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Mini Review

POLLINATION ECOLOGY OF MEDICINAL PLANTS – WHAT WE MUST NOT NEGLECT FOR THEIR SUSTAINABLE USE

Kozuharova E.*

Medical University of Sofia, Faculty of Parmacy, Department of Pharmacognosy, Sofia 1000, Bulgaria

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Summary: The animal pollination is a regulating ecosystem service that underpins food production and its contribution to gene flows and restoration of ecosystems. Analyses based on the pollination syndrome of the medicinal plants revealed that about 85% of medicinal plants benefit from insect pollination. The decline of the bee population on a global scale has negative consequences for plants and all elements of the ecosystem. The link between pesticide use and the decline of pollinators is an important and debatable subject that is unlikely to find a solution soon. There is evidence that commercially managed honeybees and bumblebees can contribute to the decline of wild pollinators. In this review we summarise the conservation measures, which must be based on conservation of the mutualistic networks of plants and their pollinators. It is crucial that the seed propagating entomophilous medicinal plants are investigated with regard to their pollination for a sustainable use.

Keywords: Pollinators; bees; generalists; medicinal plants; sustainable development.

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INTRODUCTION

Sustainable development

The term sustainable development was coined the Brundtland Report. It is the organizing principle for meeting human development goals while at the same time sustaining the ability of natural systems to provide the natural resources and ecosystem services upon which the economy and society depend. Formerly known as the World Commission on Environment and Development (WCED), the mission of the Brundtland Commission (Chairperson of the Commission, Gro Harlem Brundtland) is to unite countries to pursue sustainable development together. The Commission was created by the UN in 1983 as an organization independent of the UN to focus on the problems of environment and development. At that time, the UN General Assembly realized that there was a considerable deterioration of the human environment and natural resources (Anonymous 1991).

Ecosystem services

Ecosystem services are many and varied benefits that humans freely gain from the natural environment

*Corresponding author: ina_kozuharova@yahoo.co.uk

and properly-functioning ecosystems. Such ecosystems include, for example, agroecosystems, forest ecosystems, grassland ecosystems and aquatic ecosystems. Collectively, these benefits are becoming known as 'ecosystem services', and are often integral to provisioning of clean drinking water, decomposition of wastes, and natural pollination of crops and other plants. The concept of ecosystem services dates back to the end of the last century (Westman 1977; Ehrlich and Ehrlich 1981; Mooney et al., 1997), but it became globally popular at the beginning of the Millennium (Ecosystem Millennium Assessment 2003). Ecosystem services are grouped into four main categories: provisions (food production, use of drinking water, etc.); regulation (climate control, diseases, etc.); support (pollination of crops, etc.); and culture (spiritual and recreational activities). The concept of ecosystem services attracts more and more attention as a way of guiding society towards environmentally friendly living systems in harmony with the environment (Fisher et al. 2010; Gómez-Baggethun et al., 2010). The challenge for ecosystem services is to make a reliable framework, easy to apply, scalable and sustainable (Daily et al., 2009). An increasing number of research universities and non-governmental organizations are involved in the development of ecosystem services assessment, metricification and value calculation programs, developing approaches and tools for sizing environmental interventions. Strategies are being developed to minimize the negative impact of environmental interventions and their conservation. The results are provided to policy makers to validate legal regulations that regulate and guarantee conservation (Thompson, 2011).

POLLINATION AS AN ECOSYSTEM SERVICE

Pollination (at least by animals) is an ecosystem service, and it is classified in that way in large status-and-trend reports such as the Millennium Ecosystem Assessment and (more recently) the IPBES Assessment Report on Pollinators, Pollination and Food Production, which describes animal pollination as "a regulating ecosystem service that underpins food production and its contribution to gene flows and restoration of ecosystems" (Ollerton, 2019). The Intergovernmental Science and Policy Platform on Biodiversity and Ecosystem Services consider pollination as an ecosystem service regulating food production to achieve good quality of life (Potts et al., 2016). The mapping and assessment of ecosystems and their services are a key to Action 5 on EU biodiversity in the 2020 Strategy. Mutualistic networks of plant-pollinators and conservation strategies associated with them are an important indicator of ecosystem services assessment (Maes et al., 2014).

