Pollinator-dependent food production in Mexico

Lorena Ashworth a,b,*, Mauricio Quesada b, Alejandro Casas b, Ramiro Aguilar a,b, Ken Oyama b

a Instituto Multidisciplinario de Biología Vegetal, Universidad Nacional de Córdoba, CONICET, C.C. 495, (5000) Córdoba, Argentina
b Centro de Investigaciones en Ecosistemas – Universidad Nacional Autónoma de México, Campus Morelia, Apartado Postal 27-3 (Xangari), Morelia, Michoacán 58089, Mexico

ARTICLE INFO

Article history:
Received 12 August 2008
Received in revised form 29 December 2008
Accepted 9 January 2009
Available online 4 March 2009

Keywords:
Agriculture
Food diversity
Plant species domestication
Pollination service
Pollinator conservation

ABSTRACT

Animal pollination is one of the essential services provided by ecosystems to humans. In the face of a potential worldwide pollination crisis it is important to assess which countries may be more vulnerable in order to prioritize pollinator conservation efforts. The poverty level, the population density and the level of pollinator dependence for food provisioning are key aspects to identify vulnerable countries. We evaluate these aspects and determine the level of human food provisioning dependence on pollinators in Mexico, a developing and highly populated country. The diversity of crop species in Mexico is exceptionally high. Nearly 85% of fruit and/or seed consumed species depend to some degree on pollinators for productivity. Overall, pollinator-dependent crops generate larger income but cover a lower cultivated area and produce less volume compared to non-pollinator-dependent crops. Volume per unit area, however, as well as revenue per unit area, is much higher for pollinator-dependent crops. Native wild pollinators also play a key role in fruit or seed production of Mexican domesticated plant species and in the reproduction of many useful wild species. Thus, assuring free pollination services is particularly important in Mexico as the livelihood of a large proportion of the population exclusively and directly depends on ecosystem services for subsistence. Feasible conservation strategies involve the payment of environmental services to Ejidos (communal land tenure systems) making efforts to protect or restore plant resources and native pollinators, and the creation of new protected natural areas, which ensures food provision, mating and nesting sites for pollinators.

1. Introduction

Animal pollination is one of the essential services provided by ecosystems to humankind (Costanza et al., 1997; Allen-Wardell et al., 1998; Kearns et al., 1998; Ricketts et al., 2008). Animal pollinators are responsible for the sexual reproduction of more than 80% of the terrestrial vascular plants, including most crop species (Buchmann and Nabham, 1996). Therefore, by affecting sexual reproduction, pollinators play a key role in the maintenance of plant diversity in terms of species number, genetic variation and richness of functional groups (Costanza et al., 1997; Balvanera et al., 2001; Diaz et al., 2006; Fontaine et al., 2006), thus contributing ultimately to ecosystem services linked to plant diversity (Mittelbach et al., 2001; Diaz et al., 2006).

Currently, land-use change, biotic invasions, and climate change are factors that severely alter the diversity, structure, distribution, and functioning of ecosystems (Saunders et al., 1991; Sala et al., 2000). Land-use change, especially the destruction and fragmentation of habitats through the expansion of agricultural, pastureland, and cities boundaries, are the main driving forces of current biodiversity loss (Sala et al., 2000). The loss of biodiversity has, in turn, large impacts on ecosystem processes, ecosystem services, and therefore on human well-being (Diaz et al., 2006). The effects of anthropogenic activities on pollinator diversity have received much attention of research during the last decades (Buchmann and Nabham, 1996; Allen-Wardell et al., 1998; Richards, 2001; Vergara, 2002; Kevan, 2004; Ghazoul, 2005; Winfree et al., 2009). Local extinctions due to anthropogenic disturbances have been reported for some pollinator species of bees, hoverflies (Biesmeijer et al., 2006) and butterflies (Maes and VanDijk, 2001). Specifically, several examples of pollinator diversity and/or abundance decline have been documented to be caused by agriculture intensification (Kremen et al., 2002; Perfecto et al., 2003; Morandin and Winston, 2005; Harvey and Gonzalez-Villalobos, 2007; Winfree et al., 2009), habitat loss (Klein et al., 2003; Chacoff and Aizen, 2006; Ricketts et al., 2008; Winfree et al., 2009), alien species introduction (Morales and Maizen, 2002; Goulson, 2003) and pesticide use (Kevan, 1975; Kevan et al., 1997; Kearns et al., 1998; Parra-Tabla et al., 1998; Winfree et al., 2009).
Despite the evidence on pollinator losses, Ghazoul (2005) recently argued that the loss of certain pollinator species may not necessarily affect crop yields or wild fruit production in plant species that are wind or mostly self-pollinated or if they are insured against specific pollinator losses by a diverse array of pollinators. Nevertheless, the growing available evidence focused on crop species shows that not only self-incompatible crops but also self-compatible and even self-pollinated crops decrease their fruit/seed production and/or quality and crop stability when pollinator abundance and/or diversity are reduced (e.g. Calzoni and Speranza, 1998; Klein et al., 2003; Blanche and Cunningham, 2005; Morandin and Winston, 2005; Olschewski et al., 2006). Also, at the community level, it was experimentally demonstrated that seed production is negatively affected by decreased pollinator diversity (Fontaine et al., 2006). Therefore, in most cases documented decreases in pollinator diversity contribute to the loss of pollination service (e.g. Kremen et al., 2002; Ricketts et al., 2004; Larsen et al., 2005; but see Chacoff et al., 2008).

