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Exploring connections between pollinator health and human health

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Despite recent advances in understanding the role of biodiversity in ecosystem-service provision, the links between the health of ecosystem-service providers and human health remain more uncertain. During the past decade, an increasing number of studies have argued for the positive impacts of healthy pollinator communities (defined as functionally and genetically diverse species assemblages that are sustained over time) on human health. Here, we begin with a systematic review of these impacts, finding only two studies that concomitantly quantified aspects of pollinator health and human health. Next, we identify relevant research relating to four pathways linking pollinator health and human health: nutrition, medicine provisioning, mental health and environmental quality. These benefits are obtained through improved pollination of nutritious crops and an estimated approximately 28 000 animal-pollinated medicinal plants; the provisioning of pollinator-derived products such as honey; the maintenance of green spaces and biocultural landscapes that improve mental health; and cleaner air, water and food resulting from pollinator-centred initiatives to reduce agrochemical use. We suggest that pollinator diversity could be a proxy for the benefits that landscapes provide to human health.

This article is part of the theme issue 'Natural processes influencing pollinator health: from chemistry to landscapes'.

1. Introduction

There is increasing recognition of the reliance upon biodiversity to sustain and enhance human health [1–3]. Highly cited pioneering studies suggest that pollinators contribute to a more nutritious diet, as many of the most pollinator-dependent crops are also among the richest in micronutrients essential to human health [4–7]. Despite the large interest in this field, a systematic review of the scientific evidence for the links between pollinator health and human health has not yet been conducted.

More broadly, much of the existing research on how alterations in natural systems impact human health focuses on a single health outcome (e.g. one infectious disease) rather than focusing on the impacts of biodiversity across several dimensions of human health [3]. However, it is well known that the degradation of a particular ecosystem can result in multiple simultaneous impacts on human health. For example, deforestation can lead to both increased malaria exposure and loss of access to wild foods [3]. A similar multi-dimensional analysis has not been performed for pollinator loss.

Pollinator health can be defined as sustained pollinator functional and genetic diversity over time. Adopting such a community-level perspective is important for ecosystem management, as the health of one (e.g. invasive) species might sometimes be a poor indicator of nature's contributions to people [1]. There is a relationship of two-way benefit between pollinator diversity and the environment. Just as pollinators need resources provided by habitats to survive (e.g. food and shelter), these habitats rely on pollination services for plant reproduction. Pollinator habitats can comprise natural, semi-natural (e.g. hedgerows) and anthropic (e.g. crops) environments. The integrity and health of habitats are essential to mediate the human health benefits we derive from pollinators.

Here, we provide (i) the results of a systematic review of the studies directly linking pollinator health and human health and (ii) a literature review of several pathways that have been proposed to connect the multi-dimensional impacts of pollinator community health on human health. These pathways are nutrition, provision of medicines, mental health and environmental quality, all of which are important aspects for the prevention of diseases [8]. We recognize that mental and physical (nutrition, medicines and environmental quality) drivers of human health are interrelated (e.g. the same quality of food can have different health benefits, depending on the stress level of the person consuming it) [8], and our framework should be interpreted within this context. We did not review the links between pollinator health and income because the latter is a more indirect driver of human health [9], though they have been reviewed elsewhere, e.g. [10,11].

2. Systematic literature review: direct links between pollinator and human health

We first conducted a literature search to find studies that directly quantified the links between pollinator community health and human health. Using Google Scholar, we selected studies that contained the following pairs of phrases relating to both pollinator community health (i.e. health, diversity, habitat) and human health (i.e. health and nutrition): (i) 'pollinator health' AND 'human health', (ii) 'pollinator health' AND 'human nutrition', (iii) 'pollinator diversity' AND 'human health', (iv) 'pollinator diversity' AND 'human nutrition', (v) 'pollinator habitat' AND 'human health' and (vi) 'pollinator habitat' AND 'human nutrition'. The first 50 results of each search string were carefully reviewed for the presence of pollinator and human health measurements. The search in Google Scholar was performed during May 2021. In October 2021, we reinforced our search using Scopus and Web of Science databases to have a more systematic list of available articles. Scopus and Web of Science are only capable of searching titles, abstracts and keywords compared with the full-text search capability of Google Scholar, resulting in a very low or null count of results with the search terms previously used. Therefore, we also selected more inclusive alternatives, which consisted in (i) 'pollinat*' AND 'human health' and (ii) 'pollinat*' AND 'human nutrition'. All results (249 articles after excluding duplicates) were carefully reviewed for the presence of pollinators and human health measurements.

