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## **Disentangling the diversity of definitions for the pollination ecosystem service and associated estimation methods**

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## Abstract

Observed declines in pollinator populations due to human pressures is of critical concern because pollination is an essential regulating ecosystem service (ES). Pollination has a major role in human food production and in maintaining flowering plant diversity. Estimating the pollination ES and its trends is thus essential for informing policy and management. However, the pollination ES remains poorly defined in practice as it is a polysemic term. In practice it is considered as: the ecosystem capacity to support pollination, the social demand for pollination or the actual pollination flow, which is the match between capacity and demand. Its quantification is complicated by the coexistence of numerous indicators. In this paper, we aimed to disentangle the diversity of definitions of the pollination service along with their associated indicators and field methods in the ecosystem service literature. From 131 reviewed papers, most studies were under temperate climate with a focus on hymenopteran pollinators, overlooking the importance of hoverflies and other dipteran pollinators. We identified four main pollination ES definitions that can be separated in two categories: (1) pollinator presence and pollen transfer, which are related to the capacity of the pollination ES; and (2) pollination success and production of fruits or seeds for human consumption, which are related to the flow of the pollination ES. Importantly, when quantified simultaneously pollination capacity and flow showed varying levels of congruence. Half of the reported relationships were congruent, but almost as many were neutral. Direct indicators of the two definitional categories characterised the respective actors of the pollination function. Studies of pollination capacity characterised pollinating agents (pollinator communities), while pollination flow studies described seeds and/or fruits produced from animal pollination. Both pollination capacity definitions share insect observations and captures as most frequent methods (70% of analysed studies), with a prevalence of indicators of pollinator diversity and abundance. Pollination flow estimation methods mainly describe the amount (number, weight) and quality of seeds/fruits. Pollinators depend on availability of feeding and nesting resources for their survival, and on their ability to reach them within landscapes. Thus, common indirect indicators of pollination are environmental variables related to semi-natural habitats and flower resources. We end this review with guidelines for relevant choices by ecosystem services scholars and practitioners of indicators and methods according to study questions and constraints (technical, financial, time and skills). Further investigations will be necessary to disentangle pollination capacity and flow relationships.

**Keywords:** pollination, ecosystem service facet, direct indicators, indirect indicators, field methods.

## 1. Introduction

Pollination as an ecosystem service (ES) is receiving strong international attention given the decline of pollinator populations due to human pressures such as pesticide use (Woodcock et al., 2017), landscape simplification (Connelly et al., 2015) and their combination (Leza et al., 2018). Indeed, the interactions of pesticides and food shortage are likely to weaken bee immune systems and thus favour pathogens spread by honeybee keeping practices (Goulson et al., 2015). Global pollinator declines have been reported (IPBES, 2016; Potts et al., 2010). For instance, pollination networks between bees and forbs were degraded over a period of 120 years, with a loss of 50% of bee species (Burkle et al., 2013). Wild bee diversity declined in both Britain and Netherlands when comparing observation records from before and after 1980 (Biesmeijer et al., 2006). Bumblebee abundance decreased drastically over 20 years in North America (Cameron et al., 2011). Modelled bee abundance decreased by 23 % between 2008 and 2013 in the United States of America, a decline validated by field data (Koh et al., 2016). Moreover, pollinator biodiversity declines could worsen climate change impacts. As an example of benefits from pollinator diversity in the face of climate change, complementarity in activity periods across bee species may prevent a desynchronisation between apple peak bloom and bee activity (Bartomeus et al., 2013). These declines imperil pollination, a critical ecosystem function underpinning multiple societal values, as observed with a decline of the pollination service across 120 years of records of plant-pollinator networks (Burkle et al., 2013). Pollination is critical for global agriculture production, representing up to 5 to 8 % of the global crop production in 2015 (IPBES, 2016), and essential for highly dependent fruit and seed crops (Klein et al., 2007). Pollination and pollinators – wild and managed – also have high cultural value associated with honey production (Azeez et al., 2012) and collection, and associated cultural traditions (Kumar and Reddy, 2011). Awareness of the necessity of preserving pollinator communities is increasing (IPBES, 2016; Potts et al., 2016). For instance, in Northern Thailand, longan fruit farmers demand policies for conservation of their native bee populations (Narjes and Lippert, 2016). In the United Kingdom the public is willing to pay for the maintenance of the pollination service (Mwebaze et al., 2018).

