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ABSTRACT

The decline of pollinators has been demonstrated scientifically and this phenomenon is widely recognized by both the general public and by stakeholders. Since pollinators face different threats that are all linked to human activities, there is a unique and unprecedented responsibility for people to conserve pollinators, requiring political action to counter the substantial worldwide risk of pollinator loss. As our perception of the situation is rapidly changing, as a result of the steady accumulation of international and national reports as well as new scientific findings, we propose here to provide an updated overview of pollinator conservation globally. We present the key messages and the proposed solutions found in international reports and assessments, how European countries have interpreted these solutions proposed in the context of existing international frameworks. Next, we analyze how scientific research is addressing the issue of pollinator conservation through different international, European and national programs. The analysis of the keywords used in published scientific articles also allows us to characterize how the scientific community has engaged with this issue over time. Finally, we focus on how France and Belgium have reacted to the observed decline of pollinators, and examine their national interpretations, conservation actions and research contributions.

1. Introduction

1.1. Recent evidence documenting pollinator decline

In the last few decades, unprecedented interest in pollinators and pollination ecology has been generated through a growing awareness of the decline of pollinators that has been observed across the world (IPBES et al., 2016). The general public and policymakers have simultaneously discovered both the decline of pollinators and also the great functional importance they have for ecosystems. For insect populations more broadly, Hallman et al. (2017) found a 76% decline in insect biomass across a 27-year survey, although one must also consider the serious criticisms that have been made against measures of trapped insect biomass (Didham et al., 2020; Vereecken et al., 2021). However, two other studies have shown similar results: a drastic reduction of arthropods populations and species at a global scale (Dirzo et al., 2014; Sánchez-Bayo and Wyckhuys, 2019; Zattara and Aizen, 2021). The decline of wild insect pollinators has been also evidenced by numerous research teams through comprehensive monitoring, quantitative assessments and establishment of Red Lists, in North America and north-western European regions (e.g. Rasmont et al., 1993; Steffan-Dewenter et al., 2002; Goulson et al., 2008; Potts et al., 2010; van Swaay et al., 2010; Winfree, 2010; Kennedy et al., 2013; Vanbergen, 2013; Williams, 1994; IPBES et al., 2016; Jauker et al., 2019; Duchenne et al., 2020). This pollinator decline is caused by high anthropogenic pressures including land-use changes (habitat loss, homogenization, and simplification of landscapes), intensification of agricultural practices, pollution, most notably nitrogen through deposition thus causing eutrophication, and several other traits of global changes like climate changes and biological invasions. Studies evidencing the negative impact of urbanization have increased in frequency in recent years (e.g. Bates et al., 2011; Geslin et al., 2013; 2016; but see Hall et al., 2017), and notably the negative effects of artificial lights on nocturnal pollinators have been highlighted (Knop et al., 2017). Such effects vary among taxa that differ in their ecological characteristics which affect species vulnerability (Nieto et al., 2014; IPBES et al., 2016; Duchenne et al., 2020).

However, a huge gap in our knowledge lies in the difficulties of studying pollinator declines over the long term as for other taxonomic groups (Schatz et al., 2016). After the pioneering work of Biesmeijer et al. (2006) on the declines in bees and hoverflies in Britain and the Netherlands (see after), Powney et al. (2019) again found a decline of 33% in population size of both syrphid and bee species populations between 1980 and 2013 in the same countries. In a review of declines in bumble bees across 11 central and western European countries, Kosior et al. (2007) describe local extinctions of 13 species in at least one European country between 1950 and 2000. Furthermore, museum records are a precious resource that can be used to comment on populations and species trends for taxa facing anthropogenic pressures. Bartomeus et al. (2013) used a large museum data base of more than 30,000 records and found a decline in members of the genus *Bombus* over a 140-year period in the USA (species richness declined by 30%). Similar trends were found by two other studies in North America using museum records and field surveys (Colla et al., 2006; Cameron et al., 2011). The number of studies between past and present distribution is still scarce (Schatz et al., 2016) and have been predominantly centered on Europe and North America. Moreover, knowledge of population trends is still poorly known for many taxonomic groups of pollinators, which could be also a consequence of the decline or the total loss in taxonomical expertise (Kuhlmann, 2015; Orford et al., 2015). Large collections of identified insects lie “dormant” in national or local museums and for many of them we simply do not know the species list and/or the number of individuals stored in the collections (Raven and Miller, 2020). There is an urgent need to gather and share museum data, for example thanks to open data platforms in order to have precise information about changes in the insect faunas across time.

A global trend of ecological homogenization has also been demonstrated in pollinator communities as result of ongoing global change, specifically through the loss of rare and specialized species, within bumblebee communities (Bommarco et al., 2011), but also for a wide range of taxonomic groups (Carvalheiro et al., 2013; IPBES et al., 2018; Díaz et al., 2019). In Britain and the Netherlands, parallel declines in pollinators (specifically bees and hoverflies) and insect-pollinated plants have been documented (Biesmeijer et al., 2006; see also Carvalheiro et al., 2013). Additionally, these declines potentially have consequences for insect-pollinated plants and a few studies have linked the decline of pollinators with the decline of insect pollinated plants (Biesmeijer et al., 2006) or have projected that plant extinctions under climate change are more likely to trigger animal co-extinctions than vice versa (Schleuning et al., 2016). Burkle et al. (2013) published the variation of a large plant-pollinator network over a 120-year period and found a considerable decline of both plant and pollinator species involved in this network and degradation of the mutualistic network structure. Grab et al. (2019) recently showed that the phylogenetic diversity loss of pollinators mediated by agricultural practices leads to the disruption of the pollination service they provide.

Concerns also exist about dramatic and abrupt loss of colonies of domesticated bees for many beekeepers around the world. There is global agreement among experts and beekeepers that those losses are due to a combination of factors, mainly the parasitic mite *Varroa destructor*, different pathogenic agents (viruses, fungi such as *Nosema* sp.), predation by Asian hornet *Vespa velutina*, and the changes in beekeeping practices (Schatz and Dounias 2016) as well as the general use of agricultural pesticides (neonicotinoids, other insecticides, fungicides and others) (Henry et al., 2012, 2015; Zhu et al., 2014; ANSES, 2018). These threats also affect wild pollinators, but the domesticated and eusocial characteristics of *Apis mellifera* render this species a sentinel species for monitoring the population trends of wild pollinators (Wood et al., 2020).

Such a decline of wild and domesticated pollinators strongly contrasts with the steadily growing demand for pollination in crop production (Klein et al., 2006; Aizen and Harder, 2009; Garibaldi et al., 2013; IPBES et al., 2016; Aizen et al., 2019, 2020). Over the past five decades, agriculture has become increasingly pollinator-dependent, with a three-fold increase of crops requiring the pollination (Aizen and Harder, 2009; Aizen et al., 2020). Even if this increase in insect-attractive crops were to entirely benefit wild and domestic pollinators, the benefit is probably only partial due to the use of pesticides, particularly for certain crops (oilseed rape, fruit trees etc.). Spatial analyses demonstrate that approximately 10% of worldwide agricultural acreage is pollinator-dependent (Gallai et al., 2009), but this dependency is far from uniform across the globe and may reach as much as 30% in several agricultural hotspots (Lautenbach et al., 2012). The recommended number of honeybee colonies required to provide crop pollination (by considering the natural presence and action of wild pollinators, see Garibaldi et al., 2013) across 41 European countries rose 4.9 times faster than honeybee stocks between 2005 and 2010. As a result, 90% of the demand for honeybee stocks is unmet in 22 out of 41 studied countries (Breeze et al., 2014). Unsustainable practices have been regularly criticized, such as in the USA which has developed the world’s largest commercial pollination industry: more than two million honeybee colonies are made available for rent in order to pollinate vast monocrop fields and plantations (Morse and Calderone, 2003; Sumner and Boriss, 2006). The recent increase in scientific knowledge (see below) concerning wild and managed pollinators and their decline highlights their role as keystone species in ecosystems and our need for pollination in crop production (see also Senapathi et al., 2021). Such information has been instrumental in raising societal awareness (via NGOs) and informing policymakers about the urgency of pollinators conservation through identifying the drivers of ecologically, economically and socially unsustainable practices. Faced with this unprecedented situation, regular updates and overviews are necessary. These reviews should help us identify, and then adopt, lifestyles and bee-friendly practices that halt the drivers of pollinator decline and simultaneously encourage governmental actions and help develop international assessments, research programs and citizen science actions in favor of pollinator conservation (reviewed in Drossart and Gérard, 2020; see also papers in this special issue).

In this context, we aim to provide an integrated and updated overview of several approaches in favor of pollinator conservation, namely (i) the international assessments frameworks, (ii) national interpretations of solutions proposed in international assessments frameworks focused on European countries; (iii) scientific initiatives addressing pollinator decline through an analysis of the most frequently addressed issues; and (iv) the case study of Belgium and France in context of these previous approaches.

2. International assessments frameworks for pollinator conservation

2.1. Millennium Ecosystem Assessment and its consequences

The Millennium Ecosystem Assessment (MEA, 2005) was the first major assessment of the human impact on the environment, launched by a call from United Nation Organization and initiated predominantly by the UNEP (United Nations Environment Program) Convention on Biological Diversity and by the FAO (Food & Agriculture Organization). For the first time, this international assessment established that humans have changed ecosystems more rapidly and extensively than at any previous point in human history, and that such changes have contributed to substantial net gains in human well-being and economic developments but also to the degradation of many ecosystem services (MEA , 2005; https://www.millenniumassessment.org/). The MEA also initiated the concept of ecosystem services which are defined as the many and varied benefits humans freely gain from the natural environment and properly-functioning ecosystems. In this innovative but anthropogenic conceptual framework, the ecosystem service of pollination is recognized as one of the most important services for both ecosystem functioning and crop production for human food (but see Mace et al., 2012).