We found only two studies that quantified aspects of pollinator health and human health [4,7]. Most articles instead focused on the study of one concept (pollinator health or human health) while mentioning the possible implications on the other. For example, a large proportion of the studies explored how pollinator community health is affected by anthropogenic factors, hypothesizing the consequences that this could have on people's diets, but without quantifying such effects.

The two studies found in our systematic review address the impacts of removing pollinators on human nutrition through a modelling approach. Ellis *et al*. [4] combined data on crop pollination requirements, food nutrient densities and actual human diets to predict the effects of pollinator losses on the risk of nutrient deficiency in four developing countries and across five nutrients. Smith *et al*. [7] quantified nutrient composition and pollinator dependence for 224 foods in 156 countries to estimate how theoretical pollinator losses could reduce micronutrient and food intakes at the country level, while keeping a constant calorie intake with replacement by staple foods (the results of these two studies are described in §3).

Previous to these studies, there were very few mentions in the scientific literature of the links between human health and pollinators (figure 1), suggesting that this is a new area of research. Although only a handful of studies have explicitly connected pollinators and impacts to human health, many other studies have noted how pollinators may benefit human health. In the next paragraphs, we discuss these studies through a common framework identifying four pathways of benefits to human health (figure 2).

3. Nutrition: crops and pollinator-derived products

Pollinators support human nutrition primarily by improving yields of nutrient-rich crops (figure 2). Around 75% of the highest-production global food crop types (87 of 115) receive at least some benefit from animal pollination [12]. Though smaller by volume (approx. 35% of global agricultural production), pollinator-dependent crops make up many food groups that are healthy and micronutrient-rich, such as fruits, vegetables, legumes and nuts. It has been estimated that, in the absence of animal pollinators, global fruit supplies would fall by 22.9%, vegetables by 16.3% and nuts and seeds by 22.1% [7].

There is also evidence that pollination effects not only the quantity but also the nutritional quality of certain foods, such as apples [13], oilseed rape [14] and mandarin oranges [15]. One study found that the ratio of heart-healthier monounsaturated to less healthy polyunsaturated fatty acids increased in animal-pollinated almonds, potentially enhancing their known benefit to cardiovascular health [16].

Though pollinator-dependent foods comprise only a fraction of the agricultural production both in volume and calories, they have a disproportionate importance to dietary micronutrient supplies. Animal pollinators, through their direct action, are estimated to be responsible for only 2.5% of global calories via crops, while providing 7% of folate, 20% of vitamin C and 41% of vitamin A [5]. That global average also masks much spatial heterogeneity, with many regions shown to have higher dependencies on pollinators, as determined by finer-resolution geospatial crop datasets [6]. For instance, certain areas are estimated to have up to 50% of vitamin A provided by animal-pollinated crop sources, such as parts of Thailand, India, Mexico, USA,