Meanwhile at local to regional scales there is increasing demand for the inclusion of ecosystem services in environmental impact assessment and land planning (Albert et al., 2016; Diehl et al., 2016). The benefits of agri-environmental schemes for pollinators have been assessed in individual countries (*e.g.* United Kingdom (Pywell et al., 2011; Wood et al., 2017), Belgium (Ouvrard et al., 2018)) or across countries (comparing Switzerland and the Netherlands (Kohler et al., 2007)). And such benefits flow on to improved crop yields (review by Garibaldi et al. (2014)). The assessment of the combined effects of agri-environmental schemes and crop rotation on pollinator communities showed that both mediated bumblebee abundance and richness through increased flower resources

(Marja et al., 2018). The necessity of combining landscape and species management, usually applied separately, has also been hypothesised recently for their potential synergies (Garibaldi et al., 2017). Further, alternative hay-meadow mowing regimes had positive effects on bees (Buri et al., 2014) as had the combined effects of farm management and landscape factors on abundance and diversity of native bees (Nicholson et al., 2017). These examples support the benefits of ecological intensification, *i.e.* the enhanced use of ES for agricultural production with reduced environmental impacts (Bommarco et al., 2013), for both crop yield and flower-visitor richness (Garibaldi et al., 2016). Consistent with the importance of the pollination ES and its sensitivity to management, an ES index incorporating pollination has been proposed for prioritising sites for ecological restoration (Comín et al., 2018). Also specific ecological restoration now targets wild bee populations (Pan et al., 2017; Tonietto and Larkin, 2018).

Across this expanding field of fundamental or applied pollination studies, new indicators for estimating the pollination ES have been developed. For example, indicators of pollination potential and honey production assign a potential ES value for different ecosystems (Affek, 2017). Another indicator estimates the pollination service value of field margin flora from floral-traits (Ricou et al., 2014). Yet there is little consensus about definitions of the pollination ES or standard methods that would enable comparability between studies or use by non-specialist practitioners. Indeed the pollination ES has numerous definitions which are associated with different estimation methods. Liss et al. (2013) listed five main definitions spanning from pollinator diversity and abundance to crop yield, with quantification indicators as diverse as the definitions. These definitions range from ES supply capacity (pollinator diversity and abundance) and to ES flow, *i.e.* the relation between the ecosystem supply capacity and the societal demand for that service; crop yield (Schröter et al., 2014; Villamagna et al., 2013). Direct and indirect indicators can be linked to each of the definitions (Figure 1). For instance, abundance or species richness of pollinating insects are direct indicators for the service supply capacity. Indirect indicators are proxies for estimating pollinator presence. For example the suitability of different land uses for nesting and their floral resources for potential pollinators are used for modelling pollination supply capacity (Lonsdorf et al., 2009; Zulian et al., 2013).

These direct and indirect indicators are measured with different types of methods. Some studies use modelling such as the free and open source ES model InVEST (<https://www.naturalcapitalproject.org/>) (Davis et al., 2017). Field observations are widespread, with insect observations (Greenleaf and Kremen, 2006), observations and captures (Berecha et al., 2015), or only captures (Bartomeus et al., 2013). Some studies combine modelling and observations (Cariveau et al., 2013; Martins et al., 2015). However, a synthesis of different methods, their scope and their prevalence is not available for guiding researchers and practitioners.