Thanks to the legacy of the MEA, we know *a posteriori* that international assessments of biodiversity changes have the potential to stimulate investigation and research. Firstly, there is a still on-going philosophical discussion regarding the conceptualization of the human-nature relationship, which has been updated by the recent work about the IPBES approach by mixing ecology and social sciences (Pascual et al., 2017). There are also different attempts to apply this new concept of ecosystem services in practical and operational terms at different geographical scales following three investigations: 1) mapping ecosystem services, 2) calculating an index of pollination services, and 3) evaluating the economic benefits of the pollination service. Applied to pollination assessments, such approaches have encouraged research groups to create different maps of the pollination services provided at different scales in areas such as across Europe or Western Europe (Zulian et al., 2013; Schulp et al., 2014) or at national scales (Maskell et al., 2013; Polce et al., 2013, 2014; Beyou et al., 2016; Jacquemin et al., 2017) which are very useful to provide a global view of pollination for researchers and policymakers. A second consequence has been the establishment of pollination services, indexes, these first being applied to crop production even if their values greatly varied among regions and agricultural practices (Martin et al., 2019). However, the establishment of a pollination index acceptable to researchers, farmers, conservation organizations and policy makers remains a subject of ongoing work, as it is difficult to obtain a common and simple index applicable to all crop plants. For example, the dependence of many crops (fennel, coriander, flax, etc.) on pollinators has been studied only infrequently (but see Schurr et al., 2021). Moreover, the extension of the calculation of this pollination index to wild plants is difficult to envisage (because of the diversity and the frequent difficulty of counting fruits), except perhaps by considering only a few species as proxies of the local flora. Another consequence corresponds to the economic evaluation of pollination services focusing on crop production. In this context, Gallai et al. (2009) estimated that the crop production that is attributable to pollination corresponded to between 153 and 422 billion euros worldwide.

After the Millennium Ecosystem Assessment (MEA , 2005), the FAO developed a standardized method to estimate at the national level the economic benefits provided by pollination (http://www.fao.org/fileadmin/templates/agphome/documents/Biodiversity-pollination/econvaluepoll1.pdf): the FAO also recently published a report about the pollination services of forest, an habitat often neglected with regard to pollination (Krishnan et al., 2020). Moreover, Zulian et al. (2013) provided a general map of the pollination services at the scale of Europe by linking land cover data and crop yields, which illustrates the global North-South gradient of this service.

2.2. IPBES

Initiated by the Convention on Biological Diversity (CBD) and accomplished by a collaborative partnership among UNEP, UNESCO, FAO and UNDP, the Intergovernmental science-policy Platform on Biodiversity and Ecosystem-Services (IPBES) aims to assess the state of biodiversity and the ecosystem services in response to requests from governments, the private sector and civil society. This assessment provided a unified message from the diversity of scientific publications thanks to international experts. In contrast to other international initiatives, national governments played a role at the start of the IPBES process during the nomination of experts and the questioning and at the end during the validation of the content of the final reports (detailed report and summary for policymakers). IPBES recently produced a global report (Díaz et al., 2019) based on reports in four regions and notably one for Europe and Central Asia (IPBES et al., 2018); it previously produced several thematic reports (one on Pollinators, pollination, and food production (IPBES et al., 2016) and another one on land degradation and restoration) (see https://www.ipbes.net). Often described as the equivalent of "IPCC for biodiversity" (IPCC being the Intergovernmental Panel on Climate Change), IPBES is now one of the leading international organizations assessing biodiversity.

It is noticeable that the first report produced by IPBES concerned the theme of pollination (IPBES et al., 2016), reflecting global concern about both the conservation of pollinating insects and pollinated plants as well as food production for humanity. This thematic report provided key messages about the value of pollinators and pollination, the status and

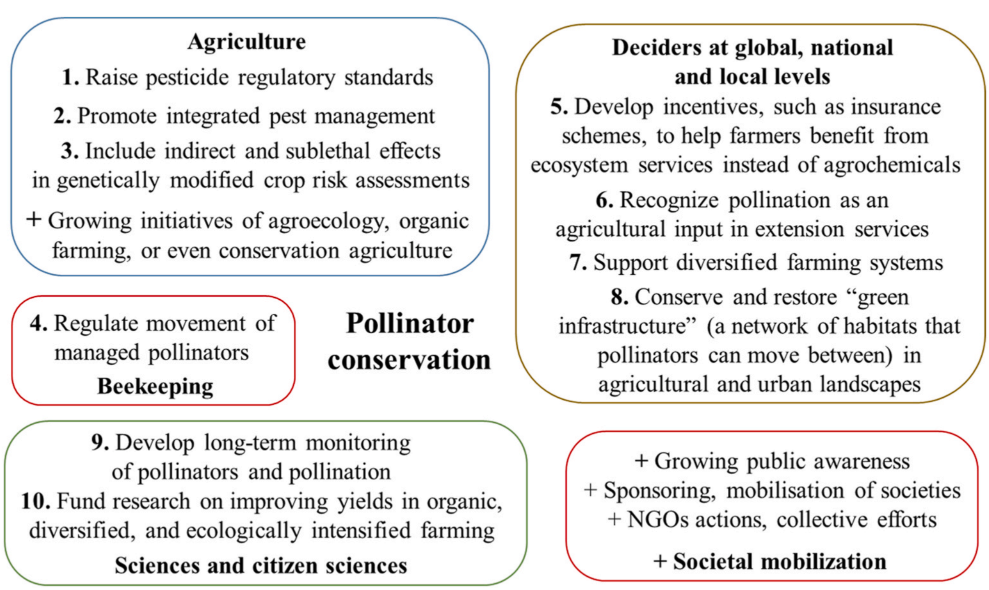

Fig. 1. Ten policies to conserve pollinators (redrawing from Dicks et al., 2016) and completed by recent identified trends (indicated by +).

trends of pollinators and pollination, the drivers of change, the risks and opportunities, and the policy and management options (IPBES et al., 2016). IPBES et al. (2016) estimated this value to be 235–577 billion US dollars and 5%–8% of world crop production dependent on insect pollination. It states that wild pollinators have declined in abundance and diversity in northwest Europe and North America (such decline has also been observed in most other world regions in spite of a lack of taxonomic knowledge of pollinators). In parallel, the number of managed western honeybee colonies globally increased despite a recorded declined in northwest Europe and North America, where colony losses have been observed.

The IPBES report (2016) also identified drivers of pollinators decline and recommended solutions. The main threats described are intensive agriculture (notably including pesticide use) and land-use change (urbanization, habitat destruction), environmental pollution, invasive alien species (see also Geslin et al., 2017), pathogens and climate change (Decourtye et al., 2019; Gérard et al., 2020). It is clear that these factors act in combination often negatively depending on location and period (Goulson et al., 2015), but a better understanding of this point has been limited by data availability or complexity. When bees are not directly killed, common pesticides can trigger behavioral and reproductive impairments leading to adverse demographic effects at population levels (Henry et al., 2012; 2015; EFSA, 2013; Godfray et al., 2014; Zhu et al., 2014; Rundlöf et al., 2015). Bees require appropriate floral resources during the adult flight season (which is sometimes short for some solitary species) (Bretagnolle and Gaba, 2015), while most flower rich grasslands have become rare (97% of them were lost in the 20th century in United Kingdom (Howard et al., 2003)).

In response to this situation, IPBES et al. (2016) proposed a clear overview of strategic responses to risks and opportunities associated with pollinators and pollination. Three goals are distinguished and associated with specific responses: 1) improving current conditions for pollinators and/or maintaining pollination by managing immediate risks (such as creating uncultivated patches of vegetation with extended flowering periods in areas such as field margins, rewarding farmers for pollinator-friendly practices); 2) transforming agricultural landscapes by agroecological intensification (Holzschuh et al., 2008) through the active management of ecosystem services (like supporting diversified farming systems), by strengthening existing diversified farming systems (such as supporting organic farming systems) and by investing in ecological infrastructure (such as restoring natural habitat) and 3) transforming society's relationship to nature by integrating peoples' diverse knowledge and values into management and by linking people and pollinators through collaborative, cross-sectoral approaches (see IPBES et al., 2016; FRB, 2016 for details).

After this first thematic report, Dicks et al. (2016) highlighted solutions by identifying ten policies for pollinator conservation (Fig. 1). Goulson et al. (2015) and Dicks et al. (2016) underlined that pesticides are the most heavily regulated of the interacting drivers of pollinator declines. Most of these policies concern agriculture which needs to be reoriented toward diversified systems and integrated pest management strategies.

Lists of protected species and the creation of protected areas are two classic policy approaches that are slowly moving towards biodiversity conservation. However, Dicks et al. (2016) indicated that these approaches are not well adapted to pollinators because of the spatial separation between protected areas and croplands and because most pollination activity is performed by widespread generalist species in agroecosystems (Kleijn et al., 2015). However, most conservation efforts in European countries focus on the management of natural reserves (and not on their creation). In comparison, recent agroecological measures are huge in terms of effort and budget and do not fall into these categories.