It was recently shown that human reliance on animal pollination food production in a global context is high: nearly 75% of the main crop species rely on pollinators for fruit or seed set (Klein et al., 2007). However, there is an opposite trend in terms of volume crop production: 60% of global food volume comes from 18 non-pollinator-dependent crop species and 35% from pollinator-dependent crops (5% unevaluated; Klein et al., 2007). Thus, although animal pollinators may be irrelevant for the few staple food crops producing the largest volume of food, they do play a key role in provisioning diversity of food crops and therefore supply vital nutrients for human subsistence (Klein et al., 2007; Gallai et al., 2008). Such diversification of human diet, which implies the consumption of many different fruits, seeds and vegetables, is essential for maintaining a healthy nutritional status, improving children’s growth rate, and consequently enhancing human well-being (WHO Report, 1990; MEA, 2005).

Pollination service decline can have short and long term consequences for human well-being. Short term consequences are basically related to decreased food provisioning (e.g. Kearns et al., 1998; Cincotta and Engelman, 2000; Steffan-Dewenter et al., 2005), whereas long term consequences are indirectly related to the cascading effects of plant diversity decrease (Cincotta and Engelman, 2000; Biesmeijer et al., 2006; Fontaine et al., 2006), affecting other ecosystem services such as air and water purification, nutrient cycling, disease control, among others (Müllerbach et al., 2001; MEA, 2005; Balvanera et al., 2006). Both short and long term consequences of pollination services decline will be severe for human population, especially among the subsistence farmers. The rural poor and traditional societies face the most serious and immediate risks as they exclusively and directly rely on wild pollinators for crop production, wild species exploitation and on other ecosystem services derived from plant diversity (Allen-Wardell et al., 1998; Cincotta and Engelman, 2000; MEA, 2005; Díaz et al., 2006). Overall, pollination service declines will be felt disproportionately by the world’s poor who cannot substitute free ecosystem services with alternative services purchased in the local and global market (Partap et al., 2001; MEA, 2005; Díaz et al., 2006).

In this context it is crucial to learn which countries are more vulnerable to the pollination crisis in order to prioritize pollinator conservation strategies. Simple and useful factors to identify vulnerable countries are the poverty level, the population density and the level of animal pollination dependence for food provisioning (MEA, 2005). Information of a country’s poverty level and population density is relatively easy to obtain from annual censuses; however, a great gap of information exists on the degree of animal pollination dependence for food production.

Mexico is a high-populated country (103 million people; INEGI, 2005) where nearly 50% of its population lies below the poverty line (Torres, 2001). The livelihoods of a large quantity of people rely strongly on the free provision of pollination services for food supply. In addition, Mexico is one of the world’s most important centers of plant domestication where populations of wild crop relatives and domesticated cultivars coexist (Harlan, 1975; Bye and Linares, 2000). Wild crop relatives represent crucial reservoirs of potentially transferable useful genes into cultivars to improve their quality and productivity (Smith et al., 1992; Maxted et al., 2007). In this regard, native pollinators may contribute to the maintenance of plant genetic resources through pollen flow between wild crop relatives and closely related cultivated plant populations (e.g. Elstrand et al., 1999; Papa and Gepts, 2003).

The aim of our study was to evaluate human food provisioning dependence on pollinators in Mexico. Our study was directed to analyze information on cultivated plant species, particularly those domesticated or semi-domesticated in Mexico, their different uses and parts used. Special attention was directed to plant species whose fruits or seeds are consumed by humans, considering information on the cultivated area, volume produced, yield crop value, and the level of pollinator dependence. Also, our study aimed to comparing those variables between pollinator-dependent and non-pollinator-dependent crop species in order to identify more productive and/or more rentable type of crops. Following the FAO crop categorization, we analyzed diversity of crop species and the level of pollinator dependence within the categories. We highlight the importance of pollinator-dependent crop species and of the use of wild plant species of Agavaceae and Cactaceae, two particularly representative plant families of Mexico. Finally, our study identifies gaps of information, and defines some management strategies for pollination services conservation in Mexico.