In this review, we aimed to establish a state of the art of existing field methods and some common biophysical modelling methods. We also aimed to provide general guidelines for selecting methods for quantifying the pollination ES according to context and resources especially in assessments of ecological impacts or restoration by practitioners. We assessed the diversity of pollination ES definitions, associated measured variables and their quantification methods. Liss et al. (2013) pointed out the variability of the pollination service definitions and the different metrics used for their measurements, albeit without considering the associated estimation methods. In order to update and complement this review, we aimed to focus not solely on pollination indicators, but also considered associated estimation methods, thereby filling a gap in the recent literature. We asked: i) which definitions of pollination are in use? ii) which variables and methods are associated to the different definitions? iii) which variables and methods are relevant in which circumstances? To answer these questions, we identified pollination definitions, quantified their use and analysed occurrences of associated variables and methods across the international literature. Results from this analysis support a decision tree for selection of definition and associated field methods according to weather and seasonal constraints, and to human and financial resources. Therefore, this review focused on pollination service definitions, indicators and estimation methods across pollinator groups. Readers are referred to the specialised ecological literature for specific methods according to individual groups.

## **2. Methods**

### **2.1. Literature review**

We reviewed the literature for a state of the art of the indicators and methods used to estimate the pollination ES. The literature search was made on *ISI Web of Knowledge* using four sets of key-words for which all results were checked between 10/02/2016 and 8/03/2016 for papers published between 2001 and the date of the search. The sets of key-words included all “pollinat\*” and “ecosystem servic\*”. The third term was: “model\*”, “map\*”, “quantif\*” and “measur\*” (details in Table A1 in Appendix A). The use of the “\*” allows to include all words starting by the specified letters. We started the research in 2001 as, consistent with the emergence of ecosystem services in the international literature, it was the first year with more than two publications with the key words “ecosystem service” and “pollination” in *ISI Web of Knowledge*. The first step of the analysis focused on pollination modelling/mapping to identify variables considered for this ES estimation. The second step focused on literature specific to ecosystem services and the underlying ecological functions/processes to find field methods for estimating pollination. The sets of key words produced

474 papers addressing pollination modelling and biophysical measures across these two bodies of literature (Table A1). We also incorporated the references from the literature review by Kennedy et al. (2013) into our analysis in order to enrich our synthesis regarding effects of landscape composition and configuration on pollination.

A first selection from these 474 papers title and abstract yielded 195 papers, keeping papers mentioning pollinators (terms: ‘pollination’, ‘pollinator’ or names of major pollinating groups - bees, hoverflies, etc.) and measures related to pollination “actors” or plant production (abundance, crop yield, etc.). Numerous papers were discarded when pollination was not estimated explicitly. Often the pollination service was only quoted in the abstract as an example of regulating ecosystem services or as a perspective. A second selection was done after reading the methods section. Papers which did not detail the model or method used were discarded. We also discarded papers focusing on economic evaluation of the pollination ES as our analysis targeted field and modelling methods. We excluded as well reviews and meta-analyses, leaving 131 papers for detailed analysis (Appendix B). A synthetic table was filled with selected papers with the consideration of different variable categories (Table A2) from which typologies were elaborated (see Analyses section). Studied pollinators were invertebrates in all selected papers besides one which focused on pollination supplied by hummingbirds (Engel and Irwin, 2003) which was thus not considered in the following analyses for consistency among the studied methods.

A new search based on the same sets of key words was conducted in 06/2018 in order to check whether major methodological changes appeared in the literature since the literature review was conducted. After the process of paper selection, its rapid analysis confirmed overall consistent results with the in depth analysis of initial search results conducted in 2016. Information on any novel insights is incorporated into the Discussion section.

## 2.2. Analyses

First we quantified the general context of the studies considering the field of study, geographic location, scale, target plant and pollinator species. Second, we developed four pollination definitions and typologies for the associated measured variables and estimation methods, as well as for associated co-variables. We aimed to link existing indicators and estimation methods to each definition of the pollination service. Accordingly we did not analyse detailed protocols (*e.g.* size of bowl traps, duration of capture sessions) or their specific suitability to different pollinator groups. The classifications resulting from these typologies were analysed through comparison of numbers of occurrences and numbers of papers using different definitions, variables and methods, as one paper could include several occurrences for a given parameter, *i.e.* different modalities of one parameter.

