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Pollinators in life cycle assessment: towards a framework for impact assessment

Eleonora Crenna [a, 1], Serenella Sala [b, *], Chiara Polce [b], Elena Collina [a]

[a] Department of Earth and Environmental Sciences, University of Milano-Bicocca, Piazza della Scienza 1, 20126 Milan, Italy
[b] European Commission, Joint Research Centre, Institute for Environment and Sustainability, Via E Fermi 2749, 21027 Ispra, VA, Italy

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ABSTRACT

Human activities are threatening biodiversity at an unprecedented scale and pace, thus potentially affecting also the provision of critical ecosystem services, including insect pollination. Insect pollinators play an essential functional role in terrestrial ecosystems, supporting ecological stability and food security worldwide. Therefore, assessing impact on pollinators is fundamental in any effort aiming at enhancing the environmental sustainability of human production and consumption, especially in the agri-food supply chains. Different drivers are leading to pollinator populations' declines. Improving a supply-chain oriented assessment of the occurrence of pressure and impacts on pollinators is needed. However, current methodologies assessing impact along supply chains, such as life cycle assessment (LCA), miss to assess impact on pollinators. In fact, none of the existing life cycle impact assessment (LCIA) models effectively accounts for pollinators. Some LCIA models have mentioned pollination, but none has presented key drivers of impact and a proposal for integrating pollinators as target group for biodiversity protection within an LCIA framework. In order to devise a pathway towards the inclusion of impacts on pollinators in LCIA, we conducted a literature review of environmental and anthropogenic pressures acting on insect pollinators, potentially threatening pollination services. Based on the evidence in literature, we identified and described eight potential impact drivers, primarily deriving from industrial development and intensive agricultural practice: 1) intensified land use as a result of uncontrolled expansion of urban areas and modern agricultural practices; 2) use of pesticides; 3) presence of invasive alien plants; 4) competition with invasive alien pollinator species; 5) global and local climate change; 6) spread of pests and pathogens; 7) electro-magnetic pollution and 8) genetically modified crops. To account for these drivers in LCIA, there are specific modeling needs. Hence, the current study provides recommendation on how future research should be oriented to improve the current models and how novel indicators should be developed in order to cover the existing conceptual and methodological gaps.

1. Introduction

Over the last decades, human activities related to industrial development and agricultural intensification have threatened biodiversity and the provision of ecosystem services at an unprecedented scale and pace (CBD, 1992; Curran et al., 2011), almost leading to the so-called sixth mass extinction (Ceballos et al., 2015).

Ecosystem services arise when nature (in its broad definition) contributes toward meeting a human demand; they are, arguably, underpinned by biodiversity (Hooper et al., 2005; Haines-Young and Potschin, 2010). Biodiversity and ecosystem services have undergone dramatic, in some case irreversible changes: as such, also the provision of critical ecosystem services is potentially at risk (Koellner and Geyer, 2013; MEA, 2005), including those related to insect pollination. As a consequence, the overall human well-being profiting from goods and services provided by nature is also potentially threatened.

To date, different classification systems for ecosystem services are in use. They invariantly discriminate among: (i) provisioning services, i.e. the goods we obtain from ecosystems, such as water,

* Corresponding author. Tel.: +39 0332 786417.
E-mail addresses: e.crenna@campus.unimib.it (E. Crenna), serenella.sala@jrc.ec.europa.eu (S. Sala), chiara.polce@jrc.ec.europa.eu (C. Polce), elena.collina@unimib.it (E. Collina).
[1] Tel.: +39 02 64482840.

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timber, fish and agricultural products, which are all traded on markets; (ii) regulating and supporting services, i.e. the capacity of ecosystems to maintain a livable environment, which include the removal of pollutants from soil, air and water, or services which support crop production such as pollination and soil erosion control; and (iii) cultural services, i.e. the non-material benefits, essentially defined by human preferences, such as nature-based recreation and tourism.

Within the regulating and supporting ecosystem services (MEA, 2005; Soussana, 2014), pollination represents a critical life-support function which is crucial for planetary ecological stability and the provision of services and resources in the agri-food sector. Indeed, a broad variety of wild and domestic insects plays an essential functional role in both natural and managed terrestrial ecosystems (Kluser et al., 2010; Vanbergen et al., 2014). At the global level, insect pollinators are responsible for pollinating more than 80% of wild plant species and almost 75% of primary agricultural crops (Klein et al., 2007), providing mankind with global food supply and other fundamental goods and services.

Recently, the global biodiversity crisis has involved insect pollinator populations as well. Several authors have documented regional reductions in the abundance and diversity of wild bees and local decreases in other pollinator populations, such as hoverflies and butterflies (Aizen and Harder, 2009; Biesmeijer et al., 2006; Carvalheiro et al., 2013; Potts et al., 2015). Moreover, significant and constant declines in the number of managed honeybee colonies have been registered on a regional scale in both Europe and North America. This alarming situation may have serious implications. It would limit the future production of pollinator-dependent crops (VanEngelsdorp and Meixner, 2010), thus threatening the agricultural and economic systems human life relies on, and would considerably affect the maintenance of wild plant diversity and natural ecosystem stability. The services provided by insect pollinators form the basis of other important ecosystem services and their loss would limit the availability of goods for future generations (Singh and Bakshi, 2009). As a result, several international institutions, local authorities and non-governmental organizations have raised deep concerns regarding potential risks to global food security and natural ecosystem functioning (Allen-Wardell et al., 1998; Bauer and Wing, 2010; Steffan-Dewenter et al., 2005), thus appealing for the promotion of an environmentally sustainable development. An integrated approach is needed in the areas of agriculture and ecology that would reduce the trade-offs between food production, biodiversity and ecosystem services (Soussana, 2014).

Understanding and identifying the role of ecosystem services, their linkages with biodiversity and human activities and the pressures that endanger their provision have been the central point of recent research (MEA, 2005; Zhang et al., 2010a, 2010b). Previous studies have already highlighted the main threats leading to pollinator populations' declines and potentially menacing the provision of pollination services (Gonzalez-Varo et al., 2013; Potts et al., 2010; Schweiger et al., 2010; Vanbergen et al., 2013, 2014). Furthermore, numerous attempts have been made in order to quantify the magnitude of human interventions leading to biodiversity loss and ecosystem service depletion (Curran et al., 2011; Koellner and Geyer, 2013; Schmidt, 2008). Despite all those efforts and the link with supply chains related impacts, life cycle oriented methodologies still miss to account for them. A lack of accounting for regulating and supporting ecosystem services would overthrow the goal of Life Cycle Assessment (LCA) methodology towards sustainability (Singh and Bakshi, 2009).