"Pollination syndromes" are specific combinations of characters of the flowers and inflorescences (both referred to as blossoms), which are considered to have co-evolved in different lines of angiosperms as a response to various types of pollinating agents (Faegri and van der Pijl 1971; Proctor et al., 1996). The problem is that until recently the pollination syndromes have rarely been subjected to critical tests with regard to their frequency and predictive value (Ollerton et al., 2009; Armbruster et al., 2011). It has been tacitly assumed that (after more than 150 years of study) we clearly know all there is to know about them, even though there have been criticisms levelled at the syndromes since their inception, a fact that has been subsequently ignored (Waser et al., 2011). The most comprehensive test of the frequency and predictability of pollination syndromes that has been conducted to date (Ollerton et al., 2009) concluded that only a small proportion of the 352,000 species of flowering plants could be categorised into the pollination syndromes, as classically described. Likewise, they estimated that the predictive power of the pollination syndromes was about 30%. Other studies have shown that "secondary" flower visitors can be just as, or more, effective pollinators than the "primary" pollinator predicted by the syndromes and that the flower traits should be approached with a holistic point of view (Junker and Parachnowitsch, 2015).

The analysis of the rare plants with regard to the functional morphology of the blossoms of the plants in the red data book of Greece reveals that the plant vulnerability increases with floral complexity (Stefanaki et al., 2015). The reason is that the more complicated the flowers, the more specialized the pollinators that are needed (Stefanaki et al., 2015). This vulnerability of the flora is influenced by climate change and related to the global pollinator decline increases on the world scale and is documented by a number of researchers (Hegland et al., 2009; Potts et al., 2010; Bartomeus et al., 2011; González-Varo et al., 2013; Vanbergen 2013, Breeze et al., 2014; Miller-Struttmann et al., 2015; Lazaro et al., 2016).

Analyses based on the pollination syndrome of the medicinal plants revealed that about 85% of medicinal plants benefit from insect pollination. This predominant dependence of medicinal plants on insects for pollination is a hazard due to the global pollinator decline (Kozuharova et al., 2018).

POLLINATION ECOLOGY AND CO-EVOLUTIONARY RELATIONSHIPS

It is crucial that the seed propagating entomophilous medicinal plants be investigated with regard to their pollination for a sustainable use. The practical benefits relate to biodiversity conservation, because this is the key factor for sustainability (Kevan 1972, 1999; Kevan et al., 2003; Valdés, 2006).

The bees, both honeybees and wild bees, are the most effective pollinators, because they feed on pollen and nectar during both larval and imaginal stages. They are very active floral visitors due to this peculiarity. Some of the bees are specialists (Proctor et al., 1996). Bumblebees are generalists in their food choice. They are polylectic (Heinrich, 1976, 2004; Bauer, 1983; Heinrich and Esch, 1994; Goulson, 2006a, b; Goulson et al., 2006, 2008, 2013). The functional floral morphology is related to the bumblebee response (Laverty, 1994). The choice of food source corresponds to the bumblebee tongue length (Pekkarinen, 1979; Teras, 1985; Goulson and Darvill, 2004). Honeybees have higher flower constancy but they are also polylectic (Ohguchi, 1983; Davis, 1991; Jato et al., 1994). The food choice is determined by a number of stimuli which interact (Waser et al., 1986; Shivanna, 2014). Recent data show that bumblebees possess intellects similar to the high vertebrates and that they can learn, use tools and teach their experience to the others (Loukola, 2017).

The composition of the pollinating bee fauna is determined by the geographical distinction of the respective plant taxa or communities. Bumblebees are spread in Holarctica and penetrate the mountain regions southwards (Heinrich, 1979; Bingham and Orthner, 1998; Kawakita et al., 2004; Goulson, 2006; Pradervand et al., 2014). Mediterranean communities are pollinated mainly by social or non-social small bees (Petanidou, Vokou 1993, Bosch et al., 1997; Petanidou, Lamborn 2005, Potts et al., 2006; Dorchin et al., 2013).

Other important pollinators are some flies from the order Diptera (Faegri and van der Pijl 1971; Proctor et al., 1996; Savage, 2002).

