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The Role of Pollinators in Maintaining the Biodiversity of Some Exotic Cultures

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Abstract
The fertilization process and the production of seeds are due to pollination, where every pollen grain from the male part of a plant is transferred to a female part of the plant. Most often, cross-pollination is carried out zoophilous, anemophilous or hydrophilous. The subject of the present paper is pollination, which has the following subtypes: entomophily, chiropterophily and ornithophily. The main entomophilyous pollinators are: bees, bumblebees, butterflies, wasps, flies and moths. Entomophily pollination is the most wide-spread and significant sub branch for agricultural and horticultural crops. It's analyzed the importance of pollinators within the agave (*Agave tequilana* F.A.C Weber) crop, durian (*Durio zibethinus* Murray), banana (*Musa spp.*), cocoa (*Theobroma cacao* L.) and vanilla (*Vanilla spp.*). Looking at different aspects such as the morphology and biology of the bloom or the particularities of adaptation to the environment, it can be concluded that for each of these cultivated species, the particularities of the pollination mechanism, evolved depending on the geographic area and the ecosystem. The aim of this work is to present the importance of pollinators, their role in maintaining genetic diversity in these exotic cultures of great economic and food importance, and the means by which they are protected for the benefits in plantations and industry.
Keywords: biodiversity, exotic cultures, food production, pollination

1. INTRODUCTION

The fertilization process and the production of seeds are possible through pollination mechanism, where every pollen grain from the male part of a plant is transferred to the female part of the plant. Pollen is either transferred by wind, by water or by animal pollinators (invertebrates and vertebrates). Self-pollination can be done by the transfer from anthers to the stigma of the same or different flower, while cross-pollination is between different genotypes of the same species. However, self-pollination can seldom be considered a dominant fertilization mechanism, due to long-term risks of inbreeding and loss of genetic diversity. Multiple advantages of insect pollination compared to wind pollination can be given, such as increased efficiency and maximized number of plant species, due to successful pollination [1,2].

A recent global estimate suggests that almost 90% of angiosperms depend on invertebrates or vertebrates pollination [3] while a significant part of gymnosperms are likely biotically pollinated [4].

In this review, firstly we introduce data of pollinators' diversity, followed by the importance of zoophilous pollinators, especially invertebrates. Finally, focuses on animal pollinators are investigated, particularly on pollinators of exotic cultures.

2. THE DIVERSITY OF POLLINATORS

Estimating the current diversity of pollinators is a subject to several disputes and is without a doubt problematic, considering the fact that public awareness concerning environmental issues is neglected and mostly giving false reports. The possibility of providing accurate estimates regarding the overall phylogenetic diversity and the number of species (mainly birds, mammals and bees) involved is achievable [5-7].

In Table 1 recent estimates of pollinator diversity on the basis of the cited reviews and studies are exemplified.

Table 1. Estimated pollinator classes for the world's wild flowering plants

Order	Categories of pollinators	Estimated taxa in the major groups	Estimated taxa of subgroups	References
Lepidoptera	Butterflies and moths	141.600		[7]
Heterocera	Moths		123.100	[8,9]
Rhopalocera	Butterflies		18.500	[8,9]
Coleoptera	Beetles	77.300		[7]
Cetoniinae	Flower chafers		4.000	[10]
Hymenoptera	Bees, wasps, ants	70.000		[7]
Anthophila	Bees		17.000	[8,9,11,12]
Pompilidae	Spider wasps		5.000	[13]
Vespoidae	Social wasps		5.000	[2,8]
Diptera	Flies	55.000		[7]
Syrphidae	Hoverflies		6.000	[8,9]
Bombyliidae	Bee flies		4.500	[8,9]
Thysanoptera	Thrips	1.500		[7,8]
Aves	Birds	1.089		[6,8]
Trochilidae	Hummingbirds		365	[8,9]
Meliphagidae	Honeyeaters		177	[8,9]
Nectariniidae	Sunbirds		124	[8,9]
Zosteropidae	White-eyes		100	[8,9]
Psittacidae	Lorikeets		53	[14]
Mammalia	Mammals	344		[6]
Chiroptera	Bats		236	[8]
Pteropus	Flying foxes		63	[15]
Nonflying mammals	Others		108	[8]
Total of major groups		346.833		

As described above, the most abundant group of pollinators is the *Lepidoptera* (particularly the moths), with more than 140.000 species which are likely to visit flowers, due to the functional mouthparts of the adult form. These pollinators are followed by the butterflies group as described by Wardhaugh (2015), which mostly feed on plant and flower exudates.