### 2.2.1. Definitions of pollination services

From the different ways of measuring pollination – as a function or as a service – we identified four definitions which can be placed along the ES conceptual framework (Figure 1) and, consequently grouped into two pairs. First, two definitions correspond to the pollination service supply capacity and focus on the organisms responsible for the pollination function, here pollinating insects: (1) The *presence of pollinators* is estimated by measures of abundance and richness of pollinating insects, representing measures of the biodiversity of the providers of the pollination service (Luck et al., 2009) (Figure 1). (2) The second definition is closely related to the first one: the *pollen transfer* rests on the pollinator's role in transferring pollen between flowers and is for example estimated with visit frequencies and/or pollen transfer efficiency (*i.e.* the number of pollen grains left during one single visit). This definition corresponds to the ecological function underpinning the service (Figure 1). The other two definitions are close and correspond to the realised flow of the pollination service and thus focus on the pollination function outcomes, *i.e.* plant production. (3) *Pollination success* is the plant reproductive success attributable to the action of pollinating insects, estimated through the number of pollen tubes developing or through seed or fruit production at individual plant scale (*e.g.* seed or fruit number/weight). (4) The *harvest for human consumption* is the reproductive success attributable to the action of pollinating insects at field or farm scale. This definition relates to all crops used as food, fodder, biofuel, etc., *i.e.* consumption in a broad sense as understood for nature's material contributions to people (food and feed, energy, materials, and some medicinal resources (Díaz et al., 2018)). It is measured in yield per unit area or describes harvest quality for consumption (*e.g.* the oil content of sunflower seeds or the sugar content of apples).

### 2.2.2. Direct indicators and estimation methods

From the four definitions, we differentiated five major variables (Figure 1), each of which can be associated with alternative indicators (Table 1). The variables *biodiversity* and *abundance* refer to the *presence of pollinators* in its qualitative and quantitative forms respectively. The variables *pollen transfer*, *pollination success* and *harvest for human consumption* refer to the eponymous definitions of pollination.

For the pollination indicators, we differentiated between “abundance” and “visit frequency” based on the definition proposed by Kennedy et al. (2013). Thus we considered as “abundance” the measures of individual numbers caught with nets or traps or counted, but without an explicit observation of visits to a flower or an inflorescence. We considered as “visit frequency” visit counts or captures of individuals visiting flowers for a given distance/area/time/unit number (flowers, plants). We did not separate the total visit frequency or the visit frequency per species or group.



As the only selected article dealing with non-insect pollinators was discarded, the pollination indicators and the corresponding methods summarized henceforth are mainly relevant for insect pollinators such as hymenopterans (bees, bumblebees, wasps, etc.), dipteran (hoverflies, etc.), lepidopteran (butterflies, moths), etc.

The pollination indicators were estimated in the field with different methods (Table 2) which we classified into five categories: (i) *observations* and (ii) *captures* are methods used for the first two definitions of pollination *i.e.* *presence of pollinators* and *pollen transfer*; (iii) *pollen analysis* and (iv) *harvest* are methods and experimental manipulations relevant for the other two definitions – *reproduction success* and *harvest for human consumption*; (v) *pollinator manipulation* was used in studies analysing consequences of changes in the pollinator community composition. It is important to note that studies analysing *pollination success* or *harvest for human consumption* often isolated flower(s) to assess the effect of animal-pollination (referred as “Manip-pollen” in Table 2) compared to self- and/or wind-pollination and/or hand-pollination. Thus we considered this methodological step, which is not part of the pollination quantification *per se*, separately from other methods. Two methods were considered apart: citizen science and the use of literature data.

### 2.2.3. Indirect indicators and co-variables

Habitat linked variables relate with the availability of feeding and/or nesting resources in the landscape for pollinating insects (Table 3). They are often measured in addition to variables directly linked to the pollinators and the target plants. They also serve to model the supply capacity of pollination from the potential presence of pollinators linked to the availability of different land cover/land use types (Lonsdorf et al., 2009; Schulp et al., 2014; Zulian et al., 2013). When crop cover was considered, we categorised this variable as feeding resources rather than nesting resources. Semi-natural habitat cover was considered as relevant for both feeding and nesting resources. A typology for the variables characterising the surrounding landscape was also elaborated (Table 4).