The development of models and indicators for biodiversity and ecosystem services in Life Cycle Impact Assessment (LCIA) has been underway for more than a decade. To our knowledge only a few studies so far have been conducted to integrate pollinators and pollination services in the LCIA framework. Zhang et al. (2010a, 2010b) proposed a framework for an ecologically based LCA, which accounts for the contribution of a handful of ecosystem services in the life cycle of industrial activities. Nevertheless, it remains not comprehensive (Singh and Bakshi, 2009).

In an era of extreme environmental changes induced by resource exploitation, it becomes necessary assessing the sustainability of production and consumption pattern in the agri-food sector, improving the existing supporting methodologies to reach the goal of a sustainable food system (Soussana, 2014). Therefore, it is fundamental including the natural capital, particularly pollinators' biodiversity and their crucial ecosystem services, in those life cycle oriented methods, such as LCA, since none of the existing LCIA methods and models accounts for their role in a comprehensive way.

The aim of the present study is to review the anthropogenic and environmental drivers exerting pressures on pollinators. This review represents the first step towards the integration of pollinators and their services in the LCIA framework. Starting from pollination as pivotal ecosystem service and pollinators as target group for biodiversity protection, this review aims to identify the modeling needs for the impact assessment in the LCIA context. Our study represents a bridge between ecological science and global product policies. Through the implementation of LCIA models and methods capable of accounting for ecosystem services such as those delivered by pollinators, we might be able to reduce anthropogenic impacts, thus meeting the goal of a more sustainable food production and consumption system.

This review is organized as follows: Section 2 is presenting the methodology adopted for the review; Section 3 presents the results of the review and it is followed by Section 4, where we discuss how to introduce the assessment of the drivers of impact on pollinators within LCIA.

2. Methodology

We conducted a review of scientific articles and reports focusing on evidence of impact on pollinator populations and pollination services. We carried out the literature search using the bibliographic database SCOPUS and the 'ConservationEvidence.com' website, a free authoritative information resource designed to support the protection of global biodiversity. We performed a preliminary search using headings based on combinations of broader terms related to pollination issues ((pollinator* OR pollination) AND (decline* OR loss* OR threat* OR impact* OR risk*)), in order to enable an early understanding of the current forces exerting pressures on pollinator populations. Then, in order to limit the results to the explicit impact drivers resulting from the preliminary search, we refined the search using more detailed criteria. We used relevant and logical keywords referring to the specific impact driving forces as follows: 'land use change', (land OR habitat) AND (transformation* OR degradation), 'chemical emissions', 'pesticide*', 'insecticide*', (invasive OR alien) AND species', 'invader*', 'competition', 'climate change', (phenological OR spatial) AND mismatch, 'pests', 'pathogen*', 'disease', (electric OR magnetic) AND 'field*' and 'electromagnetic radiation*', (GM OR genetically modified OR transgenic) AND crops. These keyword variations were combined with the above-mentioned broader terms on pollination issues using the Boolean command 'AND'. The outputs included reviews, laboratory- and field-based studies, and scientific reports manifesting clear impacts on pollinator communities and pollination services and suggesting what ecological indicators are currently adopted to measure the effects of impact drivers on pollination systems. The great majority of the selected papers proceeded from peer-reviewed journals and publications of European Agencies, such as the European Food Safety Authority (EFSA) and European Academies' Science Advisory Council. The publication years ranged from 1975 to date: we initially focused on recently published outputs (2001–2015); then, we opened a specific time window from 1975 to 2000 to include a wider variety of studies in terms of substances assessed (e.g. for ecotoxicity). We excluded studies reporting no documentation on the pressures which pollinators are subjected. We created a database (see Tables S1 and S2 in Supplementary Material (SM)) to enable efficient grouping and subsequent analysis of these studies. Information recorded included authors and publication date, brief paper description, impact driver categories, pollinator group affected, resulting effects on pollinators and their services, data type, modeling approach and indicators of impact and damage.

3. Review results: drivers and impacts responsible for insect pollinators' decline

Applying to the abovementioned keywords and criteria, we selected 108 published studies investigating different drivers involved in the pollinator crisis. The analysis of the scientific outputs revealed that the published research in this area has recently increased (Fig. 1). For instance, nearly 64% of the outputs were published from 2010 to the present (2015, with cut-off date on June 2015), about 30% between 2001 and 2009, leaving 6% of the outputs produced between 1975 and 2000 included.

This increase can be attributable to the recent growth of awareness among the wider public towards the key role that pollinators play for the global food security and its socio-economic stability.

Of the total collected outputs, 29 were reviews, 15 scientific reports and 64 research articles, whose features are briefly described in Supplementary Material (Table S1). Nearly the totality of the retrieved reviews (22 out of 29) was monothematic, focusing on the identification and analysis of a single category of impact, whereas the remaining seven reviews had a more holistic approach. We referred to these latter outputs as "multi-impact" reviews, since they gave a comprehensive understanding of the main possible pressures contributing to the decline of insect pollinator populations. In some "multi-impact" reviews authors reported descriptive or experimental analyses of interactive effects between biotic and/or abiotic stressors on pollinators (see Table S3 in SM). Amongst the selected reports, nine of them proceeded from European institutions such as the European Food Safety Authority (EFSA, 2013a, 2013b, 2013c, 2013d, 2014, 2015a, 2015b, 2015c) and the European Academies' Science Advisory Council (EASAC, 2015).

Authors investigated the relationships between human and environmental pressures and pollinator population declines through laboratory- and field-based experiments with the aim of identifying a cause-effect chain.

The majority of the selected papers tended to focus on the European honeybee (*Apis mellifera*), and to a lesser extent on bumblebees (*Bombus* spp.). Among non-Hymenoptera pollinators, dipterans, especially hoverflies (*Syrphidae* family), and lepidopterans resulted to be the most investigated (Table 1).

The review led to the identification of eight impact drivers menacing insect pollinator populations, namely: 1) intensified land use as a result of uncontrolled expansion of urban areas and modern agricultural practices; 2) use of pesticides; 3) presence of invasive alien plants; 4) competition with invasive alien pollinator species; 5) global and local climate change; 6) spread of pests and pathogens; 7) electro-magnetic pollution (including electro-magnetic radiations, electric charges and magnetic field fluctuations) and 8) genetically modified (GM) crops (Tables 2 and 3). For instance, nearly 21% of the outputs dealt with land use related issues, representing the most investigated impact driver, whereas GM crops and their potential impacts represent the least covered area, with only 4% of retrieved outputs. A more detailed analysis for each driver is reported below (Table 4).