2. Methods

We generated a list of the currently cultivated plant species in Mexico from the National agricultural census conducted by SAGARPA (Secretaría de Agricultura, Ganadería y Pesca, 2002) and from other studies on ethnobotany and processes of domestication of Mexican plants (Harlan, 1975; Colunga et al., 1986; Hernández-Xolocotzi, 1993; Casas et al., 1996, 2001; Casas and Barbera, 2002). This list includes cultivated plant species used as food, forage, medicine, ornamental, textile, or as raw material for several industrial products. We identified crop species domesticated in Mexico and other plant species currently managed by Mexican people. Managed or semi-domesticated plant species are defined as wild populations subjected to some type of human practice without significant perturbations of their habitats and directed to maintain or increase in situ the availability of their useful products (Casas et al., 2007). We searched for the uses of domesticated and semi-domesticated plant species. In the case of plant species whose fruits or seeds are consumed by humans we searched for information (SAGARPA, 2002) on the cultivated area (ha), volume (metric tonnes, mt) produced and yield value (US$). We further classified these species as: cereals, fruits, nuts, oil bearing crops, pulses, spices, stimulants, and vegetables, following FAO crop categories (http://www.fao.org/waicent/faostat/agricult/). This categorization helps visualizing and comparing crops with different nutritional attributes; while all crops within a category can be taken as potential substitutes for one another, this is not possible between categories (e.g., a fruit cannot be substituted by a spices).

Information on the degree of animal pollinator dependence for fruit or seed production was obtained by searching the published literature of each plant species in electronic databases.
such as ISI web of science and Scopus. If information was not available, we contacted colleagues working with the species. When no source of information was available we used indirect means to distinguish pollinator-dependent crop species: plant species with complex, showy flowers and rewards were considered to be mainly animal pollinated. The list of currently useful wild Agavaceae and Cactaceae species was obtained from Gentry (1998) and Casas and Barbera (2002), respectively. When information was available, we tabulated the level of yield (fruit or seed set) dependence on pollinators following Klein’s et al. (2007) categorization: Essential: pollinator absence produce a reduction of >90% of crop production compared with pollinator presence, High: between 40% and 90% of reduction in absence of pollinators, Modest: between 10% and 40% of reduction and Little: 0–10% of reduction. Non-pollinator-dependent crop species were considered those cited in original papers as anemophilous, autonomous self-pollinated, parthenocarpic, or those classified by Klein et al. (2007) as No increase: no yield increase with animal-mediated pollination. We compared the relative production in terms of area and yield value between pollinator-dependent and non-pollinator-dependent crops with ANOVA after log-transforming the data to meet homogeneity assumptions. A similar analysis was conducted within each of the categories defined by FAO (fruits, nuts, oil bearing crops and pulses). We show back-transformed data on figures.

3. Results

3.1. Crop species

A total of 316 plant species were identified as commonly cultivated in Mexico: 236 of them used as human food (including beverages), and 80 species are cultivated for a variety of uses including textile, ornamental, fodder, medicinal, and for manufacturing industrial products (Fig. 1; Supplementary Table). Humans consume the fruits and/or seeds of 171 crop species and the vegetative parts of other 65 species. Nearly 85% of fruit or seed consumed species depend, to some degree, on pollinators for successful fruit/seed production, whereas nearly 15% of these crop species are non-pollinator-dependent (Fig. 1; Supplementary Table). From these 171 species, we assessed precise information on the degree of dependence on pollinators for 108 fruit or seed-producing crops. More than 60% of these crops fall within the Essential, High, and Modest dependence levels whereas 23% and 15% belong to the Little and No increase categories, respectively (Fig. 2a). For the remaining 63 fruit or seed-producing crop species we were only able to determine whether they are pollinator-dependent or non-pollinator-dependent by their flower morphologies and by using bibliographic information. Most of these species are pollinator-dependent, but the level of dependence is unknown (Fig. 2a).
Information on the cultivated area, total volume produced, and yield value was available for 70% (99 species) of pollinator-dependent and 85% (22 species) of non-pollinator-dependent crop species (Supplementary Table). In decreasing number of species, fruits, pulses and spices categories represent more than 70% of Mexican cultivated crop species whose fruits and seeds are human food (Fig. 2a). Within each FAO crop category, on average, 80% of crop species are pollinator dependent (Fig. 2a). All vegetables and stimulants are pollinator-dependent crops, whereas cereals are entirely non-pollinator-dependent crops (Fig. 2a). As expected, essential and high pollinator dependence yield production was found in most of the species within fruits, vegetables, and nuts crop categories (Fig. 2a).