In March 2018, IPBES published the four regional reports about biodiversity and ecosystem services, notably a report for Europe and Central Asia (IPBES et al., 2018). This report confirms several main points about pollinators for this region (IPBES et al., 2018; Visconti et al., 2018): 1) the diversity, occurrence and abundance of wild insect pollinators have declined since the 1950s and severe losses of the western honeybee have occurred in several Western European countries and former-USSR countries, 2) the impacts of land-use change on natural ecosystems and current agriculture practices have caused declines in pollinators, 3) Mediterranean and Central Asian countries have become more pollinator-dependent due to their substantial production of highly pollinator-dependent fruits and 4) there is a substantial rise in public awareness about the loss of pollinators which has received significant policy interest. Recently, the global assessment performed by IPBES (Díaz et al., 2019) confirmed these findings by highlighting several strategies to be adopted by deciders, from global to local levels, and by identifying knowledge gaps.

2.3. *IUCN red list*

2.3.1. *Red lists process and pollinators*

The IUCN Red List of threatened species represents a powerful tool for conservation planning, management, and monitoring (Rodrigues et al., 2006 but see Collen et al., 2016). It is recognized as the most comprehensive tool for assessing the risk of species extinction, based on a standardized methodology that is applicable for most taxa by a group of experts (scientist and NGO experts) at different regional levels (supranational, national, regional) (Azam et al., 2016). It has been used to guide management of natural resources, national development policies and legislation as well as multilateral agreements (e.g. the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES)) (Rodrigues et al., 2006). However, it is not intended to be policy-prescriptive, and it is not in itself a system for setting biodiversity conservation priorities (Nieto et al., 2014).

Initially, the IUCN Red List criteria were developed to assess the extinction risk of entire populations worldwide by using five standard criteria to classify species in the different Red List categories (IUCN, 2012b). Nevertheless, most conservation policies (*i.e.* laws, resources for conservation measures, personal levels of Commitment) are bound within geopolitical borders and are then conducted at national levels (Gärdenfors et al., 2001). Moreover, trends and statuses could change substantially at different scales and/or between different countries. National and Regional Red Lists are then needed to guide sub-global nature conservation efforts. At this scale (*i.e.*, continental, national, regional as well as local), two options are possible: (1) publish an unmodified extract of the global IUCN Red List which can specifically be justified for endemic species or in a case of a generalized and known lack of data; or (2) evaluate the extinction risk of species at a regional scale and publish Red Lists for the area concerned (IUCN, 2012a).

From a conservation point of view, the second option would be more effective but raises several problems that do not exist at a global scale (e.g., the evaluation of populations on both sides of geopolitical borders; the presence of non-reproductive populations or non-native taxa) (IUCN, 2012a). Rodrigues et al. (2006) also highlighted that many "Red Lists" had been produced but these mostly do not follow the IUCN Categories and Criteria. Thus, they cannot be endorsed by the global Red List (with a number of them having a history pre-dating the Red List itself). This is why the International Union for Conservation of Nature has developed guidelines for applying IUCN Red List criteria at regional and national levels (IUCN, 2012a). For insect pollinators, Red Lists exist in Europe at different scales for bees and butterflies, but they have not yet been produced for hoverflies, other true flies and pollinating beetles (Orford et al., 2015).

Red lists of bees At the European scale, a first review of the status of European bee species according to IUCN regional Red Listing guidelines was published in 2014 (Nieto et al., 2014). It gathers the assessments of 1942 species, of which 77 are considered to be threatened (*i.e.,* Vulnerable, Endangered or Critically Endangered). However, this proportion of threatened species is incomplete given that 1101 species were

Table 1
National species diversity and red list status in European countries according to Drossart et al. (2019) sorted by the national percentage of threatened species. "Nsp" = number of recorded species according to IUCN data, "NRLsp" = Number of species on national red list and "%threatened" = Proportion of threatened species based on Nsp/NRLsp. Criteria used for the Red Lists assessments: IUCN = IUCN criteria, NC = national criteria, NM = not mentioned.

Country	Nsp	NRLsp	% threatened	Reference of the Red list
Estonia	179	0	0.0%	CNCEAS (2008) NM
Lithuania	295	2	0.7%	Rašomavičius (2007) IUCN
Spain (mainland)	1008	8	0.8%	Verdú et al. (2011) IUCN
Hungary	704*	12	1.7%	Sárospataki et al. (2005) IUCN; Józan (2011)*
Denmark	261	5	1.9%	Wind and Pihl (2004) IUCN
Malta	49	1	2.0%	Schembri and Sultana (1989) IUCN
Latvia	195	4	2.1%	Spuris (1998); Patiny et al. (2009) NC
Belarus	124	3	2.4%	Prischchepchik (2008) NM
Moldova	127	10	7.9%	Timuş et al. (2017) IUCN
Slovenia	552	59	10.7%	Anonymous (2002) IUCN
Norway	192	26	13.5%	Kålås et al. (2010) IUCN
Great Britain	237	35	14.8%	Shirt (1987), Falk (1991) NM
Poland	490	84	17.1%	Głowaciński and Nowacki (2009) IUCN
Finland	244	43	17.6%	Rassi et al. (2010) IUCN
Slovakia	586	105	17.9%	Feráková et al. (2001) IUCN
Sweden	283	54	19.1%	Gärdenfors (2010) IUCN
Belgium	381	113	29.7%	Drossart et al. (2019) IUCN
Ireland	101	30	29.7%	Fitzpatrick et al. (2007) IUCN
Switzerland	633	192	30.3%	Amiet (1994); Cordillot and Klaus (2011) IUCN
Netherlands	356	110	30.9%	Reemer (2018) NC
Germany	585	194	33.2%	Westrich et al. (2008; 2011) NC
Czech Republic	600	242	40.3%	Farkač et al. (2005) IUCN

assessed as Data Deficient (DD), meaning that there was insufficient information available to assess their extinction risk. The proportion of threatened species could then lie between 4% (if all the DD species are not threatened) and 60.7% (if all DD species are threatened) (Nieto et al., 2014). By applying the mid-point value (*i.e.*, corresponding to the assumption that DD species contain the same proportion of threatened species than data sufficient species (IUCN, 2016)), 9.2% of bees are considered to be threatened in Europe.

Red lists of hoverflies There is no red list of threatened hoverflies species at the European scale. However, an IUCN Hoverfly Specialist Group was established in 2018 to assess the threat of extinction of approximately 650 European hoverfly species through Red Listing by 2022 (see https://iucn-hsg.pmf.uns.ac.rs/). Moreover, a global evaluation (*i.e.* covering each European country) which do not follow the IUCN methodology was conducted by Speight and integrated into the "Syrph the net" database.

Red lists of butterflies At the European scale, a review of the status of European butterfly species according to IUCN regional Red Listing guidelines was developed in 2010 (Van Swaay et al., 2010). It gathers the assessment of 435 species of which 37 are considered to be threatened. Unlike the European red list of bees, only four species were assessed as Data Deficient. By applying the mid-point value, 8.6% of butterflies are considered to be threatened in Europe.

3. National interpretations of solutions proposed in international frameworks

3.1. Red lists

Several national and regional Red Lists on hoverflies have been developed. Ball and Morris (2014) assessed 82 species (LC species were not listed in the review) in England of which 13 were considered threatened (17.8% considering the mid-point value by considering the nice Data Deficient species). In Germany, 126 species (29.1% considering the mid-point value by considering the 31 Data Deficient species) were considered threatened among the 463 assessed species (Ssymank et al., 2011). Several regional Red Lists have been produced in Germany such as in Sachsen-Anhalt (Dziock et al., 2004), Baden Württemberg (Doczkal et al., 2001), Berlin (Saure, 2018), and Bavaria (von der Dunk et al., 2003). They assessed a high number of species: 299 in Alsace, 290 in Sachsen-Anhalt, 379 in Baden Württemberg, 252 in Berlin and 388 in Bavaria. Among these, respectively 74, 65, 73, 87 and 122 were considered threatened (respectively 27.6%, 23.4%, 20.9%, 35.8% and 34.8% considering a mid-point value).

Red Lists have also been produced at a national scale in numerous European countries (Table 1). As for the red lists of bees, the methodologies employed have varied, using either IUCN criteria, expert judgment or national criteria (Maes et al., 2019). The most threatened countries appear to be highly industrialized (NW Europe), such as the Netherlands (*i.e.* 42 threatened out of 77 assessed species; Bos et al. (2006)), the Czech Republic (*i.e.* 75 threatened out of 157 assessed species; Beneš and Konvička (2017)) and Denmark (*i.e.* 38 threatened out of 84 assessed species; Wind and Pihl (2004). Through their great importance for the decisions-making process when implementing conservation measures (Rodrigues et al., 2006; Fitzpatrick et al., 2007; Nieto et al., 2014), the Red Lists of threatened species constitute an essential tool. This tool however is notably still absent in some countries that are important for bee diversity given their size and Mediterranean habitats (e.g. Italy, France, Greece), and more broadly almost everywhere in Europe for hoverflies.

3.2. National action plans for pollinators

At the national scale, several action plans have been developed in recent years to tackle the pollinator crisis. However, we can notice vast differences between produced plans, namely in the targeted groups and proposed actions. In Belgium, proposed actions have focused on "bees" through two successive federal bee plans 2012–2014 and 2017–2019, but most of them are related to *Apis mellifera*. Conservation of wild pollinators and their habitats depends on regional governments that have not yet formulated regional strategies (Underwood et al., 2017). As described by Drossart et al. (2019), conservation actions are mainly undertaken by NGOs (*e.g.* Natagora, Natuurpunt), based on their expertise and collaborations with other structures, such as public administrations and universities (*e.g.* in the scope of the SAPOLL Interreg project).