The next diverse group is occupied by *Coleoptera* and *Hymenoptera*, which comprises more than half of the above-described group pollinators. In the *Hymenoptera* group the bees are the most abundant subgroup. In terms of existing species, Kristensen et al. (2007) suggested that nearly half a million of lepidopteran species exist, primarily moths followed by butterflies. This suggests the lack of existing studies of these pollinator types.

These major orders are followed by *Diptera* which comprise the flies. The diversity of these pollinators might change in the future by the multiple studies conducted until now [18-20]. In the studies conducted by Orford et al. (2015) and Ollerton et al. (2009), they suggested the integration of non-syrphid *Diptera* in further research along with multiple studies regarding the diversity of this order, due to the fact that the knowledge in dipterans changed greatly in the course of 30 years of research. Further studies will provide significant insights into the mechanisms by which pollinators are attracted and trapped [19]. Larson et al. (2001) also stated that these syrphid flies are the most important flower pollinators. There are little studies regarding the relationship between the response to land-use change and species-level traits of vertebrate pollinators. In fact, feeding association to land use is an important trait in bird and bat land changes [20]. It has been demonstrated that nectarivorous bats respond positively to moderate levels of forest exploitation, compared to the insectivorous pollinators. A botanical survey conducted by Hodgkison revealed that in 1 ha of old-growth forest, 13.7% of the trees were partly dependent upon fruit bats pollination and seed dispersal [21].

Even though the remaining groups exhibit rather low diversity, this will most likely change in the future due to the fact that in certain regions they are ecologically important for diverse plants.

Diversity in the vertebrate groups is rather low compared to the invertebrates. The most diverse group is occupied by the order *Aves*, followed by *Chiroptera*. The latter is significantly important in terms of pollination, especially in tropical forests.

In the following section, we will detail recent studies on the pollination mode and the pollinated species.

1.1. *Zoophilous pollination*

Among insects, main anthophilous taxa comprise: butterflies, moths (*Lepidoptera*), beetles (*Coleoptera*), flies (*Diptera*), ants, bees (*Hymenoptera*), and thrips (*Thysanoptera*).

Cantharophilly is considered to be the oldest type of pollination. The beetle-pollinated flowers are usually off-white or greenish in color, large, with a dulled texture and a heavy scent similar to *Malus spp.* [22]. Beetles usually visit flowers for pollen, even though easily accessible nectar or nutritive tissues may be also consumed, considering the fact that ovaries usually are well protected from pollinators' biting mouthparts [1].

Beetles have been abundant since at least the Mesozoic, and it is likely that some of them have been flower visitors since the origin of the earliest angiosperms. For example, the current association of beetle pollination (cantharophilly) with primitive woody angiosperms (*Magnolia*) probably dates back to the evolutionary origins of both groups. Beetle pollination is considered to be the most primitive type of pollination by animals, and is not very important in cool temperate regions. It is most common in the moist tropics, and to a lesser degree in arid areas. Beetles constitute the largest order of insects, and some of this diversity is thought to have arisen through the same evolutionary radiation of flowers and insects during the Tertiary that led to the origin of the other major orders of flower-visiting insects. They are significantly important because they can deposit larger quantities of pollen on the stigmas and can travel for longer period, compared to their conspecifics [23].

The major beetle families that commonly or exclusively contain anthophilous species are the *Buprestidae* (jewel beetles), *Cantharidae* (soldier beetles), *Cerambycidae* (longicorn or longhorn beetles), *Cleridae* (checkered beetles), *Dermestidae*, Lycidae (net-winged beetles), *Melyridae* (soft-winged flower beetles), *Mordellidae* (tumbling flower beetles), *Nitidulidae* (sap beetles), and *Scarabaeidae* (scarabs) [1].

Myophily is the pollination made by flies which visit nectar-producing flowers, except for the hover flies (*Syrphidae*) which mainly feed on pollen rather than nectar. The flowers are radial or lantern shaped, with a dull texture and a greenish, purple or dark colored. The reproductive organs are usually hidden and the pollen grain shape similar to that of myophilous taxa [1,22].

As described in the previous section, there are two groups in order *Lepidoptera*, the butterflies and the moths. It is known that butterflies are diurnal and most moths are nocturnal. These pollinators are the most visible and recognized. Pollen is often involuntarily stuck to the proboscis or other body parts, such as the head, antennae, legs etc. [22].