## 3. Results

### 3.1. Study scope

#### 3.1.1. Thematic and methodological scope

Most of the 131 selected papers addressed explicitly the ecosystem service concept while almost a third was broad ecological literature, for example wild plant pollination studies put in the context of the pollination service (Figure 2). Article methods were mainly based on field work (almost 90 %) while modelling and the combination of both approaches were a minority. Note that we did not

consider the quantification of network interactions between plant and pollinating insects as modelling given that they supported field-based analyses of pollinator communities.

### **3.1.2. Geographical scope: location and scales**

Europe and North America were the two almost equally more represented continents, and the southern hemisphere was clearly under-represented with only 16 % of the studied areas (Figure 3). Africa was the least studied continent, especially considering its total area. This spatial distribution was linked to most studies being run in temperate regions (72 %). The main represented countries were the United States of America (33.8 %), the United Kingdom (12.5 %) and Germany (7.3 %). Almost half of the studies were at plot/field scale while a third referred to configuration linking different scales – either the plot with the landscape or the landscape with the region. 49 papers considered landscape composition, using different spatial extents: 57% of the considered radii were less or equal to 1 km, and 85 % less or equal to 2 km. A single study worked on a 10 km<sup>2</sup> focal area (Woodcock et al., 2014) for an analysis of national patterns of insects associated with arable crops. A few studies considered multiple spatial scales (local, proximal and broad landscape). Radii of 2.1 and 2.7 km were selected by Greenleaf and Kremen (2006) to reflect foraging ranges of two bumblebee species. Ferreira et al. (2015) targeted 0.36 and 36 km<sup>2</sup> to study the impact of forest loss at both local and landscape scale. Moreira et al. (2015) compared impacts on plant-pollinator network of local conditions (*e.g.* structure of local vegetation) and landscape structure (*e.g.* proportion of agriculture) at 0.25 to 3 km and 6 to 12 km.

### **3.1.3. Studied plants and pollinating insects**

63 % of the studied plants were cultivated plants with mainly mass flowering crops, vegetable plants and orchards (Figure 2). Tropical crops were less represented given the lack of studies under these latitudes, with the exception of coffee plantations. Besides the studied entomophilous plant, some articles dealt with Poaceae, mainly cereals, which are anemophilous. Such studies focused on the impact of agriculture types, crop types or pesticide use on pollinating insect communities and not on pollination itself (*i.e.* pollination function or pollination ES).

21% of studies targeted all pollinating insects, with differentiated groups or not. Hymenopteran were the dominant target group, with 66 % of focus insects being bees in a wide sense (*i.e.* indifferently wild bees, bumblebees or honeybees) (Figure 2). Among these studies, some focused only on honeybees (5 %), on wild bees (15 %), or on bumblebees (10 %). Most of these studies (36 %) focused at the same time on honeybees and wild bees and sometimes on bumblebees except for some studies which did not specify the types of studied bees (for example Bennett and Lovell (2014) and

Schulp et al. (2014)). Articles focusing on other specific groups (e.g. butterflies or hoverflies) were a minority (14 %). These choices were consistent with the observed frequency of pollinator groups when these were documented: most studies (68 %) mentioned the presence of bees (wild or domestic) and bumblebees. Pollinator groups in minority such as hoverflies or butterflies were less frequently documented (respectively 11 and 7 % of the observed insect groups).