3.1. Land occupation and transformation

Recently, research has been focused predominantly on 'land use' and the impacts on pollinator populations, derived from its changes. The intensification of agricultural practices as well as the uncontrolled expansion of urban and sub-urban areas have severely modified the natural environment. Natural and semi-natural habitats have been deteriorated, with negative consequences for pollinators and their services (Burkle et al., 2013; Gonzalez-Varo et al., 2013; Kluser et al., 2010; Lautenbach et al., 2011; Ollerton et al., 2014; VanEngelsdorp and Meixner, 2010; Winfree et al., 2009). Almost all the authors agreed that monoculture expansion and the subsequent natural habitat fragmentation are the primary causes of pollinators' abundance and diversity loss (Holzschuh et al., 2011; Kells et al., 2001; Kluser and Peduzzi, 2007; Ricketts et al., 2008; Le Feon et al., 2010; Morandin and

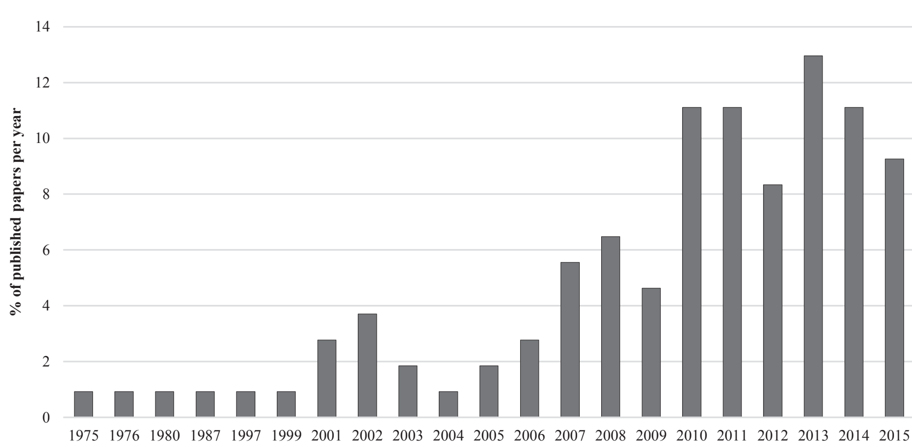

Fig. 1. Publications per year as selected in our review. X axis reports the publication years of the literature search (from 1975 to 2015). Y axis reports the relative number of published papers per each year, calculated as the percentage of selected papers per year divided by the total number of selected papers.

Table 1
Overview of the total number of outputs published for each type of investigated pollinator taxon.

	Impact drivers categories[a]									
	A	B	C	D	E	F	G	H	I	Total[b]
Total n°. of outputs	16	23	23	7	5	11	9	10	4	108
N.° of papers on honeybees (*Apis mellifera*)	10	19	20	5	1	4	8	10	4	81
N.° of papers on bumblebees (*Bombus* spp.)	11	20	12	7	4	5	1	0	1	61
N.° of papers on other Hymenoptera (e.g. solitary bees, wasps, etc)	9	19	7	4	1	5	1	0	1	47
N.° of papers on Coleoptera	3	5	1	2	0	2	0	0	0	19
N.° of papers on Diptera	5	9	1	4	0	3	0	0	0	22
N.° of papers on Lepidoptera	5	5	1	4	0	3	0	0	2	14
N.° of papers on other or not specified pollinators	4	5	0	1	1	2	0	0	1	14

[a] A) Multi-impact, B) land occupation and transformation, C) ecotoxicity, D) presence of invasive alien plant species, E) competition with invasive alien pollinator species, F) climate change, G) pests and pathogens, H) electro-magnetic pollution and I) genetically modified crops.
[b] One paper can cover one or several types of pollinator taxa. Therefore, in the last column, the sum of the number of papers for each pollinator taxon is not necessarily equal to the total number of papers.

Table 2
Total number and percentage of outputs, divided per impact category, reporting impacts on pollinator populations. Output types are reported for each impact category. Invasive alien plant and pollinator species have been included in a macro-category named "invasive alien species"; the category named "electro-magnetic pollution" includes electro-magnetic radiations, electric charges and magnetic field fluctuations.

		Output type					
	Impact driver category	Reviews	Reports	Research articles	**Total n.° outputs**	**% outputs**	
0	Multi-impact	7	4	5	16	14.8	
1	Land occupation and transformation	6	-	17	23	21.3	
2	Ecotoxicity	5	8	10	23	21.3	
3	Invasive alien plant species	-	-	7	7	6.5	Invasive alien species: 12 total outputs 11.1%
4	Invasive alien pollinator species	2	-	3	5	4.6	
5	Climate change	3	-	8	11	10.2	
6	Pests and pathogens	5	2	2	9	8.3	
7	Electro-magnetic pollution	-	-	10	10	9.3	
8	Genetically Modified crops	1	1	2	4	3.7	
	Total:	**29**	**15**	**64**	**108**	**100**	

Winston, 2005; Rands and Whitney, 2010; Vanbergen et al., 2013, 2014; Winfree et al., 2011). The massive introduction of monoculture crops such as maize, oilseed rape and sunflowers has played a crucial part in reducing ecosystem biodiversity, leading to a significant decline of wild floral plant abundance and diversity which insect pollinators depend on for nesting and foraging (Holzschuh et al., 2011; Kennedy et al., 2013; Klein et al., 2007; Weiner et al., 2011). Extreme changes in landscape structure include the fragmentation of natural and semi-natural habitats associated with the expansion of agricultural crop fields. These changes result in the rise of barriers to gene flow between populations (Garibaldi et al., 2011; Goverde et al., 2002; Nielsen et al., 2012; Steffan-Dewenter

Table 3
Number of multi-impact outputs that report the effects of a specific impact driver category. Invasive alien plant and pollinator species have been included in a macro-category named "invasive alien species"; the category named "electro-magnetic pollution" includes electro-magnetic radiations, electric charges and magnetic field fluctuations.

	Impact driver category	**N°. of multi-impact outputs ***	**% of multi-impact outputs ***	
0	**Multi-impact**	**16**	**100**	
1	Land occupation and transformation	9	56.3	
2	Ecotoxicity	11	68.8	
3	Invasive alien plant species	8	50.0	Invasive alien species
4	Invasive alien pollinator species	11	68.8	
5	Climate change	11	68.8	
6	Pests and pathogens	11	68.8	
7	Electro-magnetic pollution	2	12.5	
8	Genetically Modified crops	3	18.8	

* Each multi-impact output deals with more than one driver; therefore, in the second and third columns, the sum of the number of papers for each driver does not necessary correspond to the sum of multi-impact outputs.