At the country level, non-pollinator-dependent crops cover a much greater cultivated area than pollinator-dependent crops (Table 1). This greater area is mostly due to the traditional and particularly high incidence of wind-pollinated corn crops throughout Mexico (Table 2; Supplementary Table). Also, non-pollinator-
Table 1

Pollinator-dependent and non-pollinator-dependent crop species in Mexico. Absolute and relative values at the country level: cultivated area (ha 10^5); volume (metric tonnes 10^6); yield value (USS 10^8); volume per hectare (mean metric tonnes/ha) and yield value per Ha (mean USS/ha). Data from Mexican census SAGARPA (2002).

<table>
<thead>
<tr>
<th>Pollinator-dependent crops</th>
<th>Non-pollinator-dependent crops</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area (ha) 10^5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>49 (33%)</td>
<td>101 (67%)</td>
<td>150</td>
</tr>
<tr>
<td>Metric tonnes 10^6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>220 (38%)</td>
<td>355 (62%)</td>
<td>575</td>
</tr>
<tr>
<td>Yield value (USS) 10^8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 (54%)</td>
<td>43 (46%)</td>
<td>93</td>
</tr>
<tr>
<td>Metric tonnes/ha (±1 SD)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 ± 2.20</td>
<td>5.34 ± 2.18</td>
<td>16.34</td>
</tr>
<tr>
<td>USS/ha (±1 SD)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3480 ± 748</td>
<td>1732 ± 562</td>
<td>5212</td>
</tr>
</tbody>
</table>

Table 2

Pollinator-dependent (D) and non-pollinator-dependent (N) crop species in Mexico. Absolute and relative values for each FAO crop categories (fruits, nuts, oil bearing crops, pulses spices, stimulants, vegetables, cereals): cultivated area (ha 10^5); volume (metric tonnes 10^6); yield value (USS 10^8); volume per hectare (mean metric tonnes/ha) and yield value per hectare (mean USS/ha). Data from Mexican census SAGARPA (2002).

<table>
<thead>
<tr>
<th></th>
<th>Fruits</th>
<th>Nuts</th>
<th>Oil bearing</th>
<th>Pulses</th>
<th>Spices</th>
<th>Stimulants</th>
<th>Vegetables</th>
<th>Cereals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area (ha) 10^5</td>
<td>10.5</td>
<td>1.29</td>
<td>0.04</td>
<td>0.52</td>
<td>1.7</td>
<td>0.1</td>
<td>24.2</td>
<td>1.68</td>
</tr>
<tr>
<td>Metric tonnes 10^6</td>
<td>112</td>
<td>30</td>
<td>0.54</td>
<td>0.68</td>
<td>3.46</td>
<td>0.15</td>
<td>20.37</td>
<td>2.88</td>
</tr>
<tr>
<td>Yield value (USS) 10^8</td>
<td>19.35</td>
<td>6.78</td>
<td>0.06</td>
<td>1.14</td>
<td>0.3</td>
<td>0.06</td>
<td>9.33</td>
<td>1</td>
</tr>
</tbody>
</table>