Ireland (PPSG, 2015 with a great update in 2021 https://pollinators.ie/wp-content/uploads/2021/03/All-Ireland-Pollinator-Plan-2021-2025-WEB.pdf), Scotland (BNCBWG, 2013) and England (DEFRA, 2015) have also individually produced national plans for pollinators. Each country has wanted to provide a network of resource-rich, diverse and connected habitats that benefit pollinators, and to raise awareness and to improve knowledge about pollinators. Other specific goals, such as the enhancement of pollinator monitoring (Ireland), having healthy pollinator populations (Scotland) and a focus on pollinators in urban and agricultural areas (England) have also been stated. Lastly, some countries have specifically targeted their national plan to focus on bees (wild and domesticated bees) such as in the Netherlands (MLNV, 2018) with an action plan divided into three main parts: promoting biodiversity, improving interactions between agriculture and nature, and helping beekeepers regarding the health of honey bees.

4. Scientific initiatives addressing pollinators decline

4.1. International, European and national research programs

There are some international organizations which have pooled information about global biodiversity and notably about pollinators such as the Global Biodiversity Information Facility (GBIF; http://www.gbif.org) or more dedicated to wild bees like the Integrated Taxonomic Information System which includes a checklist of the world's bee species, providing details of all synonyms and subspecies (ITIS; http://www.itis.gov/). The International Commission for Plant-Pollinator Relationships (ICPPR) (http://www.uoguelph.ca/icpbr/index.html) has organized meetings and networks, and promotes research on plant-pollinator interactions and favors the interface between researchers and decision makers. There are also some international organizations of pollinator information that are located and coordinated by a European country such as the IBRA (International Bee Research Association www.ibra.org.uk/located in the UK), Apimondia (https://www.apimondia.org located in Italy), and SuperB (Sustainable pollination in Europe) (COST program located in the Netherlands, http://www.superb-project.eu/).

The European Commission has funded a series of international research projects (each for several millions euros) focused on pollinators such as ALARM (www.alarmproject.net/), STEP (www.step-project.net/), LIBERATION (www.fp7liberation.eu/TheLIBERATIONproject), POSHBEE (https://www.poshbee.eu/), QUESSA (www.quessa.eu) or a program focused on measuring farmland biodiversity called BIO-BIO (www.biobio-indicator.org). All of them include essential findings and datasets about pollinators and pollination. For example, the main goals of the European Commission funded STEP project (Status and Trends of European Pollinators) were to provide a better understanding of the ecology of pollinators and pollination services, and establish better policy and better practices. The STEP project has helped science and policy move forward on many of the above challenges, illustrated in the following chapters (Potts et al., 2010, 2015). Specifically, this program had the following objectives:

i) document the status and trends of pollinators (managed honeybees, wild bees and hoverflies) and animal-pollinated plants (e.g. Nieto et al., 2014)
ii) assess the main driver of changes in pollinators and animal-pollinated plants at scales ranging from single fields, to landscapes, to the whole of Europe (e.g. González-Varo et al., 2013),
iii) the effectiveness of strategies to mitigate the impacts of changes in pollinators and animal-pollinated plants (e.g. Scheper et al., 2013),
iv) develop ways to improve the interface between the scientific knowledge-base on pollinator shifts and policy instruments (Biesmeijer et al., 2011),
v) develop communication and educational links with a wide range of stakeholders and the general public on the previous points.

There are also several national programs dedicated to pollinators or pollination research. One of the most significant examples is the "UK Insect Pollinators Initiative" which invested £9.65 million (2009–2014) in nine projects thanks to a collaboration among six research funders. The research covered the health, ecology and conservation of both managed and wild pollinators and crop pollination. Such a national program resulted in several scientific findings like evidence for pathogen transfer between wild and managed bees (Fürst et al., 2014), negative interactive effects between pesticides (Gill et al., 2012), maps of current and future services pollination for the UK (Polce et al., 2013, 2014), and studies on the diversity and abundance of managed and wild bees in different parts of urban areas (Baldock et al., 2015, 2018).

Several supra-national research groups have also been set up to promote collaboration between neighboring countries and similar bioclimates. This is the case of the SCAPE, the Scandinavian Association for Pollination Ecology (https://scape-pollination.org/). There is also Super-B (https://superb-project.eu/), which is a COST Action that will bring together scientific and societal communities involved in the conservation and sustainable management of ecosystem services mediated by pollinators (30 countries involved).

Table 2
Results of the bibliometric analysis assessing the international research effort dedicated to the study of bees, their threats and their contribution to crop pollination. The average % annual growth rates over 10-years windows since 2007 onwards are provided to highlight emerging research fields. Research fields with different letters (a-c) display significantly different growth rates (Wilcoxon pairwise signed rank test with Hochberg P-value adjustment for multiple testing).

Research fields	Publication numbers 1975–2016	Publication numbers 2007-16	Percentage of annual growth rate in 2007–2016 (±sd) (pairwise test grouping)
Web of Science	46,189,660	17,778,999	3.9 ± 0.47 (a)
Global bee research literature	36,198	18,294	7.3 ± 0.92 (b)
Threats: Bio-aggressors	2598	1370	6.3 ± 2.50 (ab)
Threats: Environmental changes	559	429	15.0 ± 6.81 (c)
Threats: Pesticides	940	547	12.1 ± 4.80 (c)
Crop pollination services	595	459	15.0 ± 2.98 (c)

4.2. Keyword analysis as proxy of research on pollinators and pollination

To gauge the growing scientific interest for insect pollinators and their environmental threats, we performed a standardized comparative bibliometric analysis covering the past 40 years (1975–2016, Decourtye et al., 2019). We focused our bibliometric review on bees as a model research group that is likely to reflect the prevailing concerns and research efforts of pollination scientists. We applied a systematic publication search procedure on the online Thomson Reuters Web of Science (WoS) database, inspired from the Interactive Query Formulation (IQF) process (Wacholder, 2011), to (i) quantify the number of scientific publications contributing to scientific research on bees through time, and (ii) to monitor more particularly the rise of the research on bee threats and pollination within the bee research literature.

The IQF we developed herein to extract the global bee research literature from the WoS includes the following steps: 1) search the WoS using keyword queries related to bees (honeybee and beekeeping terminology, wild bee families and genera, …), 2) export the resulting reference set and check for possible misleading keywords returning inappropriate references, 3) extract all the keywords from the resulting reference set, 4) browse the resulting keyword list for new relevant keywords and 5) supplement the initial query with the new keywords, than start over from step 1 and proceed iteratively until the resulting reference set reaches a ceiling (see Decourtye et al., 2019).

Once the global bee research literature was established, we further refined the search with secondary IQF levels to monitor some specific fields within bee research, including pollination services and the main bee threats. Research on bee threats covers bio-aggressors (keywords related to *Varroa* mites, *Nosema* microspores, bee viruses, and other bee pathogens, parasites and predators), environmental changes (keywords related to climate changes, natural habitat fragmentation, agricultural intensification, floral resource scarcity and biological invasions) and pesticide exposure (keywords related to fungicide, insecticide and herbicide formulations, modes of action, risk assessment and biomonitoring methodology). Research on pollination services targeted entomophilous crops, and was therefore extracted in two steps. We first selected pollination references using pollination service, pollinator and crop pollination keywords. Second, we selected references related to agricultural sciences with keywords related to crop production, crop yield, arable land, orchard and other entomophilous crop terminology. At the end of

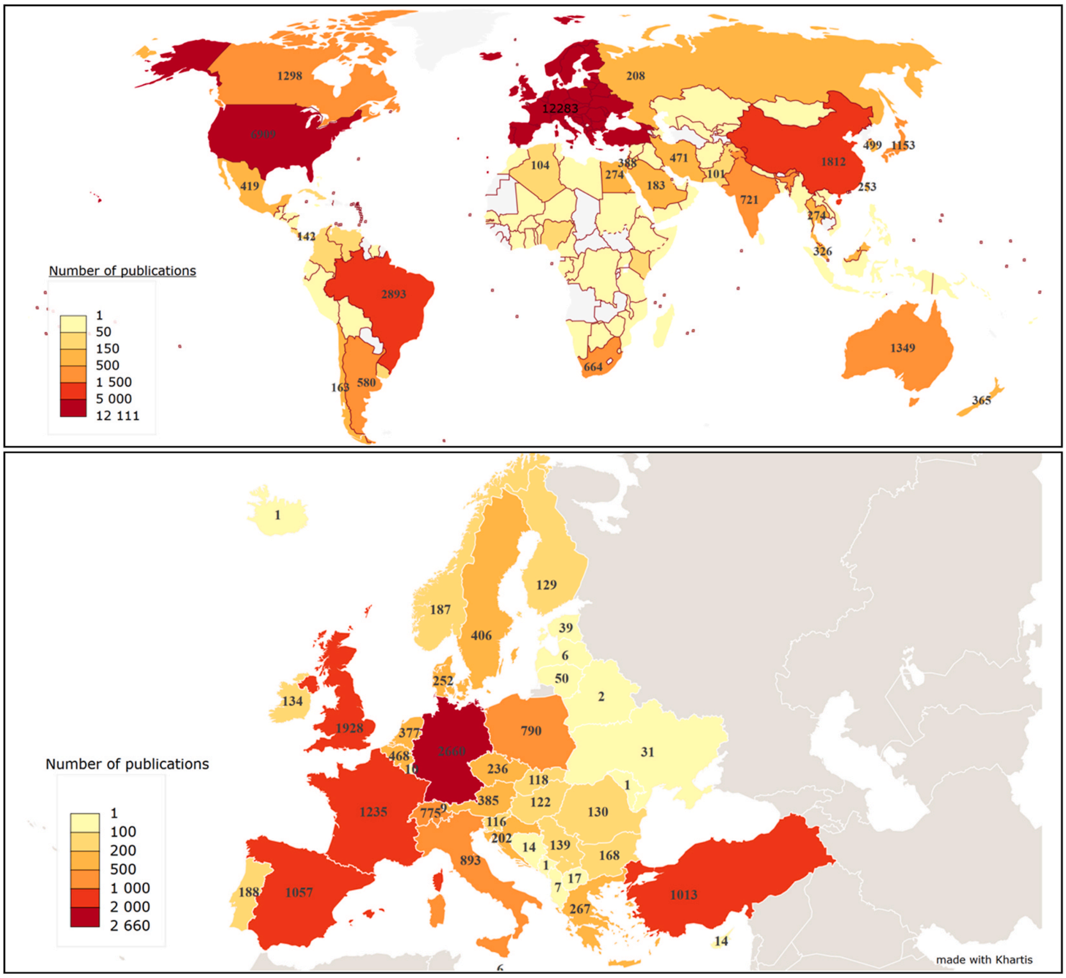

Fig. 2. Worldwide and European contributions to bee research over 1975–2016. Numbers refer to the occurrence of institutional affiliations in bee research publications, *i.e.* with keywords related to honey bees, beekeeping and wild bees. Computed with the Khartis® software.

the IQF processes, we carefully inspected the resulting reference subsets and corresponding abstracts to ascertain the consistency of the bibliometric analysis.