Table 4
Summary of the potential direct and indirect effects of each impact driver category on insect pollinators and pollination services.

	Impact driver categories	Potential effects on insect pollinators and pollination services	
		Direct effects	Indirect effects
1	Land occupation and transformation	Loss of natural and semi-natural habitats meaning loss of favorable nesting sites and food supply; pollinators tend to remain in isolated fragments, which act as barrier to gene flow; subsequent loss of pollinator species richness and abundance	Local species extinction; consequent lower visitation rate to flowering plants in fragmented areas; resulting pollination deficit. Biotic homogenization, with loss of specialist pollinators; resulting pollination deficit Wild plant biodiversity loss due to the tendency of pollinators to forage in huge monoculture fields where the density of floral resources is higher than in natural margins; resulting pollination deficit
2	Ecotoxicity	Potential toxic lethal (i.e. premature individuals' death and colony collapse) and sub-lethal effects, due to poisoning for direct exposure to pesticide spray and dust or for ingesting contaminated pollen and nectar (e.g. disrupted foraging activity, impaired homing ability, reduced learning performances)	Pollination deficit as a result of pollinators' loss
3	Invasive alien plant species	Double effect: Invasion by non-native plants, which compete with native plants for pollination. Facilitation of both the survival of native pollinators when food resources are scarce, and native plant reproduction.	Reduced pollination success of native species Positive effect on pollination of native plants. Potential for hybrid formation, which may have poor germination rate and limited growth; resulting pollination deficit.
4	Invasive alien pollinator species	Competition for food resources and nest sites; displacement of native organisms toward less profitable forage leading to limited quantity of pollen carried to the hive.	Spread of exotic pests and pathogens causing infections leading in some cases to death; resulting pollination deficit.
5	Climate change	Loss of synchrony (phenological mismatch) between insect pollinator activity and flowering/fruiting time; geographic shifts (e.g. migration) with species either losing or expanding their range.	Local species extinction with negative consequences on the structure and the functioning of plant-pollinator systems; resulting deficit in the provisioning of pollination ecosystem services; reduction in reproductive success and species richness of both pollinators and plants (e.g. reduced seed production in crop plants); competitive relationships among species or hybridization
6	Pests and pathogens	Infections predominantly reducing colony growth, disrupting foraging activity, orientation skills and behavioral performances.	Spread of other parasites, particularly virus, causing secondary infections leading in some cases to death; resulting pollination deficit.
7	Electro-magnetic pollution	Behavioral and physiological changes (e.g. increased aggressiveness, irritability and hyperactivity, increase in piping signal, disrupted homing ability, decline in colony growth, decrease in the activities of seminal enzymes in drones)	Death due to hyperactivity, disorientation and premature swarm; resulting pollination deficit.
8	Genetically Modified crops	Potential toxic sub-lethal effects similar to those caused by pesticide exposure, for ingestion of nectar/pollen containing toxins (e.g. antifeedant effect, reduced learning ability, altered flight activity).	Tendency of GM plants to hybridize with sexually compatible native plants, increasing the risk of plant diversity extinction; resulting loss of pollination services.

and Tscharntke, 1999), potentially causing their isolation from one other, and thus increasing the risk of pollinator species extinction in the long term (Kremen et al., 2007) and facilitating the disruption of plant-pollinator mutualisms with resultant severe pollination deficit. In fact, as a consequence of this progressive amalgamation at the landscape level in favor of monoculture croplands, insect pollinators have gone through a sort of “biotic homogenization”, thereby altering the structure and the stability of plant-pollinator communities at local and regional scales (Carvalheiro et al., 2013; Rands and Whitney, 2010; Winfree et al., 2011). The pollination service is driven by both generalist and specialist pollinators. Both the two groups contribute to maintain biodiversity, which underpins pollination services. Their vulnerability to environmental and anthropogenic pressures is different due to their ecological traits: specialists are more susceptible to changes than generalists, since they rely on limited varieties of plants for feeding and nesting. For instance, in the long term, specialist pollinator species that depend on floral and habitat resources threatened by land transformations, are expected to be lost in favor of generalist species, which in turn will dominate anthropogenic habitats (Donaldson et al., 2002; Steffan-Dewenter et al., 2002; Vanbergen et al., 2013; Winfree et al., 2011). Indeed, loss of specialist pollinators' species means loss of species richness and abundance; it consequently means loss of a certain amount of pollination service, since generalists would not be able to completely supply pollination services provided by specialists.

The expansion of urban and sub-urban areas has similar negative effects on the environment and its inhabitants, as agricultural intensification. Ahrne et al. (2009) and Bates et al. (2011) observed that urban sprawl towards the countryside has a significant impact on flower-visitor communities. Indeed, the abundance of insect pollinator populations significantly changes through the urban-rural gradient, with mainly generalist species populating urban degraded sites.

3.2. Ecotoxicity

According to the results of our review, pesticides represent another important threat to biodiversity of pollinators that visit cultivated fields and natural edges nearby. It has long been known that pesticides are a cause of concern for pollinators, especially for bees. The increasingly massive use of plant protection products in modern agriculture and their potential impacts on pollinators have received considerable attention especially over the last decades. Within the various classes of insecticides, recent research has been focused on neonicotinoids.

Almost all of the analyzed studies (such as Kessler et al., 2015) proposed an experimental approach, predominantly based on controlled experimental settings in laboratory, focusing almost exclusively on chronic oral exposure of adult bees. Honeybees and, to a lesser extent, bumblebees were fed with a sucrose solution containing field realistic, sub-lethal concentrations of pesticide, within the range found in crop nectar and pollen in the field, in order to evaluate the effects of the exposure as close as possible to real conditions. In some cases, such as in Gill et al. (2012) and Henry et al. (2012), experiments were performed under semi-field conditions: pollinators received contaminated nectar or pollen in laboratory and then were let free to move and forage into the field.

Only some authors have investigated the effects of neonicotinoids on solitary wild bees, both under laboratory and field conditions, assessing both contact and oral exposure (Blacquiere et al., 2012; Brittain and Potts, 2011; Rundlof et al., 2015).

