletin4298_index.htm. South Perth: Research Officer, Animal Research and Development Services.
(4) **Dolce NR, Rey HY** (2006) Cultivo *in vitro* de ápice de *Ilex paraguariensis*: efecto del pretratamiento con medios líquidos sobre la brotación. In: *Comunicaciones Científicas y Tecnológicas*, http://www.unne.edu.ar/Web/cyt/cyt2006/05-Agrarias/2006-A-026.pdf. Corrientes: Universidad Nacional de Corrientes.
Data on the remaining crops was obtained from **Klein A, Vaissiere B, Cane J, Steffan-Dewenter I, Cunningham S, Kremen C, Tscharntke T** (2007) Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society B: Biological Sciences* **274**, 303-313.

Appendix 2 Number of crops by pollinator dependency and FAO categories.

Pollinator dependence category*	**FAO crop category**										
	Cereal	**Roots, tuber**	**Stimulant**	**Sugar crop**	**Spice**	**Nut**	**Pulses**	**Oil-bearing crop**	**Vegetable**	**Fruit**	**Total**
Essential								1	2	1	4
High						1				9	10
Modest							3	4		2	9
Little					1		2	3	3	5	14
Increase - breeding		3							2	2	
Increase - seed production			3						3		
No increase	9		1	1		1	3	1	1	1	32
Total	9	3	4	1	1	2	8	9	11	20	68†

* Classes “no increase”, “increase - breeding” and “increase - seed production” = pollinators do not increase production; “little”= production reduction >0 but <10% without pollinators; “modest”= 10-40% reduction; “high”= 40-90% reduction; and “essential”= reduction >90%.
†Accumulated number of crops cultivated in Argentina between 1961 and 2007 following FAO data base.