We found that bee research is rapidly expanding, particularly with studies on environmental changes and pesticide threats showing a pronounced development over the past 10 years. The bibliometric analysis returned 36,198 publications contributing directly or indirectly to the global bee research effort over the past 40 years, *i.e.* about 0.08% of the 46.2 million scientific publications referenced in the entire WoS database over the same period (Table 2). The ratio eventually reaches 0.11% in 2013 and beyond. Since 2007, the bee research literature has increased nearly twice as fast as the average global WoS database (7.3% vs. 3.9% average annual increase over 10 years, respectively). Within the bee research literature, bee threats research accounted for a relatively modest (4097 publications, 11.3%), but ever-increasing proportion (Table 2). Research on environmental changes and pesticide threats, in particular, are both rapidly emerging with 15.0% and 12.1% average annual increases, respectively, *i.e.* about twice as fast as the global bee research literature. Research on bio-aggressors is not expending faster than the bee research but represents historically the bulk (about two thirds) of the recent bee threats research. Finally, crop pollination science within bee research is expending as fast as environmental change and pesticide threats, highlighting the pervasive concern of bee scientists of a pollination crisis.

From a geographical perspective, the two most significant contributors to global bee research effort are the Western Europe countries (34%, Fig. 2) followed by the USA (19%, Fig. 2). Within Western Europe, the two principal contributors are Germany and the United Kingdom (but see later). Such sorting also reflects the financial resources invested by different countries in the study of pollinators and pollination. Moreover, it should be noted here that within Europe, the number of studies is not linked to the specific diversity of wild bees (Wood et al., 2020), which is rather centered on the European countries on the northern shore of the Mediterranean (Nieto et al., 2014; Ropars et al., 2020a, 2020b). However, given their taxonomic richness in wild bees, it is regrettable that some countries publish relatively little, such as surrounding the Black Sea or Greece. The same applies to the countries to the north-east of the Adriatic Sea, which certainly have a greater diversity of wild bees than is currently documented. Furthermore, Nieto et al. (2014) show that the northern Mediterranean countries have a concentration of both data deficient and endemic species, which should stimulate further scientific study. Finally, there is an urgent need to list, by country, which flowering plants support specialization for wild bees and other pollinators. This information would provide a new and more functional vision for conservation priorities.

A wide variety of crop groups have been studied with relation to the pollination services provided by bees in agricultural environments (Fig. 4). Nine major groups of farmers, excluding the categories “other” and “nesting habitats and food resources”, were identified when they represent more than 2% of all studies considered. Finally, farmers account for 27 different crops (excluding the “other” category) out of a hundred or so that are dependent on insect pollinators (Klein et al., 2006). The most studied groups are flowering tree crops and field crops, with respectively 116 and 95 papers. In orchards, research usually focuses on apple trees and, to a lesser extent, on almond trees, passion fruit, cherry, mango, and kiwi fruit. This bibliographic analysis does not reveal a study dedicated to orchard crops such as apricot, peach or pear, whose acreage and commercial values are substantial. In the field crop group, rapeseed and sunflower, whose dependence on pollinating insects is classified as moderate, remain the two most studied models. The other groups represent about a third of the world's crops: Cucurbitaceae (*Cucurbita pepo*, watermelon, melon, cucumber) and berries (blueberry, strawberry, cranberry, raspberry) are the most studied with 48 and 46 papers respectively. Forage species (alfalfa, clover) (30 papers), agroforestry (mainly coffee) (28 papers), Solanaceae (tomatoes, peppers) (24 papers), Fabaceae (soybean, field bean) (14 papers) and vegetables (eggplant, onion, carrot) (14 papers) each constitute less than 6% of the body of knowledge. Curiously, the interest of Fabaceae for the conservation of pollinators remains little studied globally, particularly with regards to their diversity (peas, fava beans, soya beans, lupins, lentils, chickpeas, beans, sainfoin, alfalfa, various clovers, trefoil, vetch …) and their attractiveness during very long flowering periods (from early flowering such as fava beans to late flowering such as trefoil).

Agroecological elements in cultivated environments are essential ecological compartments for pollinating insects, providing habitats for nesting and meeting their nutritional needs. The bibliographic analysis identified 117 publications that correspond to studies evaluating these agroecological elements as an indirect factor in pollination service, outside cultivated plots. On this subject, the scientific articles focus mainly on the food resource (non-crop floral resource) and then, on the nesting or wintering grounds of bees (natural/semi-natural habitats). Finally, some articles treat the pollination service at the agricultural landscape scale.

The pace of scientific publications on the pollination service provided by bees has accelerated over the last 10 years. This acceleration of studies has also promoted an increase in the diversity of taxa monitored in the agroecosystems. Either the papers do not specify the insects studied ("pollinators"), or the studies are dedicated to particular genera or species from the families Apidae or Megachilidae (families *sensu* Danforth et al., 2013) or a mix of wild bees or pollinators. More precisely, a small majority of the literature studies concern the family Apidae (225 papers) with a particular focus on bees from the tribes Apini (101 articles including 76 on *Apis mellifera*) and Bombini (50 papers including 10 on *Bombus terrestris*) (Fig. 5). An equal proportion of the bibliography focuses on a broader scale of classification: that of pollinating insects (178 articles) or bees (44 publications), without specifying the species (in the title, key words or abstract). In both cases, the honeybee is usually considered in the study. Also, 69 publications focus only on wild bees (excluding *Apis mellifera*). Finally, the family Megachilidae represents 44 papers, of which 33 papers study the Osmiini tribe (five papers on *Osmia cornuta*, a common species in Europe). The other four families of wild bees (Melittidae, Colletidae, and especially the Andrenidae and Halictidae) are very neglected even though they correspond to almost half of the species in France. The last two families (corresponding to more than a third of French species) are also abundant and frequently observed pollinators in flowering crops (Kleijn et al., 2015). These families probably suffer from their difficulty of identification, which could be reduced by the diffusion of online identification tools in the future (https://www.idmybee.com/). This situation is sub-optimal, especially for the halictids, which are the subject of only 1% of studies on crop pollinators. Yet they are considered major crop pollinators, and one of the few groups of bees that seem to benefit from agricultural intensification and adapt well to agricultural landscapes (see Bartomeus et al., 2013). They are fairly abundant and ubiquitous in agroecosystems, both at national (Le Féon et al., 2016) and landscape scales (Rollin et al., 2015).

5. Case studies of France and Belgium with regards to pollinator conservation

5.1. Response to international initiatives

In this international and European context, France and Belgium developed their own assessments and contributed by different ways to build such scientific knowledge. After the Millennium Ecosystem Assessment, they used the method proposed by the FAO (see before) to estimate the economic benefits provided by pollination. For Belgium, the corresponding values are estimated to be 251.6 million euros and 11.1% of crop production (values for 2010) (Jacquemin et al., 2017). In France, an estimate of 2.3–5.3 billion euros and to 5.2–12.0% of crop production was made (values for 2010) (Beyou et al., 2016). The group of EFESE (French Evaluation of Ecosystems and Ecosystem Services) published a report about the pollination service, with a map of the pollination service and map of the vulnerability index (proportion of pollinator-dependent crops) detailed at the departmental scale (French administrative units) (Beyou et al., 2016).

French and Belgian scientists are also great contributors to the different reports of the IPBES. In France, the FRB (Foundation for the Research on Biodiversity, which is the national focal point of IPBES) published a report indicating more than 250 initiatives in favor of pollinators regarding the assessment performed by IPBES (FRB , 2016). Each initiative details the effect on pollinators and pollination, an explanation of the goal of the initiative, the level of use (currently used, used and tested, tested in pilot sites, suggested by IPBES), the actors involved (private individuals or companies, local public authorities, national public authorities, European Union), and several examples of local operational programs. This report is a "suggestion boxes" of local operational programs for different stakeholders to conduct actions in favor of pollinators, and its replication in other countries is merited to update a similar list of initiatives. The Belgian Biodiversity Platform is the IPBES Belgian focal point: their main activities consist in involving Belgian experts and stakeholders in IPBES work program and organizing regularly events and exchange meetings.