Pollinators are not target organisms of neonicotinoids, but they may recurrently be directly or indirectly exposed to such chemicals as a consequence of their foraging activities. As systemic pesticides, neonicotinoids are taken up by the plant and transported to all the tissues (leaves, flowers, roots and stems, as well as pollen and nectar). Both lethal and sub-lethal effects have been identified through the literature search. All the retrieved articles mentioned at least a sub-lethal effect, whereas registered evidence of seasonal individuals' mortality in pollinators was limited (e.g. Kessler et al., 2015). Laboratory- and field-based studies allowed authors to record disruption of some pollinators' abilities. In particular, chronic exposure to field realistic, sub-lethal concentrations of neonicotinoids can affect pollinator reproductive performance and social behavior, leading in some cases to loss of species richness and decline in population size (Sandrock et al., 2014). The majority of authors recorded altered foraging activities (EFSA, 2013a, 2013b, 2013c, 2013d; EFSA, 2015a, 2015b, 2015c; EASAC, 2015; Gill et al., 2012; Kessler et al., 2015) or behavioral changes like impaired olfactory memory, learning dysfunction and alteration of navigation skills leading to failure in the ability of relocating the hive (Blacquiere et al., 2012; Brittain and Potts, 2011; EASAC, 2015; Godfray et al., 2014; Goulson, 2013; Henry et al., 2012; VanEngelsdorp and Meixner, 2010). Especially in bumblebee colonies, authors observed reduced colony growth due to a decline in brood and queen production, potentially resulting in premature colony collapse (Gill et al., 2012; Godfray et al., 2014; Goulson, 2013; Rundlof et al., 2015; Whitehorn et al., 2012). The exposure to sub-lethal doses of neonicotinoids may also significantly elevate vulnerability to certain pathogens, as described in Doublet et al. (2015) and Pettis et al. (2012), increasing the mortality rate of bees.

Overall, neonicotinoids used on mass flowering crops may affect pollinator health and performance, but still represent a controversial topic in scientific and policy context. Based on scientific findings indicating that some insecticides belonging to neonicotinoid group showed high risks for bees (EFSA, 2013a, 2013c, 2013d), in 2013 the European Commission restricted the use of three pesticides. However, even though there is strong evidence for important sub-lethal effects, to date there is little evidence outside controlled experimental settings (Godfray et al., 2014), being Rundlof et al. (2015) one of the few studies reporting field condition of the experiments.

Through a specific search for other plant protection products, we selected five additional papers showing effects on pollinators exposed to non-neonicotinoid pesticides. Similar to neonicotinoids, other pesticides such as pyrethroids, organophosphates and carbamates may alter learning, foraging and homing ability of pollinators and impair their biological development (Taylor et al., 1987; Thompson, 2003). Evidence of reduced survival in adult bees exposed to other pesticides different from neonicotinoids was registered as well (Balanca and De Visscher, 1997; Barker et al., 1980; Kevan, 1975).

3.3. Invasive alien species

Along with chemical emissions, invasive alien species (IAS) are considered another leading cause of biodiversity loss worldwide, after habitat alteration (EC-JRC, 2015). They are novel species in their non-native range that act through the modification of plant-pollinator communities, thus having mainly adverse effects such as resource depletion and competition (EC, 2014).

IAS, introduced accidentally or intentionally for economic purposes especially in the agricultural sector, may alter natural plant-pollinator communities and the structure of their networks. The majority of the studies showed that non-native plants generally invade and monopolize ecological interactions, competing with native plants for pollination, thus potentially provoking disruption of native species connections and reducing the pollination success of native species (Aizen et al., 2008; Brown and Mitchell, 2001; Brown et al., 2002; Chittka and Schurkens, 2001; Kluser and Peduzzi, 2007; Larson et al., 2006; Lopezaraiza-Mikel et al., 2007; Vanbergen et al., 2014). Only a few authors (Bartomeus et al., 2008; Munoz and Cavieres, 2008) described how invasive alien plants may, in some cases, facilitate both the survival of native pollinators when food resources are scarce, and native plant reproduction. Indeed, non-native plants can attract native pollinators to areas populated by both native and non-native species that otherwise they would not visit, positively affecting the pollination of native plants.

Even the introduction of alien insects can have strong impacts on native ecological communities. Non-native insects may prey on native pollinators (Monceau et al., 2014) or compete with them for floral resources or nesting sites (Goulson, 2003; Nagamitsu et al., 2010; Stout and Morales, 2009; Thomson, 2004, 2006; Traveset and Richardson, 2006; Vanbergen et al., 2013, 2014). Alternatively, they may modify native plant-pollinator communities, with a possible displacement of one or more native pollinator species towards other areas and leading to local losses of pollinator specialists. These events, associated with the increasing role of non-native generalist species and their potential to hybridize (Schweiger et al., 2010), may have alarming consequences such as biodiversity and pollination loss in natural ecosystems (Aizen et al., 2008; Stout and Morales, 2009). Non-native pollinators can also act as dispersal vectors of exotic parasites and related diseases, potentially leading to the collapse of native pollinators' colonies (Goulson, 2003; Traveset and Richardson, 2006).

3.4. Climate change

Several authors have investigated how changes in climatic conditions are likely to affect plant-pollinator networks. Changes in climatic conditions may act on the occurrence of insect and plant species (Ewald et al., 2015), thus causing temporal or spatial mismatches between pollinator populations and the floral resources they rely on. These mismatches can potentially lead to local species extinction with expected consequences on the structure and the functioning of plant-pollinator systems and, as a result, on the provisioning of ecosystem services such as yield derived from pollinator-dependent crops (Bellard et al., 2012; Polce et al., 2014). Fluctuations in the flowering and fruiting periods and a general contraction of the growing season may partially or completely disrupt the natural time-sensitive relationships between plant blooming time and pollinator flight period, resulting in potential negative consequences which alter the rates of reproduction and survival of both plants and pollinators (Kluser et al., 2010; Robbirt et al., 2014). Indeed, under climate warming, plant and insect phenology may not respond equally to changes in climatic conditions, and the natural synchrony may be lost (Gordo and Sanz, 2005; Schweiger et al., 2010). Moreover, climate change may trigger modifications in the geographic distribution of floral resources, influencing the composition of pollinator populations and the spatial dislocation of processes like pollination (Polce et al., 2014; Vanbergen et al., 2014). As a result of the above-mentioned aspects, a decline in nectar production and pollen availability may occur, bringing about concerning consequences such as reductions in pollinator fitness and species richness (Le Conte and

Navajas, 2008; Memmott et al., 2007; Petanidou et al., 2014) and declines in plant reproductive success (Hegland et al., 2009; Kudo and Ida, 2013). Climate-induced temporal and spatial shifts may therefore be particularly detrimental for specialized plant-pollinator mutualisms (Kuhlmann et al., 2012; Le Conte and Navajas, 2008; Polce et al., 2014).

As reported by Schweiger et al. (2010) and Pradervand et al. (2014), climate change may also affect morphological matching of plant and pollinator species, homogenizing morphological diversity and modifying population patterns with the prevalence of more generalized species, which are more adaptable to climate variations.