Phalaenophily (moth pollination) is mostly associated with nocturnal light-colored flowers that have anthesis at night, whereas butterfly pollination (psychophily) is related to diurnal anthesis, but with more colored spectra, such as yellow, red and blue flowers [1]. Flowers pollinated by butterflies are usually open during the day and closed at night. They have a light scent and are brightly colored. The species included in this description are *Aster spp., Buddleia spp., Lonicera spp., Rubus spp., Silene and Solidago spp.* These species' flowers are tube-like shaped with hidden nectarines [22].

As described in the previous section, the members of order *Hymenoptera* visit flowers for nectar and pollen. Here, the *Agonidae* (fig wasps) are highly specialized pollinators of figs [24], whether ants are rather poor pollinators, known to visit on average only 20 plant species and rarely pollinating them [1,22,25].

While invertebrates are the most widespread pollinators, mammals, birds, and lizards have also been documented as pollinators [2]. These include pollinators like bats, which primarily visit flowers for nectar and pollen, as well as nonflying species like the Australian marsupials.

Although chiropterophily is geographically widespread, the other mammalian pollinators are more restricted and less known, together with lemurs in Madagascar and some species of Australian marsupials (sugar gliders, honey possums, marsupial mice).

Regarding ornithophily, multiple bird families are significantly important and primarily nectarivorous. There are six major families that include the hummingbirds (*Trochilidae*), honeyeaters (*Meliphagidae*), sunbirds (*Nectariniidae*), sugarbirds (*Promeropidae*), flowerpeckers (*Dicaeidae*), and Hawaiian honeycreepers (*Drepanididae*). Other families that include lower estimated taxa are *Thraupidae* (honeycreepers), *Zosteropidae* (whiteeyes), and *Psittacidae* (lorikeets) [2,26].

The last group is occupied by two families of bats which contain flower-visiting species: the leaf-nosed bats (*Phyllostomidae*) and the fruit bats (*Pteropidae*). The flowers that they visit are usually night-blooming and solely dependent on bat pollination [26].

Measuring pollinators' importance is time-consuming and difficult, especially in terms of global perspective [27,28]. All of the species presented above have the potential to be useful pollinators, each for their distinctive plant group.

2. TARGETED CROPS POLLINATORS

In this section we will discuss the pollinators' importance in pollinating the most cultivated crops, as well as the importance of exotic cultivated species in terms of industry, propagation and future perspectives. The main discussed species are represented by agave (*Agave tequilana* F.A.C Weber), durian (*Durio zibethinus* Murray), banana (*Musa spp.*), cocoa (*Theobroma cacao* L.) and vanilla (*Vanilla spp.*) (Figure 1).

Figure 1. Localization of the targeted crops on the world map; *Agave tequilana* F.A.C. Weber - Mexic; *Vanilla spp.* - South America /Mexic; *Theobroma cacao* L. - Africa; *Durio zibethinus* Murray - South Asia

2.1. *Agave tequilana* pollinators

The genus *Agave* is the most richest and diverse group of plants in Mexico. The locals developed several technologies in order to produce Agave-derived alcoholic beverages. Until now they produced different beverages, such as: tequila, bacanora, mezcal, pulque and raicilla. The evolution of *Agave* species is related to nectar-feeding bats, which play main roles as functional pollinators. Nowadays, the increasing demand of agave-derived products led to a reduction in species' genetic diversity and bat food availability. Management practices reduced their dependence on bat pollination focusing on replanting the fields with clonal shoots and harvesting the plants before flowering. This negatively affected both agaves and bats. In the study conducted by Trejo-Salazar et al. they collected data of the amount of Agave pollinated bats in order to evaluate their importance in plant diversity and bat nectar supply [29]. They concluded that allowing 5% of the plants in 1 ha to flower (222 individuals), then at least 89 bats could feed every night during flowering period. This means that if producers allow 5-10% of *A. tequilana* F.A.C. Weber. to flower, more than 2 million bats could feed every month.

Three main nectarivorous bats are known to pollinate the *Agave* species: *Choeronycteris mexicana* Tschudi, *Leptonycteris nivalis* Saussure and *L. yerbabuenae* Martínez & Villa-R. Multiple studies were conducted in order to describe and record the relationship between agaves and bats [29-33]. The nectarivorous pollinators are also integrated in the protection list by Mexican and US as Threatened and Endangered and in US Fish and Wildlife Service 2006, Diario Oficial de la Federación 2012 and IUCN 2016 [34-36].