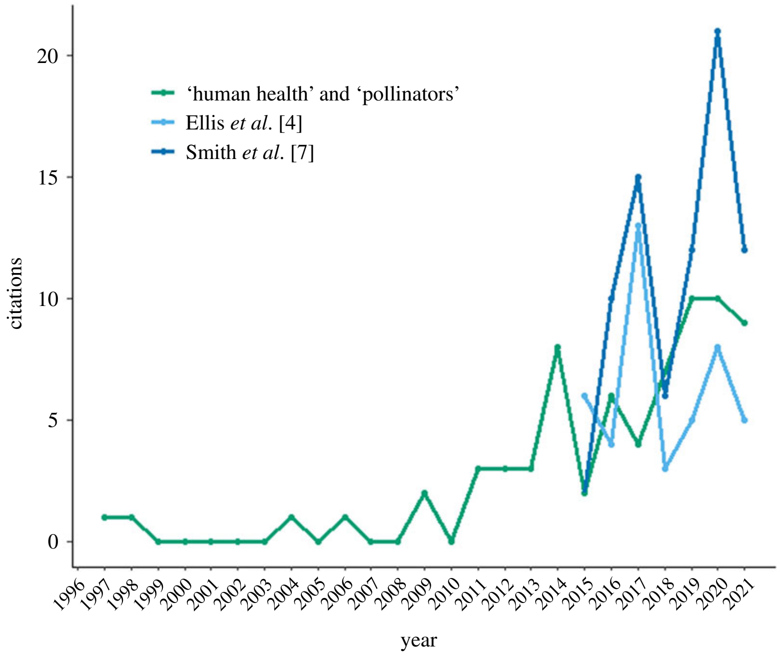

Figure 1. Number of citations per year (retrieved from the Scopus database) for each of the two papers found to analyse both pollinator health and human health in our systematic review. As a general baseline, we also show the number of publications using 'human health' and 'pollinators' in their title, abstract or keywords. Statements in the scientific literature connecting pollinators and human health become more common only since 2010. Despite the increased interest, only two papers accounted for the relationship between pollinator and human health (both published in 2015). (Online version in colour.)

Romania, Iran, Australia and Argentina, as well as 12–15% pollinator dependence for folate and iron in areas of China, Central African Republic, South Africa, Mexico, Brazil (iron only) and Southeast Asia (folate only). Indeed, a study in South Korea found that the share of the total production accounted for by pollinator-dependent crops was 50% for vitamin C, 40% for vitamin E, 37% for vitamin A, 33% for copper, 37% for iron, 36% for potassium, 28% for calcium and 27% for folate [17]. More importantly, there exists a spatial correlation between regions most reliant on animal pollination of crops for vitamin A and iron supplies and those most likely to suffer from deficiencies of those nutrients, with micronutrient deficiencies three times more likely in the highest pollination-dependent areas [6]. This relationship highlights an urgent need to link pollinator conservation and health in vulnerable regions.

Approaching the same question from another direction, dietary surveys in low-income countries have also revealed a significant reliance on pollinated foods for micronutrient supplies. One study, using 24-hour dietary recall data for children under 3 from districts in Bangladesh, Mozambique, Uganda and Zambia, found that 33–47% of total vitamin A intake was directly provided by animal pollinators, as well as 18–22% of folate, 19–20% of iron and 15–17% of zinc [4]. A second study that focused on five African countries (Ethiopia, Malawi, Nigeria, Tanzania and Uganda) using nationally representative household-level data found that, when looking solely at the crops grown and consumed by smallholder farm households, 43% of those calories were provided by foods that benefited from animal pollination to some degree, as well as 42% of riboflavin, 48% of protein, 60% of niacin, 75% of folate and 98% of both vitamins A and C [18]. Furthermore, this study showed that the nutritional reliance on pollinator-dependent subsistence foods was greater in poorer female-headed households, placing these already strained farming households at greater risk from pollinator declines. This is in addition to poorer households' reduced intake of animal source foods compared with nearby wealthier households, an effect especially pronounced in low-income countries [19], which increases vulnerable households' nutritional exposure to variations in crop production, including pollinated crops. Of course, the importance of protecting local pollinator communities to improve local diets only holds if consumed pollinated foods are grown nearby.

Some studies have also gone further to simulate how full losses of pollinators could theoretically translate into higher rates of nutritional deficiency, with one study also quantifying potential consequences for mortality and morbidity. Among children under 3 in certain districts in four low-income countries (Bangladesh, Mozambique, Uganda and Zambia), the risk of micronutrient deficiency could increase between 0% and 56% if pollinators were lost, although those values omit large populations already deficient that would become more so [4]. The second, a global modelling study, estimated that a total loss of pollinators could place an additional 71 million people at risk for vitamin A deficiency (95% uncertainty interval: 41–262 million), and 173 million people (134–225 million) at new risk of folate deficiency, in addition to the 2.2 billion people already vitamin A deficient and 1.2 billion folate deficient whose deficiencies would presumably worsen [7]. Pollinator-improved crops (particularly fruits, vegetables and nuts) safeguard health not only by providing critical micronutrients but also by preventing increasingly prevalent non-communicable diseases like heart disease, stroke and some types of cancer. When these health benefits are included in modelling studies, investigators find that total removal of pollinators could increase annual global mortality by 2.7% or 1.42 million deaths and life-years lost by 1.1% or 27 million per year [7].