3.5. Pests and pathogens

During the last decades, the enormous increase in trading and the degradation of ecosystems caused by human activities such as the sprawl of urban or peri-urban areas and the expansion of intensive farming have facilitated the spread of parasites and other pathogens that may affect both managed and wild pollinators (Gonzalez-Varo et al., 2013; Kluser et al., 2010).

Most of the evidence on threats to pollinators from pathogens and diseases around the world comes from managed honeybees, which represent the model species in the nearly totality of retrieved papers. The analysis of the outputs highlighted that an assembling of pathogens has been clearly implicated in the so-called "Colony Collapse Disorder" (CCD), a recent documented phenomenon of sudden bee colony death, with a loss of healthy adult bees in the hives, that has occurred especially in Europe and North America (Kluser et al., 2010). Infections with the acarine mite *Varroa destructor* (Le Conte et al., 2010; Rosenkranz et al., 2010) and the small hive beetle *Aethina tumida* (Charrière, 2011; Cuthbertson et al., 2008; Ellis and Delaplane, 2008; FERA, 2013) are unanimously considered the most detrimental pathologies to honeybees worldwide, with high impact on terrestrial ecosystems (EC-JRC, 2015). Both parasites affect bee colonies predominantly reducing the number of adult foragers and increasing the mortality of brood (Ellis and Delaplane, 2008). Moreover, *V. destructor* contributes to transmit a broad array of other pathogens, particularly viruses such as Deformed Wing Virus (DWV), Acute Bee Paralysis Virus (ABPV), Israeli Acute Paralysis Virus (IAPV) and Kashmir Bee Virus (KBV) (Charrière, 2011; FERA, 2013; Kluser and Peduzzi, 2007; McMenamin and Genersch, 2015; Meeus et al., 2011; Vanbergen et al., 2014; VanEngelsdorp and Meixner, 2010), which are implicated in secondary infections leading to colony immune weakness and death. Microsporidia of the genus *Nosema*, such as *Nosema ceranae* (Dussaubat et al., 2013), and bacterial diseases such as European (Forsgren, 2010) and American foulbroods (EFB and AFB respectively), are other causes of increased mortality of infected bees and reduced performance and productivity of colonies (Charrière, 2011; Dussaubat et al., 2013; FERA, 2013; Vanbergen et al., 2013). All these diseases and disease-causing agents may potentially cause the failure of pollinator communities, with likely negative effects also on the services they provide (e.g. pollination of crop and natural vegetation).

3.6. Electro-magnetic pollution

Most recent research has identified electro-magnetic pollution as a potential additional threat to insect pollinators. We decided to include electric charges, magnetic fields and electro-magnetic radiations in the same impact category because of their similar effects on insect pollinators, and a similar underpinning cause-effect chain.

The majority of studies dealt with electro-magnetic radiations and was carried out by the same authors who improved their own investigations with supplementary experiments in subsequent years. Honeybees were unanimously chosen as a model organism since they are good biological indicators for electro-magnetic pollution (Ferrari, 2014). Radiations transmitted by cell towers and cell phones have been recognized to be the major sources of electro-magnetic pollution, significantly affecting the biological and physiological processes in bees (Kumar, 2012). There is clear evidence that honeybees exposed to high or low energy fields or electro-magnetic radiations tend to suffer dramatic behavioral and physiological changes in both laboratory- and field-based experiments. Exposed honeybees showed increased aggressiveness, irritability and hyperactivity (Dalio, 2015; El Halabi et al., 2013; Kumar et al., 2011; Warnke, 1976), resulting in a premature swarming process (Favre, 2011). Cell phone radiations can alter even navigational skills of bees: numerous authors measured statistically significant decreases in the number of adult bees returning to their colonies under field conditions (Dalio, 2015; El Halabi et al., 2013, 2014; Ferrari, 2014; Sahib, 2011; Sharma and Kumar, 2010). Several authors observed also that colonies exposed to electro-magnetic pollution were subjected to a strong decline in their brood productivity with a reduction in egg laying rate of queen (Dalio, 2015; El Halabi et al., 2013, 2014; Sahib, 2011). In addition, Kumar et al. (2011) and Kumar (2012) recorded a considerable increase in the concentration of biomolecules such as carbohydrates, proteins and lipids in the semen and a significant decrease in the activities of seminal enzymes in drones exposed to electro-magnetic radiations from cell phones. These deviations from the normality represent clear signs of disturbance in the normal physiology of drone semen. Hence, there is concern that changes in reproductive behavior and physiology of insect pollinators may potentially lead to inadequate mating and reproduction, both of which can further contribute to the global pollinator crisis.

3.7. Genetically modified crops

Potential impacts on pollinators and their services associated with the expansion of the currently commercialized GM crops correspond to the least covered area, with an exiguous number of retrieved papers. This limited quantity of outputs is probably due to the barely recent interest within scientific circles about the safety of GM crops. The effects of GM crops are studied mainly on honeybees, chosen unanimously as model organisms under controlled conditions.

GM crops were developed as a substitute for pesticides in order to ensure crop yield and plant health: enabling plant species to produce naturally occurring pesticides, for instance, allows them to become resistant to the actions of certain pest insects, without the need to use insecticides (Sanvido et al., 2007). However, this ultimate purpose of crop protection has raised concerns that commercial transgenic crops with insecticidal properties would result in potential adverse effects on the environment, especially on flower-visitor insects. Currently, there is little evidence of sublethal effects linked to toxicity of Bt-proteins (*Bacillus thuringiensis* toxins). Bt-proteins are toxins with insecticide properties commonly used for the production of GM crops; they can be traced in nectar and pollen, with potential negative effects on non-target insects feeding on them. Only a few experiments showed negative consequences for pollinators' behavior, such as reduced foraging efficiency and disrupted learning performances (Han et al., 2010; Malone and Burgess, 2009; Ramirez-Romero et al., 2008; Sanvido et al., 2007). Beside their potentially toxic effects, which in the long-term would tend to reduce pollinator populations, GM crops may also act as a pressure in indirect ways: their tendency to hybridize with sexually compatible native plants may increase the risk of plant diversity extinction (Sanvido et al., 2007), consequently leading to contingent pollinator and pollination losses.

Actually, studies related to transgenic crops gave controversial results, since the toxicity depends on the real exposure level of organisms. There is ambiguous evidence that GM plants, which constitutively express insecticide properties, have such negative impacts on pollinators (Kluser and Peduzzi, 2007; VanEngelsdorp and Meixner, 2010). Some authors, such as Morandin and Winston (2005), recognize the urgent need to study more deeply this topic, to manage agroecosystems and to promote the sustainability of food production.