Multiple publications include reports of bats visiting flowers of additional agave species through the presence of agave pollen on the body or feces of bats [32,37]. Successful pollination occurs at night due to the reduced time (few hours after dehiscence) of pollen germination [38]. Bats' nectar consumption changes in response to energy requirements and Agaves' sugar concentration [39]. Almost 50% of Mexic is covered in semiarid and dry zones and almost 6000 species (20%) of the Mexican flora are found. This highlights the importance of bats' conservation and plants' genetic diversity.

2.2. *Theobroma cacao* pollinators

The genus *Theobroma* is exclusively pollinated by ceratopogonid midges, such as *Forcipomyia spp.* Alongside, other insects from the order *Diptera* have been documented to visit the flowers of cocoa, such as *Cecidomyiidae* (gall midges), *Chironomidae* (non-biting midges), *Drosophilidae* (fruit flies), and *Psychodidae* (moth flies). Unfortunately, their contribution to pollination is scarce, studies confirming that microscopic observations of pollen grains were noted only on *Forcipomyia spp.* [40].

Overall, Cocoa (*Theobroma cacao* L.) is the third agricultural export commodity, after coffee and sugar. In terms of production, Côte d'Ivoire occupies the first position with 1000 t of raw cocoa beans/year [41].From a total of 4 million tons globally produced cocoa dry beans, 60% are obtained in Africa [42].

Nowadays multiple inadequate systems endanger cocoa yield. These comprise unshaded monocultures, which lead to soil erosion, increased disease and pest occurrence, water shortages and weed development [43-46]. Even though multiple studies demonstrated that cocoa is a shade-tolerant tree, increased productions have been observed in full sun-kept plants [47].

In multiple studies, researchers observed that along with sun exposure, precipitation was the main driver initiating flowering in the rainy season (April), compared to the dry season [48-50]. This aspect is in opposition to the weather conditions that affect *Forcipomyias'* visiting activity: rainy or cloudy weather decrease their activity compared to sunny weather [40].

Even though fluctuations of *Forcipomyia* population synchronizes with cocoa flowering peaks, only about 5-10% of flowers are pollinated [44]. Kaufmann (1975) reported that out of the 70 ceratopogonid species only eight are attracted to flowers and even fewer succeed in carrying pollen grains to ensure pollination. Regarding their breeding conditions in Côte d'Ivoire, they require moist and decaying organic material [52], but massive landscape degradation led to decreased breeding opportunities, excepting the vicinity of natural forests [51,53,54]. Cribbs' laboratory experiments showed that *F. townsvillensis* eggs did not develop without complete blood meals [55]. As future requirements, *Forcipomyia spp.* mass breeding and release is an important aspect considering that no attempts have been undertaken up to date. Also, many research gaps must be completed, such as improving pollination efficiency [56], pesticide control, enhancing ant pollination and improving crop systems (soil mulching, agroforestry).

2.3. *Durio zibethinus* pollinators

The genus *Durio* display floral characteristics that specifically attract large, nocturnal pollinators. Pollination is mainly realized by flying foxes (*Pteropus spp.*, *Acerodon spp., Desmalopex spp.*) the largest worldwide-known pteropodids. Investigations into pollination [57] are scarce compared to seed dispersal [58-60]. Rather than flying foxes, the former focused on the relationship between smaller, nectarivorous pteropodids and fruit economic importance [61,62].

As described above, chiropterophilous plants exhibit bat–flower syndrome, the best example being *Durio zibethinus* Murray, an economically and culturally important crop [62].

Pollination made by flying foxes or other pteropodids (*Eonycteris spelaea* Dobson) led farmers to have a negatively perception that they cause damage (flower consumption or destruction) and negatively affect fruit production [63,64]. Recent experiments contradicted these perceptions, cave nectar bats being major pollinators of *Durio spp*. In a study conducted in Sulawesi (Indonesia), Sheherazade et al. (2019) presented the first evidence that durian flowers are pollinated by bats. In his research the most frequent pollinator with the longest visits was *Eonycteris spelaea* Dobson, followed by *Pteropus alecto* Temminck (black flying fox) and *Acerodon celebensis* Petters (Sulawesi flying fox) [65]. Furthermore, they estimated that bat pollination services are valued at around ~$ 117/ha/fruiting season, signaling the importance of bat conservation in order to increase the production of durian. *A. celebensis* Petters is listed by the International Union for Conservation of Nature (IUCN) as vulnerable due to excessive hunting [36].