In addition to the role of pollinators in supporting agriculture, there is also widespread consumption of bee

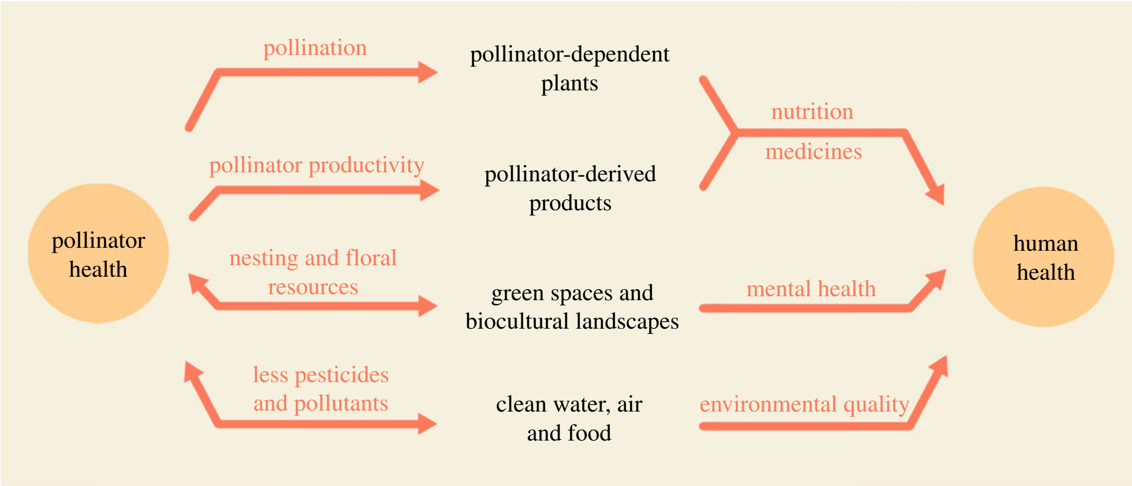

Figure 2. Pollinators contribute to human health through nutrition, medicine provisioning, mental health and environmental quality. These benefits are mediated by healthy (i.e. functionally and genetically diverse) pollinator communities through pollination of nutritious crops and medicinal plants, pollinator-derived products, green spaces and biocultural landscapes associated with pollinator habitats and clean air, water and food associated with actions to reduce pesticides and pollutants. (Online version in colour.)

products as food: primarily honey, but also propolis, royal jelly and pollen, among others. For nutrition, however, no bee product can be considered a significant contributor to global diets [20]. Instead, they play a more important role in many traditional medical systems, discussed in more detail in §4.

4. Medicines: pollinator-derived products and medicinal plants

Pollinators have an important and often overlooked role in the provisioning of medicines to support human health. The role of animal pollination in supporting human medicine is explored in the following two subsections: (a) direct, through the creation of medicinal pollinator-derived products such as honey and propolis [21] and (b) indirect, through the pollination of medicinal plants (figure 2). Pollinator declines and the associated loss of pollination services put human health at risk by reducing the quantity and quality of pollinator-derived medicinal products and threatening the supply of medicines from pollinator-dependent medicinal plants. Rural populations in low-income countries will be most severely affected as they often lack access to modern synthesized medicines; thus, their dependence on these traditional plant- and pollinator-derived medicines is greatest [22].