MUTUALISTIC NETWORKS OF PLANTS - POLLINATORS AND CONSERVATION STRATEGIES

According to the modern environmental perceptions, organisms do not exist in a simple linear relationships. They participate in complicated interconnected networks. Knowing the mitualistic relationships in these networks and their principles is extremely important from a fundamental point of view. There is also a practical aspect related to conservation biology. Conservation of a single organism is not effective because it does not exist in isolation from other organisms. Therefore the conservation measures must be based on conservation of the mutualistic networks. Survival of the mutualsitic networks and the ecosystems in which they are located depends on maintaining and preserving the aggregate of the interacting taxa (Kearns et al., 1998; Bronstein et al., 2006; Memmott et al., 2007; Vázquez et al., 2009; Toby Kiers et al., 2010; Thébault and Fontaine, 2010; Fortuna et al., 2005, 2010; Hegland and Totland, 2012). The entomophilous medicinal plants propagating by seed depend on their pollinators and it is extremely important to know these mutualsitic networks. This knowledge is the base for developing successful conservation strategies.

The networks of relations between the plants and their pollinators are one of the most important forces generating and sustaining the biodiversity of terrestrial ecosystems (Olesen and Jordano, 2002; Vázquez and Aizen, 2004; Forup et al., 2008; Alarcón et al., 2008; Valdovinos et al., 2009; Bosch et al., 2009). The richer the components of a network, the greater is its stability. These networks are affected by anthropogenic impacts, the global reduction of pollinators and the reduction of biodiversity of local/aboriginal plant species, threatened by invasive species and other influences that endanger their dynamic equilibrium and stability (Bartomeus et al., 2008; Hegland et al., 2009; Vilà et al., 2009; Breeze et al., 2011). The species richness of pollinators is directly related to the species richness of plants and hence, to the sustainability of communities. Most pollinators that do not have economic value are actually essential to ensure the optimal functioning of ecosystems and they must not be underestimated (Senapathi et al., 2016).

The stability and sustainability of the plant-pollinator interactions are due to their plasticity (Ollerton et al., 2015).

Ecosystem services and related scientific research aim to underpin the natural resource management plans (Kremen, 2005). Recently, the concept of multi-networks (networks of networks) has been established and there is a consensus that despite difficulties and challenges due to the nature of the problems, strategies for managing complex systems of interacting nodes need to be developed (Bohan et al., 2016).

DECLINE OF THE BEE POPULATIONS – HONEYBEES VERSUS WILD BEES

The decline of the bee population on a global scale has negative consequences for plants and all elements of the ecosystem (Kevan 1999, Kevan and Phillips, 2001; Hegland et al., 2009; Potts et al., 2010; Bartomeus et al., 2011; González-Varo et al., 2013; Vanbergen et al., 2013; Miller-Struttmann et al., 2015). As the problem is of economic importance, it is widely publicized and most people have heard that pollinators are in trouble, and with them agricultural products worth $ 200 billion a year (FAO 2017). Pollinators are fundamental to preserving both biodiversity and agricultural productivity, but destruction of habitats, loss of flowering plants' resources, and increased use of pesticides (neonicotinoids etc.) causes a decline in their abundance and diversity (Potts et al., 2010, 2015; Goulson et al., 2015). A decline in pollinators in Northwestern Europe has been documented by Biesmeijer et al. (2006) and Carvalheiro et al. (2013). Ollerton and co-authors (Ollerton et al., 2014) confirm that 23 species of bees and wasps have disappeared in the UK. It has also been shown that the rate of disappearance is highly variable and raised the big question of whether these disappearances have stopped or will continue in the future (Ollerton et al., 2014). The link between pesticide use and the decline of pollinators is an important and debatable subject that is unlikely to find a solution soon. Neonicotinoids are systematically applied during treatment of seed crops and their negative effect on pollinators is expressed when nectar and pollen are collected. Neonicotinoids lead to a decline of the bee biodiversity (Stanley et al., 2015a, b; Goulson et al., 2015; Woodcock et al., 2016, 2017). The relative importance of pollinating honeybees, *Apis mellifera*, compared to other species, has been discussed for more than 20 years (Aebi et al., 2012; Ollerton et al., 2012). Scientific facts suggest that honeybees pollinate only about a third of the crops (Breeze et al., 2011). Also, only a small part of wild plants depend on honeybees for their pollination - wild bees, hover flies, butterflies and other pollinators are much more important than honeybees managed by humans and are collectively responsible for this pollination. No one denies that honeybees are important, but their role should not be exaggerated (Ollerton, 2012). Therefore, the role of wild bees in the pollination process should not be neglected. The flowering plants in general were described by Faegri and van der Pijl (1971) regarding their functional blossom morphology (flower or compact inflorescence morphology) and pollination syndromes as anemophilous (wind pollinated) and entomophilous (insect pollinated). Medicinal plants in particular are no different. The plants that require insect vectors for their pollen transport are divided into several pollination syndromes. The dish/bowl syndrome has free access to the nectar and pollen, and radial symmetry. Pollinators are a vast number of insects. Bees are no doubt the most effective pollinators but even some primitive pollinators like beetles can do the job. For example, *Adonis vernalis* is pollinated both by honeybees and beetles (Fig. 1). Also the quince flowers have easy access to the pollen and nectar and honeybees are common pollinators

Figure 1. Beetle *Oxytherea funesta* pollinating *Adonis vernalis.*

Figure 2. Honey bee pollinating the quince flowers (*Cydonia oblonga*).