Until recently, no attempt has been made to assess the specific role of flying foxes in durian reproductive ecology [57]. Using camera traps, Aziz et al. (2017), demonstrated that flying foxes primarily visit durian flowers to feed on nectar, without causing damage.

As future requirements, the relationship between flying foxes and plant productivity is an important aspect to improve peoples' perception of why plant productivity and bat populations decline. The former aspect has been pointed out by few studies on bat hunting or legal killing as pests, as well as habitat changes [66-69].

2.4. *Musa spp.* pollinators

The genus *Musa* comprises all edible cultivars and is divided into four sections, *Australimusa*, *Callimusa*, *Eumusa* and *Rhodochlamys*. *Musa acuminata* Colla and *Musa balbisiana* Colla, comprised in the *Eumusa* section, are the main ancestors of the modern edible banana cultivars, [70].

Flower characteristics displayed by genus *Musa* attract nocturnal visitors [71-73]. As described in section 3.3 about *Durio* species, pollination is mainly realized by flying foxes, such as *Pteropus vampyrus* Linnaeus. Upright banana inflorescences are visited by birds, whereas pendant inflorescences are visited by bats [72]. Due to excessive hunting, the population decreased and it is listed by IUCN as near threatened [74]. Also, future habitat loss (increased deforestation rates) may be responsible for the extinction of 24% of *Pteropodidae* species. This situation determined the bat populations to relocate, which usually occurs due to food shortage and roosting sites [75,76]. For instance, influx of *P. scapulatus* Petters populations in eastern areas of Australia led to public health concerns.

In order to evaluate their foraging patterns and behavioral ecology, Hengjan et al. (2018) recorded two individuals of *Pteropus vampyrus* Linnaeus and several *Pteropus spp.* via satellite telemetry. The maximum distance between the bats' location release and their furthest roost was □100 km. Also, the number of bat-visits corresponded with the number of fruit dropping [77].

Pedrozo et al. (2018) studied the multiple approaching strategies of phyllostomid bat species on *Musa paradisiaca* L. inflorescences [78]. They discovered a novel feeding behavior in *Glossophaga spp.* Furthermore, the activity pattern of nectarivorous bats differed greatly compared to omnivorous bats. The former species' visiting peaks were at 21:00 and 23:30 hs and the latter species visiting peaks were at 23:45 and 02:30 hs.

The understanding of *Pteropodidae* foraging behavior and movement patterns is crucial for species' conservation, landscape management, disease prevention and minimized conflict between humans and flying foxes.

2.5. Vanilla spp. pollinators

Up to the 19th century it was believed that the genus *Vanilla* was pollinated by *Melipona beecheii* Bennet [79] and later by *Euglossa spp*. and *Eulaema spp* [80]. The smaller bee species *Euglossa* are pollinators of *Vanilla planifolia* Jacks. ex Andrews and *V. trigonocarpa* Hoehne, whereas the larger bee species *Eulaema* pollinate *V. bahiana* Hoehne (Brazil), *V. pompon* Schiede and *V. insignis* Ames (Mexico). A diversity of bees in genera *Euglossa*, *Exeretes* and *Melipona,* as well as hummingbirds were observed visiting *V. planifolia* Jacks. ex Andrews and *V. hartii* Rolfe (Mexico) [80,81].

Although Colombia is the most *Euglossa*-rich country, no definite registration for *Vanilla* pollinators has been made [82].

Even though *Vanilla* flowers present a physical-barrier to self-pollination, in several species (*V. bicolor* Lindl., *V. palmarum* (Salzm. ex Lindl.) Lindl. and *V. planifolia* Jacks. ex Andrews) the abundance of stigmatic fluid is able to reach the pollinia, facilitating pollination [80,83]. The decrease in euglossine bee populations is linked to *Vanilla* plantations, resulting in a loss of natural pollination.

Further analysis of pollination syndromes and floral anatomy are essential in order to develop more commercial cultivars and reduce the cultivation costs. Furthermore, effective cross-pollination is vital to maintain genetic variation and pollinator conservation.

3. CONCLUSIONS

Pollinator diversity and the role of pollination greatly progressed by the years, but further studies need to be conducted. Understanding the evolution of pollination system and ecology requires additional experimental and observational data, field monitoring and surveying on larger groups in order to overview pollinators' declines and diversity.

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