(a) Pollinator-derived products

The use of bee-derived products in human medicine dates back thousands of years and their role remains important today in both traditional and modern medicine [21]. Through selective foraging on floral and extra-floral products, bees sequester a range of plant-derived secondary compounds that provide anti-pathogenic properties, protecting them and their offspring against disease [23]. These secondary compounds are present in a range of different bee products including honey, propolis, bee venom, wax, bee pollen and royal jelly, all of which are co-opted by humans for medicinal purposes. Although these products are primarily derived from honeybees (*Apis* spp.), the use of stingless bee products is also widespread in traditional medicine [24]. The active organic compounds within bee products include various flavonoids, proteins, sugars, amino acids, enzymes, vitamins and minerals that confer a range of medicinal properties including anti-bacterial, anti-fungal, anti-viral, antioxidant and even anti-cancer effects (reviewed in [21]). For example, their effectiveness has been demonstrated in the treatment of the Herpes simplex virus [25], various respiratory conditions [26] and even cancer cells [27]. Their anti-bacterial properties make them effective in wound dressings [28] and give them promise in the fight against antibiotic-resistant strains of bacteria, including methicillin-resistant *Staphylococcus aureus* [29]. Furthermore, honey has been shown to be efficacious in the treatment of more routine but widespread conditions such as cough in children [30] and the topical treatment for wounds [31].

(b) Pollinator-dependent medicinal plants

An estimated 80% of the world's population rely on herbal (plant-based) medicine for some part of their primary healthcare, and its use is rapidly growing in both lower and higher income countries [32]. An estimated 33 443 plant species are currently recorded as being of medicinal use, of which 32 155 (96%) are flowering plants [33]. The global reliance of medicinal plants on animal pollination has not been systematically assessed (figure 3), but given that an estimated 87.5% of flowering plants are animal pollinated [34], we might expect something in the region of approximately 28 000 medicinal plants (84%) to benefit from animal pollination. This is likely to represent a conservative estimate, given that the two most important medicinal plant families (Fabaceae and Lamiaceae), which collectively make up 25% of all medicinal plants [33], are considered strongly entomophilous. The pollinator dependence of a medicinal product is influenced by two main factors: the pollinator dependence of the plant that provides it, and the part of the plant that is used (e.g. fruits, leaves or roots). In an extreme case such as *Argania spinosa* (Argan), in which the fruits of the plant are used for medicine and the fruit development relies on cross-pollination [35], the supply of the medicinal product is directly dependent on animal pollinators (figure 3). A study in the Nilgiri Biosphere Reserve in India found that