(Fig. 2). The flowers of fireworth are attractive both for honeybees and bumblebees (Fig. 3). The bell syndrome has more or less hidden nectar, wide corolla tube, radial symmetry to slight zygomorphy. Pollination service can be delivered by short tongued insects like some bumblebees or flies, which match in size to enter the flower (Figs. 4, 5). The funnel syndrome is characterised by hidden nectar, narrow and deep corolla tube, radial symmetry to slight zygomorphy. Pollinators need to have long enough proboscises and pollination is specialized respectively. The sexual organs of flag syndrome are found in the lower part of the flower, which is zygomorphic and the pollen is deposited on the abdominal side of the insect (stemotribic pollination). Members of family Fabaceae, subfamily Faboideae are a good example (Fig. 6). The gullet syndrome is characterized by sexual organs restricted to the functionally upper side of the zygomorphic flower. The pollen is deposited on the dorsal side of the insect and upper part of the head, more or less hidden nectar (nototribic pollination). Labiate plants have this pollination syndrome (Fig. 7).

Although beekeepers currently lose around 40% of their colonies (such as Varroa marsh, inhospitable arable land, etc.), there is a clear tendency of an increase of up to 45% in the honey bee population in the world over the past half century (Aebi et al., 2012; Ollerton et al., 2012). Many of the wild bees, however, are in danger of extinction. There is an evidence that commercially managed honeybees and bumblebees can contribute to the decline of wild pollinators. Commercial apiculture often involves the maintenance of colonies at high density, which is a prerequisite for the rapid spread of diseases that pass to the wild bees too (Hatfield et al., 2012). There is a documented evidence of negative impacts that the commercially introduced *Bombus terrestris* has on natural ecosystems, which include: negative impact on local honeybee, competition for appropriate nesting sites, genetic contamination of local bee species, etc. (Dafni and Shmia, 1995; Dafni et al., 2010). The bees introduced by humans interact with the local wild bees and usually the impact is negative due to competitive relationships. This is particularly true in places where local flora is threatened by invasive plant species. All this requires very careful study and assessment of the massive spread of commercial bees (Goulson, 2003). There is a great deal of evidence for the negative impact of the commercial beekeeping on local bee fauna. It has been experimentally proven that commercially produced colonies of bumblebees spread infections and parasites, which are hazardous to the wild bees (Graystock et al., 2015, Goulson and Hughes, 2015). In other cases, the impact is neutral - although honeybees and wild bees are often expected to compete, no clear evidence is found in experimental conditions in Mediterranean plant communities for such interaction (Goras et al., 2016). Therefore, in order to establish sustainability of the pollination ecosystem service, it is necessary to achieve equilibrium between honeybees and wild bees (Morales et al., 2017).

A sustainable model involves regulation of the price of pesticides and the development of commercial bees in order to restore the wild bee populations even when they are threatened with extinction (Kleczkowski al., 2015).

Figure 3. Bumblebee worker pollinating *Epilobium angustifolium*.

Figure 4. Bumblebee queen pollinating *Crocus veluchensis.*

Figure 5. Hoverfly pollinating *Gentiana asclepiadea.*

Figure 6. Bumblebee worker pollinating *Atragalus dasyanthus.*

Figure 7. Bumblebee worker pollinating *Stachys officinalis.*

Recently the use of min robot-bees which pollinate crops has been brought forward as a solution of the pollination problem. The inapplicability of this idea has been convincingly demonstrated by Goulson (2017). In addition, it should be noted that, even though the technical solution would have some success with some food crops such as almonds, apples and others, for medicinal plants this is absolutely inapplicable. Functional flower morphology of various medicinal plants is complicated and programming of robots to perform the strictly specific pollination function of each individual plant species is impossible (Figs. 1-7, see above). Knowing the specific relationships between the medicinal plants and their pollinating agents is extremely important in order to design adequate strategies for their conservation.

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