On a national scale, several Red Lists on wild bees have been developed in European countries over recent decades (Table 1; Drossart et al., 2019). As the methodology widely diverges among countries and as well as the number of assessed species, it is difficult to compare them. Nevertheless, the most complete and updated national Red Lists reported a high proportion of threatened bee species, namely in countries bordering France (Switzerland, Belgium and Germany). The bee fauna of Belgium is one of the most threatened with 55 threatened out of 112 assessed species; Fichefet et al. (2008) for Wallonia and Maes et al. (2012) for Flanders). Recently, Drossart et al. (2019) produced an assessment of the IUCN status of Belgian wild bees. Over the 403 assessed species, they highlighted that 32.8% were considered threatened (*i.e.* 113 species). In addition, 6.8% were assessed as Near Threatened (*i.e.* 26 species) and 11.8% were Regionally Extinct (*i.e.* 45 species), suggesting that more than half of the Belgian species (*i.e.* 184 species) are (nearly) threatened or extinct in Belgium. For 22 species that were collected only once in Belgium, these were assigned to the category Not Applicable (NA). Thirty-six species were assigned to the category Data Deficient (DD) because of insufficient information about their risk of extinction. Finally, the 161 remaining species were classified as Least Concern. In parallel, the will to establish a Red List on wild bees in France exists (see Philippe 2020; Terret et al., 2020), and it should become a reality in the coming years however depending on the politician's will to fund such initiative. Nevertheless, numerous Red Lists developed at a regional scale (e.g. the regions of Auvergne, Alsace, Picardie, Nord Pas-de-Calais) highlighted a higher proportion not for bee but for threatened butterfly species (Bachelard, 2013; Hubert and Haubreux, 2014; Imago, 2014; Picardie Nature, 2016). One challenge for France, as well as for other meridional countries, is to deal with the highly diversified Mediterranean bee fauna in the southern regions, which entails a suit of species complexes with an obvious deficiency in taxonomist expertise.

5.2. List of protected species and national action plans

In France, there is no national list of protected species for pollinating insects, except in butterflies, for which several dozen species are protected. However, there is a regional red list (in the Paris region of the Ile-de-France) which includes several Hymenoptera species (only seven species of bumble bees), some Lepidoptera species (48 diurnal and nocturnal species) and some pollinating beetles. In Wallonia (Belgian Region), 47 wild bee species as well as 40 butterfly species are currently under legal protection since 2001 while there is no legal protection in Flanders (except for one butterfly species, *Hipparchia semele*) and in the Brussels-Capital region. Among the protected bee species, some of them were assessed as Least Concern (LC) in the Belgian Red List (e.g. *Dasypoda hirtipes*) while others were Regionally Extinct (RE) (e.g. *Bombus distinguendus*). No hoverfly species are protected in Belgium.

In France, the National Action Plan (https://pollinisateurs.pnaopie.fr/plan-national/) was created for the period 2016–2020 by the ministry of environment to halt the decline of pollinators and preserve the pollination service (Gadoum and Roux-Fouillet, 2016). For this, twenty concrete actions were proposed to (i) improve the knowledge about pollinators and their conservation, (ii) favor a better scientific knowledge sharing and awareness-raising, and (iii) identify better and virtuous practices to promote for stakeholders of conservation. With too little funding from the French authorities, the results of this plan are modest overall, marked by the failure to reduce pesticides but by the emergence of regional action plans in almost all metropolitan regions. At the time of completion of this document, a new national plan is being drafted to continue and update a new set of conservation actions for pollinators. This more ambitious plan is co-sponsored by the Ministry of the Environment and the Ministry of Agriculture, with a view to ensuring consistency, particularly with regard to the necessary reduction in the use of pesticides and the ecological transition of agriculture, but also with regard to the no less necessary harmonization between beekeeping and the conservation of wild pollinators. There is also a complementary but independent National Action Plan developed in France for 38 species of butterflies (2018–2028), which develops convergent actions to foster the conservation of this taxonomic group (Houard and Jaulin, 2018). These two National Action Plans are being implemented at the regional level in the majority of French regions with varying level of success, thus multiplying actions by adapting them to regional contexts and actors.

In Belgium, the BELBEES project (Multidisciplinary assessment of BELgian wild BEE decline to adapt mitigation management policy; 2014–2018) financed by the Federal Public Planning Service Science Policy (BELSPO) aimed at (i) collecting and analyzing historical and recent data to document changes in wild bee populations in Belgium and (ii) assessing the respective roles of the different hypotheses on their decline (*i.e.* food resource depletion, habitat fragmentation and genetic homogenization, disease emergence, pesticide development and climate change). This national research program has led to establishment of a national Red List in Belgium (see above: Drossart et al., 2019). It has also highlighted several negative points for pollinator conservation:

- the decrease in the diversity of floral resources which has a global impact on the wild bee fauna (Moerman et al., 2017; Vray et al., 2017),
- the negative impact of climate change and land-use on bumblebees (Martinet et al., 2015; Rasmont et al., 2015, 2017; Marshall et al., 2017; Vray et al., 2019; Rollin et al., 2020),
- the manifestation of many unknown pathogenic associations in the bee and the fact that wild bees harbor their own set of parasites with little to no connection with honey bee diseases (Schoonvaere et al., 2016, 2018),
- and validation of two gene expression biomarkers as indicators of insecticide-induced stress under natural field conditions (De Smet et al., 2017).

Besides these two national action plans, there was also a relevant cross-border initiative, occurring in an area that shares a common pollinating fauna, specifically the two main regions of Belgium and the north of France. Therefore, to organize the protection of pollinators, it is necessary to consider their wider distribution and act at the scale of the entire cross-border area. Indeed, isolated actions from different sides of the border would have low chances to succeed and to lead to the sustainable management of the pollination resource. That is the goal of the Interreg SAPOLL (2016–2020; http://www.sapoll.eu) project which aims at initiating the creation of a cross-border action plan with partners from Wallonia, Flanders and the north of France. This plan is designed to encourage the development of actions for pollinator conservation by spreading scientific, educational and applied information to all - that is to citizens, stakeholders, business managers and managers of natural areas. Adapted to the local context of each region, it was developed together with the cross-border territory stakeholders and exposes the goals and issues for the area and the actions that need to be done for pollinator conservation. For this, 35 actions were divided into three axes: (i) knowledge enhancement; (ii) knowledge sharing and awareness-raising and (iii) pollinator support through concrete actions. This action plan is available on the SAPOLL website through a (i) numerical version available according to the type of activity, stakeholder or space but also (ii) a complete manuscript version (Folschweiller et al., 2019). Several novel achievements can be highlighted in the scope of the Interreg SAPOLL project (160 awareness raising actions were organized to >35,000 people; > 500 people followed our pollinator courses, creation of a cross-border database and >450 new sampled sites, >850,000 pollinator specimens). In the future, such cross-border initiative could be repeated in another geographical context such as between France, Switzerland and Italy in an Alpine context or between France, Spain (and Andorra) in a Pyrenean context, or even between Corsica (France) and Sardinia (Italy) in a Mediterranean context.

5.3. Raising public awareness of pollinator conservation

With regards to participative sciences, the Spipoll (http://www.spipoll.org/) is a French citizen science-based monitoring scheme of plant-pollinator interactions across France. It proposes to sample the flower visitors of plants using a standardized protocol based on photos, coupled with a website for the participants to visualize the data, discuss it and contribute to check data quality. These taxa have various taxonomic resolutions as most French flower visitors cannot be identified to the species level from photos. Participants can discuss each other's observations and take part in a collaborative validation process. Since 2010, more than 36,000 plant records have been sampled by more than 1500 observers. Such a sampling scheme associated with appropriate statistical methods can be used to investigate the response of flower-visitor richness, and composition, to a great variety of environmental variables. Results to date revealed contrasting effects of urban, agricultural and natural land uses on the diversity of flower visitors depending on the insect order studied (Deguines et al., 2014). These results show a focus on urbanization, a strong biotic homogenization of pollinator communities (Deguines et al., 2016), but also highlighted the mitigating effects of flower availability (Desaegher et al., 2018) and domestic garden (Levé et al., 2019). This dataset was also used to characterize the pollinator community of particular plants such as apple trees (Cornille et al., 2015), to track biological invasion (Le Féon et al., 2018a) or to map pollinator diversity over large areas (Theron et al., 2017). In addition to producing a large dataset to study plant-pollinator interactions, such citizen science projects link together a community of mostly neophyte observers that generates both academic and local knowledge (Pocock et al., 2016). A striking example of this is the