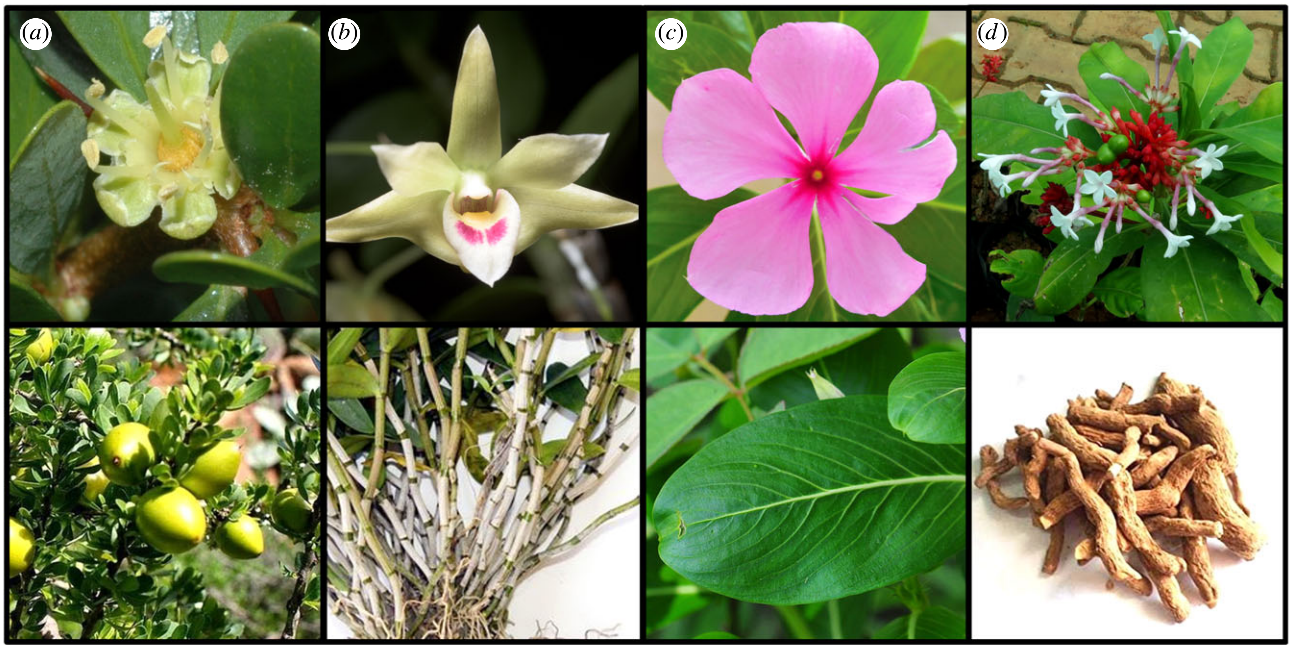

Figure 3. The flowers (top) and medicinal products (bottom) of four pollinator-dependent medicinal plants: (*a*) *Argania spinosa* whose highly pollinator-dependent fruits and seeds are used to make argan oil; (*b*) *Dendrobium catenatum*—an orchid whose medicinal leaves and stem are widely cultivated in East Asia, requiring cross-pollination to produce new seed; (*c*) *Catharanthus roseus*—the Madagascar periwinkle that benefits from pollination by moths and butterflies to produce viable seed for commercial production of its leaves, which are a major source of chemotherapy drugs; and (*d*) *Rauvolfia serpentina*—a pollinator-dependent shrub whose roots are widely used in South and Southeast Asia for treating conditions such as hypertension. Very little is known about the pollination ecology of these economically and medicinally important plants, despite the role that pollination management could play in boosting their production. Even less is known about the other *ca* 28 000 medicinal plants that are predicted to benefit from animal pollination. Images: Diversity of Life, Alchetron & Wikimedia Commons. (Online version in colour.)

this may be the case for up to 40% of wild-harvested medicinal products [36]. However, even when the product itself is not dependent on animal pollination, successful propagation of the plant may still depend upon pollinators. For example, leaves of the Madagascar periwinkle *Catharanthus roseus* (figure 3) are a major source of the chemotherapy medications vinblastine and vincristine [37], and although leaves are not pollinator-dependent, commercial propagation of the plant still relies upon seed production, which requires cross-pollination by butterflies and moths [38]. The same is true for the medicinal orchid *Dendrobium catenatum* (figure 3), which is hand-pollinated in commercial production due to a lack of animal pollinators [39]. Many medicinal plants are not cultivated at all and are instead harvested from the wild, in which case the long-term persistence and genetic viability of their populations may be dependent on animal pollinators, even if the short-term production of the medicinal product is not. For example, the continued persistence of the wild-harvested medicinal plant *Minthostachys verticillate*—one of the most important in Andean folk medicine—was found to be entirely dependent upon animal pollination [40]. Understanding and managing pollination services offers the potential to safeguard and even enhance the supply of cultivated and wild-harvested herbal medicines, with positive outcomes for human health.

5. Green spaces and biocultural landscapes supporting mental health

Pollinator community health is also related to human health through the availability and sustenance of green spaces and biocultural landscapes (figure 2). Collectively, these vegetated features benefit pollinator community health by providing food and nesting resources and favourable abiotic conditions in urban and rural scenarios [41–43]. In turn, pollinators enrich our interactions with nature and allow or improve the reproduction of many plant species, especially those with flowers aesthetically valued by people [41,44]. People benefit directly from these environments in different ways, from simply resting and relaxing, to exploiting them as catalysers or substrates to socialize, exercise or cultivate, among other activities that promote health through multiple mechanisms [45].