4. Pollinators in LCA: where we are and where to go

Despite the recognized importance of pollinators and the services they deliver for human well-being and for the maintenance of terrestrial biodiversity, current LCIA frameworks appear missing these components. In fact, considering the LCIA frameworks of several LCA methods currently used (e.g. CML (2002); ReCiPe 2008 (Goedkoop et al., 2009), LIME (Itsubo and Inaba, 2003), Impact 2002+ (2002), TRACI (Bare, 2002), ILCD (EC-JRC, 2011)), pollinators are not considered by any approach as target organisms of any impact. Even the most advanced proposals, for example for land use (Chaudhary et al., 2015; Verones et al., 2015) do not include pollinators, predominantly because of the lack of data on species richness and geographic range. However, in the last years, LCA specialists from the UNEP/SETAC life cycle initiative have advanced several LCIA models to characterize land use-driven impacts on ecosystem services (Koellner et al., 2013). Despite there is no mentioning to pollination services, those models are certainly more conceptually advanced than current LCIA operational methods like ReCiPe or ILCD. To date, the most advanced attempts to include ecosystem services are those of Koellner and Geyer (2013) and Saad et al. (2011, 2013). Recently, the models proposed by Saad et al. (2013) have been implemented in Impact world+ (2015), which is the only methodology presenting an area of protection devoted to resources and ecosystem services. The only approach that specifically mentions pollinators is EcoLCA (Zhang et al., 2010a, 2010b), using an input–output framework (Baral et al., 2012). In fact, the authors introduced, for the first time, a life cycle framework to assess the dependency of target industrial sectors on pollination services and the model is under further development (Chopra et al., 2015). EcoLCA is probably the most advanced life cycle-oriented approach to link pollination services to economic/technological systems. However, the model is not fully operation for what concerns the quantification of impacts on pollinators.

Overall, the different available LCIA frameworks incorporate some of the above-mentioned threats to pollinators as impact categories (i.e. land use, ecotoxicity and climate change – Fig. 2) while lacking an impact pathway leading to assess damage on pollinators. Besides, some threats are completely missing, namely an impact category is not existing, although there is evidence of potential environmental concern related to the topic.

In detail, assessing e.g. the ILCD LCIA framework, the threats which are already included are:

- Climate change. Assuming that a midpoint indicator as GWP (Global Warming Potential) is useful, from midpoint to endpoint a link with pollinators is missing. In models such as LIME (Itsubo and Inaba, 2003), where biotic production is taken into account, the role of pollinators might be considered as intermediated step in the cause-effect chain leading to a reduction in productivity.
- Ecotoxicity. Over the last years, freshwater species and relative responses to chemical emissions have received the most attention in LCIA (Curran et al., 2011). Although models assessing terrestrial biodiversity responses to chemical pollution exist, they do appear to be unsuitable for pollinators as well as for the area of protection related to ecosystem quality. The current consensus model for ecotoxicity in LCA (USEtox, 2015) is a multimedia box model, which calculates three components: fate, exposure and effects on freshwater organisms for a given chemical emitted into the environment. USEtox is applied for calculating characterization factors as a result of the multiplication of a fate factor, an exposure factor and an effect factor. Each of these three elements needs an adaptation for pollinators. In fact, there is need of an improved estimation of plant uptake for some substances (e.g. neonicotinoids), the definition of equations reflecting the peculiar elements of the exposure pathways of pollinators (e.g. contact exposure (Barmaz et al., 2010)), and the calculation of effect factors for pollinators that are not currently included. Thereby, integrating fate, exposure and effects of chemicals affecting pollinators in the ecotoxicity models is of high priority. This will allow us to better assess impacts in terrestrial ecosystems, especially the agricultural ones.
- Land occupation and transformation (commonly referred to as land use changes in the most of models). Notwithstanding the role of habitat loss and fragmentation is increasingly discussed and considerable efforts have been recently made with the proposal of novel methodologies aiming at assessing land use related biodiversity impacts (Maia de Souza et al., 2015; Teixeira et al., 2016), current LCIA models are still unable to capture impacts at landscape level, e.g. accounting for relevant elements of habitat composition and configuration (Maia de Souza et al., 2013; Teixeira et al., 2016) such as the presence or absence of field margins in agroecosystems. A new approach is necessary to integrate in the inventory those features that highlight the loss of relevant pollinator habitats in the current land use models (such as field margins). Representing the most important resources of food and nesting sites for all pollinators (Kells et al., 2001; Rands and Whitney, 2010), field margins and their role should be taken into consideration. Additional future challenges are related to inventory issues: it is necessary to improve life-cycle inventories, including land management details as mentioned, in primis, presence and typology of field margins. These improvements would move the approach from a “field focus” to a “landscape focus”, enabling us to better represent the characteristics of the landscape such as the variety of its habitats, in other words representing a landscape as a mosaic rather than through each single piece.

Other fours drivers of impacts are currently missing: invasive alien species, pests and pathogens, electro-magnetic pollution and GM crops. From an LCA point of view, there is a potential of linking processes and products with: invasive alien species (e.g. traded goods and risk of invasive species introduction, as in Hulme, 2009), GM crops and electro-magnetic fields (e.g. associated with the presence of specific infrastructure in a system). Despite being a relevant source of impacts, pests and pathogens are more difficult to be linked to a specific process or product, therefore their inclusion in the impact framework is unlikely.

Finally, current LCIA framework does not effectively account for the functional role of pollinators in providing pollination services at endpoint level. The existing indicators for biodiversity are based on data of species richness (PDF/PAF = Potentially Disappeared/Affected Fraction of species), but they do not take into account the functional aspect of biodiversity in the landscapes. Ecosystem services need to be introduced in the current