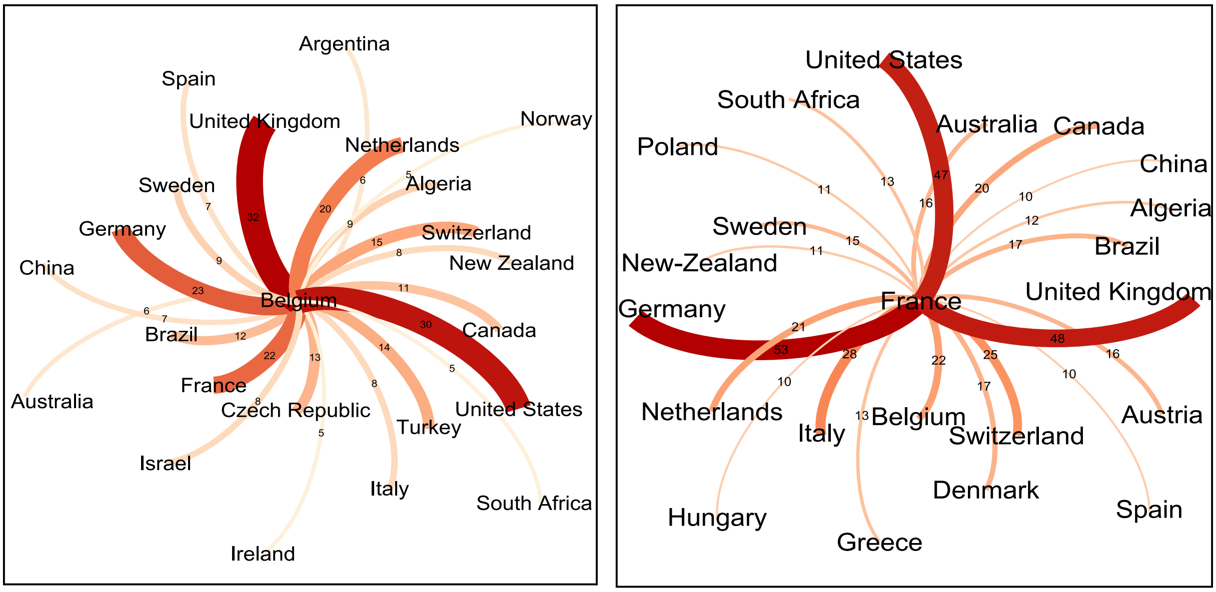

Fig. 3. Belgium and France co-authorship networks showing the recent (2013–16) international collaborative bee research. Numbers refer to referenced publication with shared authors between countries. Computed with the Gephi® software.

substantial increase of identification skills among Spipoll observers (Deguines et al., 2018; Wilson et al., 2017). In parallel, other citizen sciences programs emerged like the "Observatoire des Bourdons", funded in 2009 by the *Museum national d'Histoire naturelle* (MNHN) and the *Groupe Associatif Estuaire* (http://www.observatoire-asterella.fr/bourdons/). It is aimed to assess bumblebee population trends by uploading the observations of each citizen on a website hosted by the MNHN. Finally, there is also the exotic bee observatory, describing the ecology and updated progress of the Giant Resin Bee (*Megachile sculpturalis*) https://oabeilles.net/projets/observatoire-abeilles-exotiques (see also Le Féon et al., 2016; 2021; Le Féon and Geslin, 2018).

In Belgium, the citizen sciences system is jointly managed by two naturalist associations (Natagora in Wallonia and Natuurpunt in Flanders) and represents several hundred thousand of data points. At the same time as carrying out research projects (e.g. BELSPO BELBEES) or cross-border collaboration projects (e.g. Interreg SAPOLL), these structures have mobilized their volunteers in working groups whose aim to improve the monitoring of some specific groups and species and to improve the coverage of areas prospected. These naturalist associations also lead several local projects to draw up large inventories or target one specific bee species. These inventories help them to provide recommendations for wild-bee friendly management to public and local administrations. Thanks to their efforts, some intensively mown nutrient-poor lawns have been replaced by flower-rich meadows. More specifically in Wallonia, the "Quinzaine des Abeilles et des Pollinisateurs" proposed several hundred initiatives about the role and the importance of pollinators (conferences, documentaries, exhibition, workshops, etc.). In the Brussels region, BRUBEES project aimed to raise awareness of citizens and green space managers for the richness of wild bee species.

With the interest of many researchers and associations and the development of public awareness regarding pollinator decline, several initiatives from local to more global scale have emerged to document the trends and status of pollinators. In France, the French Bee Observatory, (Observatoire des abeilles, https://oabeilles.net/), and the Taxonomic Group Apoidea Gallica, mostly composed of French-speaking Belgians and French, have worked for many years to advance knowledge about wild bees. Over recent years, these two groups have actively worked to produce taxonomic lists from very local to larger scales. Thus, Le Féon et al. (2018b) as an example, referenced the bees of two small islands in Brittany; Dufrêne et al. (2017) listed the bees of the Ile-de-France Region and recently, an updated list of Western France has been produced (Observatoire des abeilles, 2018). These kinds of local initiatives also exist regarding Syrphid flies, (e.g. Top and Wartelle, 2015), and more globally for butterflies (Lafranchis, 2014). There is no doubt that many taxonomic lists, from the very local (private garden for example), to the country scale do exist, and referencing all these lists is beyond this paper's scope. However, it has not yet been possible to accurately document the trends of many groups of pollinators. Compared to Great Britain (see Else and Edwards, 2018), the detailed geographical distribution of the wild bees of France and Belgium is not known or published (except for the exotic bee *Megachile sculpturalis*, Le Féon et al., 2018a). Of course, this is worse for other groups, such as non-syrphid flies which are only a little studied. Taken together, the task to document the trends and status of French and Belgium pollinators appears immense, but we hope that the new initiative will help to fill this huge gap in our knowledge.

5.4. *Scientific research on pollinator conservation*

A few years ago, Maes and Van Dyck (2001) illustrated a substantial decline of the species richness of butterflies in Belgium (19 of the 64 species becoming extinct) using museum and private collections combined with field observations pre- and post- 1991. The decline of butterflies in France, Belgium and Luxembourg over 34 years was demonstrated with significantly higher rate of disappearance in urbanized and intensive agriculture areas of northwestern France and Belgium and a greater decline among habitat specialist species (Delpon et al., 2018). Declines of bumblebee populations have been demonstrated since 1972 in Germany and 1975 in Belgium (Leclercq et al., 1980). In Belgium, later studies confirmed these declines (Rasmont, 1988; Rasmont and Mersch, 1988). The huge dataset gathered by the team of Prof. Jean Leclercq at the University of Liège from the 70's, then by the team of Prof. Pierre Rasmont at the University of Mons represents thousands of maps, keys and taxonomic revisions that have been used for keystone studies in wild bee research (e.g. Kerr et al., 2015). For the first time in 1993, Rasmont et al. produced a comprehensive study about the status of Belgian wild bee species. They compared the distribution of 360 species before and after 1950, highlighting that 91 species were regressing, 145 species were stable, 39 species were in expansion and the status of 85 species was not evaluated. Finally, as mentioned above, the most up-to-date assessment about the population trends of Belgian bees consists in the Red List produced by Drossart et al. (2019).

Unfortunately, no comparable research program to the UK (in terms

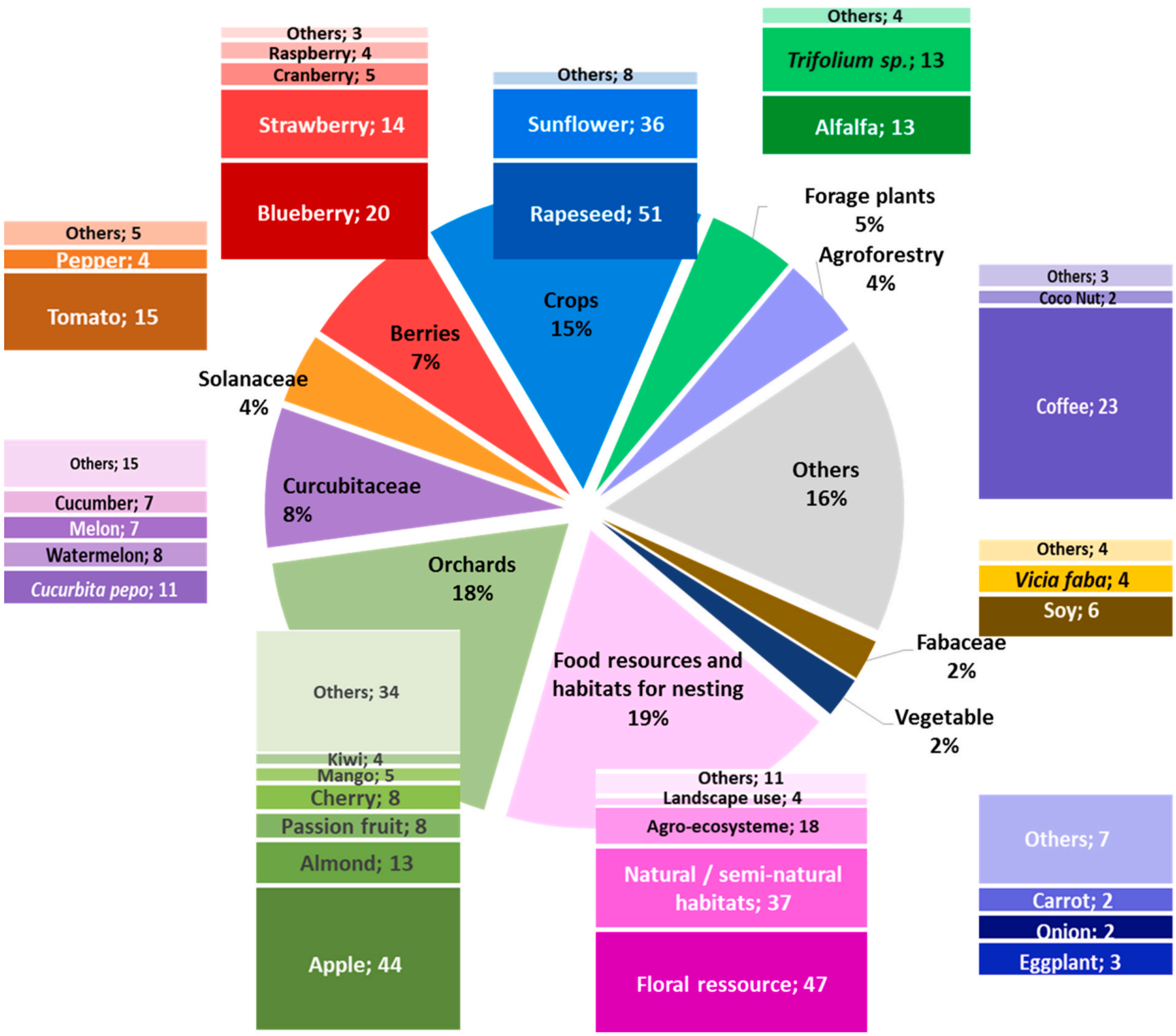

Fig. 4. Distribution of studies on the pollination service provided by bees according to the crop groups studied in agricultural areas. The detail of each item is represented by stacked histograms with the number of corresponding items. For histograms, the term 'others' refers to crops comprising only a minority of studies. For the "Other" group of pie charts (102 papers), it represents all the unidentified crops (in the title, key words and summary, as well as inter-category mixtures of cultures and minority cultures not classified in the large categories (aromatic plants, *Jatropha curcas* …).

of financial support) was developed in France or Belgium. For smaller amounts, there have nevertheless been several research programs that generate knowledge. Historically in France, there was the Urbanbees 2010–2015 program) which started research efforts on wild bees and their conservation (increase in favorable habitats, establish and disseminate management actions in favor of pollinators, and raise awareness among different publics (Fortel et al., 2014, 2016). Several programs funded by the ANR (National Agency of Research) have followed and have progressively involved the study of pollinators.