Since most people live in towns and cities, urban green spaces are key points of influence for pollinator conservation but also provide diverse health benefits [46]. Private urban gardens, and urban agriculture in general, constitute conspicuous landscape features directly sustained by healthy human behaviours [47], hosting a high diversity of vegetation that depends on the action of pollinators to produce seeds or fruits [41,43]. Some benefits of urban agriculture include promoting therapeutic and recreational activities, social inclusion, increase in livability, awareness of good dietary habits and food commerce and education [47]. Urban green public spaces are also important for human health, reducing emotional and physiological stress by the contact with nature and by promoting physical activity and socialization [48–50]. Several studies show that the high vegetation and structural diversity of green public spaces boost their value not only for pollinators (e.g. [42]) but also for people, as we seem to be attracted to variety [51–53]. This variety exists not only in the form of vegetation as the mediator between pollinators and human health, but also through the sight of charismatic pollinator fauna, like butterflies, hummingbirds and large bees, directly adding aesthetic and experiential value to green environments [54–56]. Biocultural landscapes add spiritual, historical and cultural dimensions of mental health to the previously described features and promote the conservation of ecosystems with their dynamic human–nature interactions [57]. Many of these are highly diverse and structurally complex vegetated environments [57] that demand animal pollination to great extents [44].

The importance of the accessibility to green spaces is exemplified by the finding that differences between urban and rural self-perceived health are, to a large extent, explained by the density of green spaces, which makes it a better indicator of health status than direct measures of urbanity (i.e. address density; [48]). Both cross-sectional and longitudinal studies suggest strong inverse associations between all-cause mortality and proximity to green spaces, and multiple mechanisms and mediators behind this connection have been discussed [45,58]. These may include promoting physical activity (e.g. for leisure or active transportation), stress reduction and improved relaxation and restoration (with stress and social cohesion as mediators) and improved immune function possibly mediated by the exposure to diverse sets of microorganisms [45,51].

6. Environmental quality: pesticides and pollutants

Pollinator conservation initiatives benefit human health through their promotion of pollutant-free environments that provide clean water, air and food (figure 2). An estimated nine million excess deaths resulted from global pollution of air, water and land in 2015 [59], and numerous human diseases associated with pollutant exposure have been identified and described [60–62]. Pollution of aquatic surfaces and groundwater used for consumption or recreational purposes is a common occurrence [60,63–65], as well as air contamination due to agrochemical use [60,66]. Agrochemical residues are also frequently found in animal products intended for human consumption [64,65,67], expanding their impacts into the food industry.

Numerous studies have also proven the negative effects that artificial substances can have on pollinator health, particularly in agricultural systems [68,69]. Pollinators can contact residues when foraging on sprayed flowers [70,71], feeding on contaminated nectar and pollen [69] or collecting water from polluted sources [70]. Agrochemicals such as herbicides can also indirectly affect pollinators by modifying the characteristics of their habitats, for example, by eliminating plants that deliver resources for their survival [70,72]. The recognition of pollinators as providers of fundamental services [12,73,74] has prompted the development of reports and initiatives aimed at their conservation, mainly through reductions in the use of pesticides and other substances with polluting effects [75–77].

One of the most widely implemented practices to reduce pesticide application is integrated pest management [60,70,78]. With adequate consideration, it is possible to expand the focus of this approach (i.e. pest control) into plans that benefit both pollinators and biocontrol agents (integrated pest and pollinator management; IPPM), thus favouring pollination and reducing dependence on pesticides [79,80]. IPPM also contemplates landscape management and promotes environmentally friendly measures that enhance different ecosystem services, for example, the restoration of natural and semi-natural habitats [80], in which many native plants can act as weed controllers, hence reducing the need for chemical intervention [63]. Sowed buffer strips are also an important asset, as they offer plant diversity for pollinators and biocontrol agents while protecting soil integrity and reducing erosion and pesticide runoff [63,70], a major driver in environmental pollution. So, we can safely predict that healthy pollinator habitats supported by good practices can provide sustainable solutions to pollution and improve habitat quality and human health, either by presenting lower levels of chemical input or by facilitating the functioning of natural ecosystem processes [81,82].

7. Knowledge gaps and future directions

Pollinators are affected by multiple stressors present in their surroundings, such as habitat loss and pesticide overuse [74,82,83]. As pollinator loss continues around the world, we expect to see additional burdens of disease. Because of these alarming trends, highlighting future research gaps is a pressing need. Here, we describe some of the remaining questions that would strengthen the necessary body of evidence linking pollinator and human health.