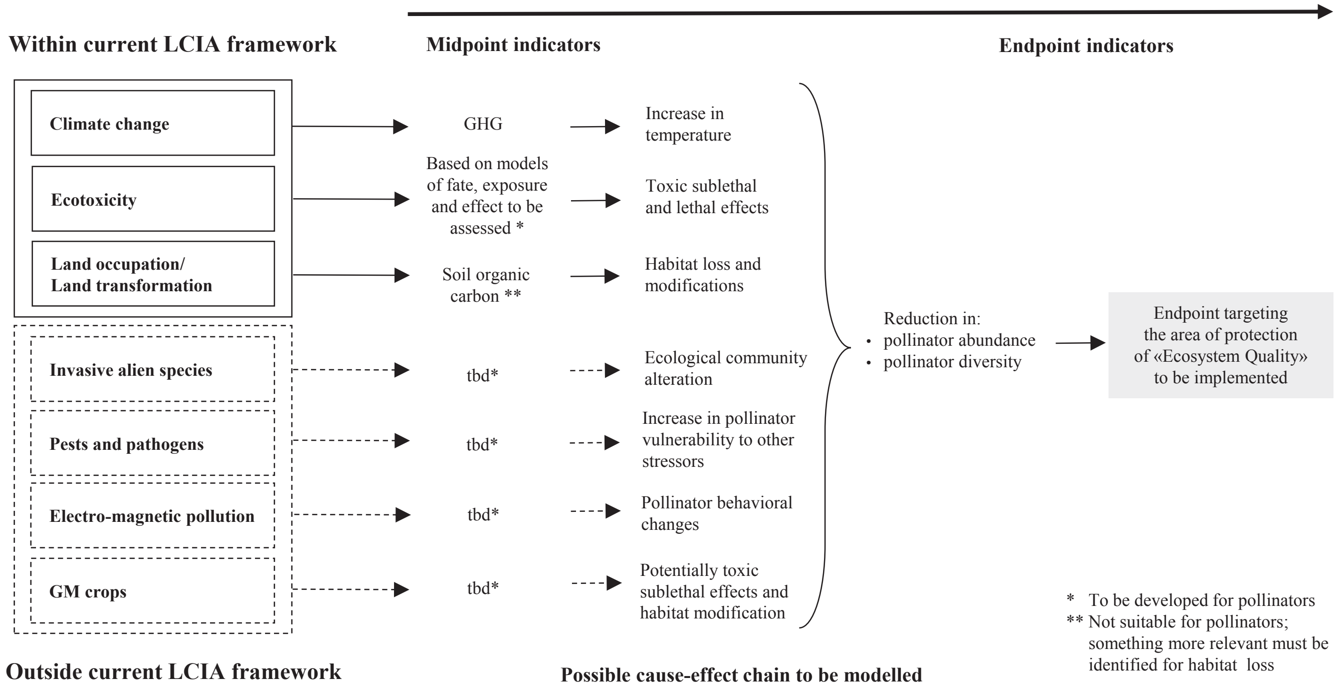

Fig. 2. Identified drivers of impacts on pollinators. In some cases an impact category already exists within the traditional LCIA framework (solid line boxes), whereas in other cases new impact categories should be included (dashed line boxes). The direct endpoint indicator should address the area of protection "ecosystem quality". However, the reduction in the provision of ecosystem services, such as pollination, may lead to subsequent loss in the global economic system, nutrition supply and genetic resources.

LCIA framework. Thereby, a further goal is to overcome the classical biodiversity measurements in the LCIA framework to embrace novel concepts, such as those related to functional diversity (Maia de Souza et al., 2013) for land use related impacts: species are not equal as they offer a wide range of functions supporting ecosystem processes, which in some cases are not replaceable. Functional diversity has a strong ecological importance, since it influences ecosystems' dynamics and consequently socio-economic productivity, being a more understood option for an ecosystem service indicator. Current biodiversity land-use modeling tend to oversimplify the real dynamics and complexity of the interactions of species among each other and with their habitats (Maia de Souza et al., 2015). Of course, the inclusion of pollinators may need to expand the elements currently covered by the area of protection "ecosystem quality", checking whether current metrics are suitable for expressing and then aggregating ecosystem-related results.

There are serious conceptual shortcomings in the way the current models are built. It is necessary to overcome the existing weaknesses, setting new models based on meaningful and robust indicators of impact and damage for biodiversity. These should cover not only the part related to ecosystem diversity, but also the key role that some species such as pollinators play and that could not be replaced if lost.

5. Conclusion and outlook

This review contributes to our current understanding of the factors leading to pollinator populations' declines and represents the first step to overcome problems related to the lack of appropriate LCIA models for assessing impacts on biodiversity. Our study aims at bridging ecological and environmental sciences and global product strategies. We discussed existing conceptual and methodological gaps between LCIA and the assessment of key ecosystem services, such as pollination.

Several authors have long recognized the main drivers of impact acting on pollinators, potentially threatening also pollination services. Intensive agricultural practices are responsible for the majority of the identified threats, which are 1) intensified land use as a result of uncontrolled expansion of urban areas and modern agricultural practices, 2) use of pesticides, 3) presence of invasive alien plants; 4) competition with invasive alien pollinator species; 5) global and local climate change; 6) spread of pests and pathogens; 7) electro-magnetic pollution (including electro-magnetic radiations, electric charges and magnetic field fluctuations) and 8) genetically modified crops.

Notwithstanding the importance of pollination for environmental and socio-economic reasons, existing LCIA methods and models appear to be incomplete with respect to pollinators. This is principally due to a general lack of knowledge on how different anthropogenic pressures affect changes in pollinator biodiversity and pollination services, and on how species diversity is connected to ecosystem functioning and human well-being. Therefore, there are specific research needs towards the integration of pollinators as a target group for biodiversity protection in the LCIA framework. Firstly, future investigations are to be oriented to improve the models and the indicators currently used in the LCIA framework. Thus, it is of high priority integrating within inventories those features which highlight the loss of relevant pollinator habitats in the current land use models as well as the fate, exposure and effects of the chemicals affecting pollinators in current models of ecotoxicity. Then, for other categories of impacts, novel models and indicators both at midpoint and endpoint levels should be developed to cover the existing conceptual and methodological gaps. Particularly, new impact categories and related models should be developed and the feasibility of including them in the LCIA methodology should be assessed.

We also investigated models and indicators proposed in the studies we selected for the review; however, easily implementable models are not yet available. The only exception would be for ecotoxicity, where the procedure proposed by Barmaz et al.

(2010) could be used for estimating the exposure of pollinators to plant protection products. The authors developed a procedure for predicting pesticide exposure for pollinators based on the foraging behavior of honeybees (*A. mellifera*). This approach is overcoming the current official procedures to assess pesticide risk -based on a Hazard Quotient- and may be a starting point for integrating the assessment of pollinators in multimedia box models used in LCA (such as USEtox), particularly for calculating the exposure factor.

Moreover, given that at the endpoint level, different target organisms are considered for different impact categories (e.g. plants, freshwater organisms, mammals etc), the use of indicators of impact for pollinators may be a promising unifying endpoint for different impact categories.

Considering the role of crucial ecosystem services for sustaining life, including impact on pollinators is an impelling step for increasing the comprehensiveness of LCA. The services provided by pollinators represent an important function supporting the global food security and its socio-economic stability. Thereby, accounting for them is fundamental in any effort aiming at achieving sustainable growth and sustainable use of natural resources.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2016.02.058.

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