Regarding the standardized comparative bibliometric analysis, France is the third greatest contributor to bee research, followed by Spain and Turkey, while Belgium ranks 9th amongst European countries. International bilateral networks (Fig. 3) show that French bee research collaborations are dominated mainly by Germany, the United Kingdom and the USA, while Belgian researchers display a more balanced network, including substantial collaborations with the Netherlands, Switzerland and Turkey. However, for France as for Belgium, it is a pity to note the too low number of publications with Mediterranean countries (Spain, Greece, Portugal) or others close to the Black Sea (Hungary, Romania, Ukraine) given their taxonomic richness, but also large number of data deficient and/or threatened species. The two most prolific publishing institutions in France are INRA (renamed INRAE in 2020) and CNRS, ranking 1st and 7th, respectively, among the 1550 European affiliations recovered from the bee research literature in 2007–16 (Table 3). Those are also arguably amongst the largest research institutions in Europe. Belgium has three institutions within the top 20, namely Ghent (UGent), Louvain (UCL) and Mons (UMONS) universities.

As for the initiatives of supranational research groupings (SCAPE, UK Insect Pollinators Initiative, …), France, Belgium and Switzerland (French-speaking part for the latter), have also joined together to form the GDR Pollineco (research group on the theme of POLLINisation, interaction networks and ECOlogical functionalities) which is financed by the CNRS and the French Ministry of the Environment. Created in 2019, this group exists for 5 years (renewable for another 5 years) and currently brings together more than 160 researchers, technical staff and (post)doctoral students from some 40 laboratories. This group is very active in its collaborations between laboratories, co-publishes special issues, initiates actions with protected areas and decision-makers and develops identification tools (www.IDmyBEE.com) and awareness-raising and political decision-making tools in favor of pollinators.

6. Discussion and perspectives

We provided here an updated review of the international and

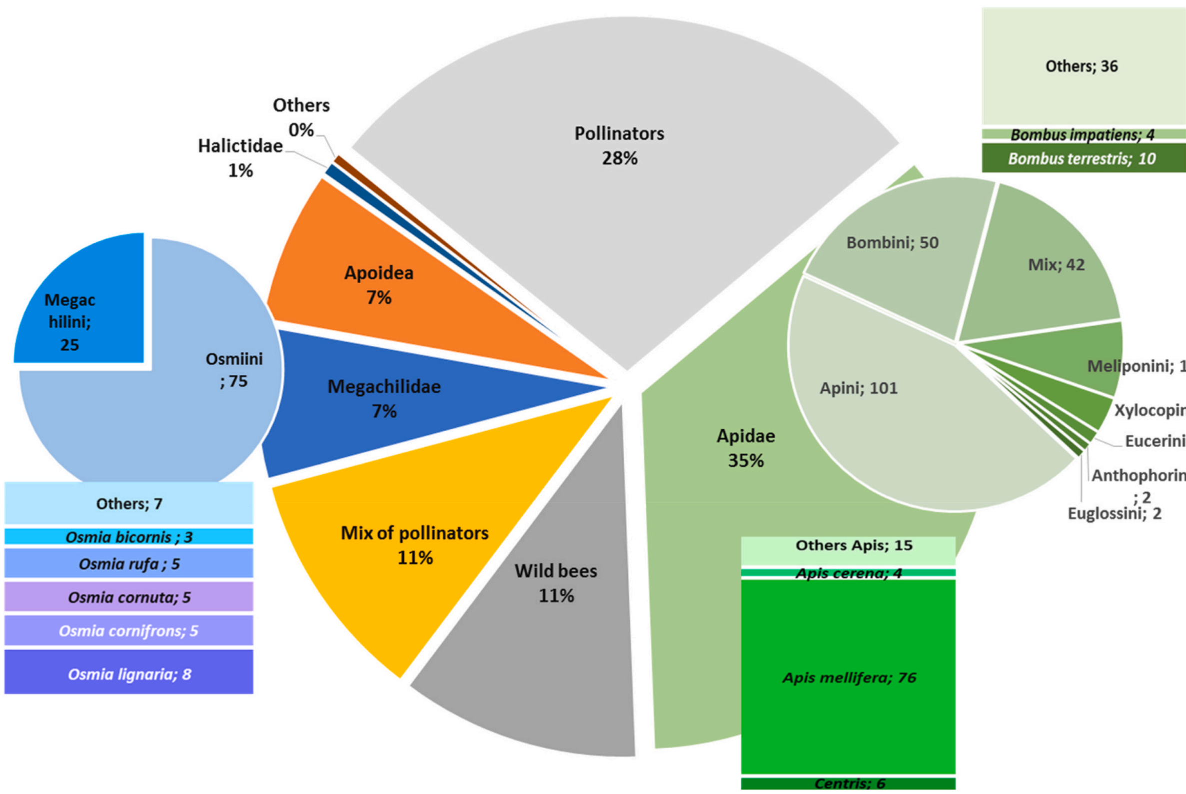

Fig. 5. Distribution of the groups of insects studied in publications focusing on bee pollination of crops with, for each category, the proportion of articles of the respective body of knowledge at worldwide scale. For families of Apidae and Megachilidae the details of tribes and species are given in pie charts, or histograms stacked with correspondent number of publications.

Table 3
Top-10 of the 1550 publishing European institutions with affiliations referenced in the bee research literature over 2007–16, and top-5 of the most publishing Belgian and French institutions, highlighted in grey.

European institutions	Country	Publication numbers (2007–16)	Rank
INRAE	FR	206	1
Univ_Halle_Wittenberg	DE	173	2
Univ_London	UK	170	3
Erciyes_Univ	TR	162	4
Univ_Wurzburg	DE	160	5
Agroscope	CH	159	6
CNRS	FR	153	7
Ghent_Univ	BE	137	8
Univ_Sussex	UK	135	9
CSIC_Spanish_Natl_Res_Council	ES	132	10
…			
Univ_Catholique_Louvain/ Katholieke_Univ_Leuven	BE	91	16
Univ_Mons	BE	87	20
Univ_Toulouse_3_Paul_Sabatier	FR	79	25
ANSES	FR	46	62
Univ_Liege_ULg	BE	41	71
Univ_Libre_Bruxelles_ULB	BE	38	81
MNHN_Museum_Natl_Hist_Nat	FR	30	109

national frameworks as well as the contribution to research for pollination and pollinator conservation, by ending with a focus on these actions in the France and Belgium cases. All this information and these resources are likely to concern a broad set of target audiences, including researchers, beekeepers, farmers, policymakers and the general public about pollinator conservation. We confirm here that national initiatives are relatively weak in countries with a low number of publications, which confirms that having a large national scientific community boosts the creation of action plans. Moreover, Cook et al. (2013) described four classical steps to achieve effective knowledge exchange in conservation science. i) boundary organizations spanning science and management, ii) scientists embedded in management agencies, iii) formal links with decision-makers at research-focused institutes and iv) training programs for practitioners. Several points of these approaches can be identified around the world but also at a European level. As well, the recent rise of citizen sciences in the UK (Roy et al., 2016), Belgium and France represent an opportunity to provide useful, qualitative and widely distributed occurrences of rare and common pollinator species (Dickinson et al., 2010). Indeed, this huge monitoring effort can be carried out in under-sampled areas, at larger scale and with a finer resolution (Hochachka et al., 2012).

To conclude, we can make the disappointing observation that although knowledge about pollinators and their relationships with plants is increasing worldwide, the decline of pollinators has never been so high as now! This paradox striking and is surely a sign that research must be redirected towards conservation actions by reducing or even eliminating negative effects (pesticides and biocides, habitat fragmentation and artificialization, various types of pollution) and promoting positive effects (increase in floral resources in abundance and diversity, connectivity between habitats). We should certainly not wait for this knowledge to be further increased before starting action to raise awareness of the general public and conserve this plant-pollinator interaction. The tremendous species diversity of both pollinators and plants and their difficult identification has certainly hindered the implementation of these actions. They have never been so many international and national reports on pollinators and their conservation, with such a concern to move from the fundamental to the operational. This factual observation should encourage pollination ecologists to carry out conservation actions, help decision-makers and conservation stakeholders make decisions and raise public awareness.

CRediT authorship contribution statement

Bertrand Schatz: Conceptualization, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Funding acquisition. **Drossart Maxime:** Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **Henry Mickael:** Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **Geslin Benoît:** Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **Allier Fabrice:** Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Savajol Colette:** Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Gérard Maxence:** Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition, &. **Michez Denis:** Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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