Much of the existing research linking pollination services with human nutrition and health relies on global meta-analyses synthesizing the empirical relationship between yields and pollination. More detailed information illuminating how local pollinator communities are contributing to crop yields and diets could provide a more accurate picture of our dietary and nutritional reliance on pollinators. Additionally, the role of animal pollination in the nutritional quality of crops has only been investigated for a handful of crops, and mostly focused on nutrients relevant to crop marketability (i.e. sugar or oil content) and not human health. More research is warranted to investigate the link between pollination and crop micronutrient density to establish its importance for supporting human health. Furthermore, given current declining trends in pollinator abundance, richness and range, as well as human consumption becoming more pollinator-dependent, additional future-looking research is crucial to better grasp how protecting pollinators is a necessary condition for supporting human health.

While our knowledge of crop pollination is growing rapidly, woefully little is known about the pollination of medicinal plants that are also an important pillar of human health. With up to 84% of medicinal plants potentially dependent upon animal pollination, it is imperative to learn more about their degree of pollinator dependence, the taxa involved in their pollination and how this service can be conserved and managed. We might be experiencing a concomitant global loss of pollinators and pollinator-dependent medicinal plants with important but unknown consequences.

Humans have long benefited from the medicinal compounds present in bee-derived products, but the quality of these medicines is ultimately dependent upon the ecology and health of the bees that provide them. The chemical composition, and therefore the medicinal value, of bee products may be influenced by a range of ecological factors including the plants they visit and the diseases and environmental contaminants they encounter. A more thorough understanding of these factors may help us manage bees in a way that improves the quality and effectiveness of these important medicinal products.

In the past decades, many studies have characterized the rich variety of urban green spaces, focusing on their value to pollinator communities and human health. Building on this knowledge, research on green spaces and biocultural landscapes should prioritize mechanistic experimental set-ups and larger temporal (multi-year) and spatial scales. For example, which community functional traits drive sustainable positive health outcomes in which socio-ecological contexts? What features do people value and how can they be provided in different places? In addition, most studies rely on perceived health and preference reports. Although these are very valuable and cost-efficient, direct measurement of the exposure to pollinator-friendly landscapes and its effects on health could bring new insights [50,51]. These may be feasible only in smaller samples and experimental set-ups but could uncover key indicator variables and their associations with cost-efficient measures of human and pollinator community health, both in the short and long term.

Finally, the vulnerability of humans to changes in pollinator diversity will depend on the extent to which they rely on pollinator-related services and products, how close they are to thresholds whereby further reductions in services have immediate impacts on human health and their ability to replace these services with engineered infrastructure, markets or philanthropy [3]. The people who are likely to be most impacted by pollinator loss, therefore, are those who are geographically located in areas of greatest change and who have the fewest resources to insulate themselves from these changes through markets or infrastructure. Poor people become less healthy as a result of degraded natural systems, while wealthy people who can access improved engineered infrastructure and markets are likely to be less impacted [3]. Future studies linking pollinator health and human health should consider such inequalities in the potential impacts of pollinator loss.

8. Conclusion

Human activities are driving fundamental biophysical change at rates that are much greater than have existed in the history of our species [84]. Growing evidence indicates that biodiversity loss may have widespread consequences for human health [1–3], the decline of animal pollinators being one such change. However, only two studies have quantified the connections between pollinator health and human health. Future work should quantify pollinator health, environmental quality and the physical and mental health of people associated with those environments [85]. We propose four pathways through which maintaining healthy pollinator communities may contribute to human health: two direct pathways through the provision of nutrients and medicines, and two indirect pathways, through maintaining green spaces and biocultural landscapes that improve mental health, and through reducing the concentration of pesticides and pollutants in water, air and food. The diversity of pollinators could be an indicator of the benefits that landscapes provide to human health. Multidisciplinary work among ecologists, health and social scientists and planners is much needed to conduct research and develop policies that promote human interaction with biodiversity [85]. Land-use planning should place human health at its centre.

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Authors' contributions. All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Conflict of interest declaration. We declare we have no competing interests.

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