4. Discussion

The diversity of crop species in Mexico is exceptionally high (316 species); overall this country has 20% more crop species than 15 countries of the European Union altogether (264 crop species; Williams, 1994, 2002). More than a half of the currently cultivated plant species in Mexico are crops whose fruits or seeds are consumed by humans and more than 80% of these crops depend in some degree on pollinators for efficient production. This high proportion of pollinator-dependent crops is similar to that observed at the continental (European Union 84%; Williams, 1994) and global scales (74% Klei et al., 2007). Most of food production volumes in Mexico, however, derive from non-pollinator-dependent crops, which are also used as medicine or ornamental plants (Supplementary Table). Most of these species are gathered in the wild (i.e., non-cultivated, Fig. 3). Similarly, from the native Agavaceae species that are commonly used or consumed, most of them are non-cultivated and gathered in the wild (Fig. 3).
implying that these species depend almost exclusively on wild Cactaceae and Agavaceae species are wild, non-cultivated, ically vital plant species. Remarkably, most of the widely used the level of pollinator dependence fruit production in these histor-
Council, 2007). Future research should be oriented to determine
within the fruits and spices categories (see alsoNational Research
found no information on the level of pollinator dependence for
are of land. Surprisingly, although most of crop species within the
level of dependence is still unknown (Fig. 2a). More work should be oriented in determining the depen-
dence level of this diverse category.
Mexico is one of the world’s most important centers of plant
domestication (Harlan, 1975; Bye and Linares, 2000), containing populations of many wild crop relatives, which represent import-
ant socio-economic resources. Wild crop relatives’ populations are reservoirs of likely useful genes; therefore, native pollinators can play a key role contributing to gene flow between cultivated species and their wild crop relatives. An example is the case of Mexican Cucurbita crops, where several species have been domestici-
ted and are basic subsistence crops for rural people (Lira, 1988). All Cucurbita species are highly dependent on animal pollination; thus native pollinators may be key actors in maintaining their ge-
etic diversity and production stability (Canto-Aguilar and Parra-
Tabla, 2000; Montes-Hernandez and Eguiarte, 2002). As for Cucur-
bita species, most of Mexican domesticated and semi-domesticated plant species produce edible fruits and seeds, and their successful production depends on pollinators. Because these native plant species share evolutionary history with their native pollinators through mutualistic relationships, it is reasonable to assume that native wild pollinators should achieve more efficient pollination through mutualistic relationships, it is reasonable to assume that native pollinators and plant genetic resources through the Ejidos system is a high priority for sustainable use of natural resources in Mexico. Ejidos (managed by ejidatarios) are one of the two types of communal land tenure systems in Mexico. Members of this
the much larger area of land assigned to these crops. When examining the relative volumes of food production per unit area, pollinator-dependent crops produce twice as much volume as non-pollinator-dependent crops. Thus, on average, less area of land is required for producing a metric tonne of a pollinator–dependent crop. In economic terms, pollinator-dependent crops in Mexico are more profitable: pollinator-dependent crops produce on average twice as much income per hectare as non-pollinator-dependent crops. A similar trend, with even larger differences, was recently found at the global scale (Gallai et al., 2008). Therefore, pollinators seem to be important in Mexico and globally, not only for contrib-
uting to human nutrient balance by providing food diversity, but also for maximizing food volume production and incomes per hect-
are of land. Surprisingly, although most of crop species within the
fruit category are pollinator dependent, there is a substantial num-
ber of species for which the level of dependence is still unknown (Fig. 2a). More work should be oriented in determining the depen-
dence level of this diverse category.

As far as we know, this is the first study to assess the pollination dependence of a country’s main crops production, thus compar-
tative analyses between countries are not possible at this time. Habit-

Fig. 3. Proportion of useful wild and cultivated species of Agavaceae and Cactaceae in Mexico.
system have the capacity to allocate and enforce their own rights to resources under a communal scheme. In 1992 the law was modified and today ejidatarios can claim individual parcels or transfer ownership of their lands (Waman, 2001). This change has increased risks on the country's ecosystems because the communal property rights system has acted as a protective shell for ecologically sound productive practices (Toledo, 1996; Alcorn and Toledo, 1998).

The conservation practices for native pollinators should be accompanied by new conceptions of land use management by local rural people, such as avoiding the use of pesticides, ceaseing the destruction of bat caves, and ensuring habitat connectivity for the pollinators (National Research Council, 2007). One possible mechanism to accomplish this strategy is to develop a program for the payment of environmental services to those Ejidos or individuals making efforts to protect or restore plant resources and native pollinators. The creation or improvement of protected natural areas will offer greater availability and diversity of food source for pollinators throughout the seasons, as well as mating and nesting sites, which will result in a higher diversity of native pollinators. This chain of events would improve pollination services in croplands and would guarantee the maintenance of plant diversity, contributing to the overall conservation of Mexico's biogeographical megadiversity and therefore to the conservation of worldwide ecosystem services.

Acknowledgments

Our research was supported by Grants from the ANPCyT, Argentina (PICT04-20341 and PICT06-0132), CONACYT, Mexico (Grants 2005-C01-51043 and 2005-C01 50863), and DGAPA at the Universidad Nacional Autónoma de México (UNAM; Grants IN221305, IN224108, and IN219608). Three anonymous referees made very constructive critiques and suggestions, all of which led to improvements in the final version of this manuscript. This research was conducted while L.A. and R.A. were Postdoctoral Associates at Centro de Investigaciones en Ecosistemas (CIEco, UNAM). L.A. and R.A. are now researchers from the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET). M.Q., A.C., and K.O. are researchers from CIEco, UNAM.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.bioccon.2009.01.016.

References