## **3.2. Definitions and associated direct indicators and methods**

### **3.2.1. Definitions**

Most studies focused on the *presence of pollinators*, which is the easiest definition to estimate using indicators for pollinating insect abundance and richness (Figure 4). A third of the definition occurrences focused on *pollen transfer* and one quarter on *pollination success*. *Harvest for human consumption* appeared less often, with 5 % of the 211 occurrences. Most reviewed articles dealt with one or two of the pollination definitions. Out of the 71 articles dealing with at least two pollination definitions, only 23 quantified the link between pollination supply capacity and pollination flow – i.e. between indicators associated respectively with the first two and the last two definitions. For each of these articles, we counted as one occurrence the presence of each category of relationship (i.e. positive, negative or absence of relationship) regardless of the number of relationships. For example a paper reporting two positive and one neutral relationship would be counted as one positive and one neutral relationship in this analysis. A total of 42 relationships were reported. 21 articles reported positive relationships between capacity and flow indicators and three were negative. For 18 articles there were no significant relationship between both indicator types (Figure 2). We excluded from this analysis articles comparing insect pollination with netted flowers in exclusion experiments if they only considered the contribution of the presence of insects to the pollination flow. These could be considered as a measure of the plant reproductive success dependency towards insect pollination rather than quantifying the pollination service.

Most of the 10 articles which did not contain one of the four aforementioned definitions estimated pollination through the quantification and qualification of potential habitats – for feeding and/or nesting – as they dealt with modelling approaches.

Among the pollination-related variables linked to the *presence of pollinators*, *biodiversity* indicators occurred more often than *abundance* indicators with respectively group richness and total abundance being the most frequent (Figure 5). Both indicator categories often occurred together and were estimated with the same field methods. For the *pollen transfer* definition, visit frequency represented 75 % of the indicator occurrences, while the estimation of the pollen transfer *per se* represented the remaining quarter.

### 3.2.2. Pollination supply capacity definitions

The variables and indicators estimated for *presence of pollinators* and *pollen transfer* (which co-occurred in 35 of the 131 reviewed papers) shared estimation methods (Figure 5). However while the use of captures and observations was balanced for quantifying the *presence of pollinators*, observations were used in **71 %** of studies estimating *visit frequency* (central three-part panel of Figure 5). This may justified by avoiding disturbance of insect activities and risks of modifying their behaviour associated with captures. Considering both definitions together, 57 % of the methods were observations. Static observations and **traps** were more common (51 %) than mobile observations.

The second and eponymous variable of the *pollen transfer* definition was mainly estimated through flower/inflorescence isolation from pollinators, most often after a first visit and count of the pollen grains dropped by the visiting insect.

### 3.2.3. Pollination flow definitions

Among the indicators measured for the *pollination success* definition, number of seeds/fruits/etc. was the most common, closely followed by the measure of production of seeds/fruits and fruit or seed weight (Figure 6). In the same way, the most common indicator for the *harvest for human consumption* definition was harvest.

The pollination-related indicators for the two pollination flow definitions had common estimation methods with counting being the most common method for both definitions, closely followed by the weighing of fruits and seeds (central three-part panel of Figure 6) . Most studies under these two definitions used the method of isolating flowers from pollinator presence in order to control for its effect on plant reproduction success (Figure 6).

## 3.3. Indirect indicators and co-variables

Feeding resources were considered more often than nesting resources with their consideration respectively in 98 and 75 articles (Figure 7). Quantitative availability was the variable measured for feeding and nesting resources.

Co-variables were often considered with landscape characteristics present in 64 articles and human management such as type of agriculture or chemical inputs in 31 articles (Figure 7). The consequences of human management on the landscape were the most commonly considered in both cases.

## 4. Discussion

We identified four pollination definitions that are explicitly related to different steps and processes of the pollination ecosystem service conceptual framework (Figure 1), from the presence of the interacting species – pollinators and entomophilous plants, to the quality of harvested plants. For each definition we identified the associated direct and indirect indicators along with their more common field estimation methods that can be appraised for ES assessment or environmental impact studies. Previous studies summarised pollination definitions and associated indicators (Liss et al., 2013), or compared detailed methods for specific processes (*e.g.* single visit pollen deposition (Howlett et al., 2017)) or pollinators (butterfly sampling methods (Kral et al., 2018); bee sampling in tropical forest and agroecosystems (Prado et al., 2017)). However, to our knowledge none has considered the pollination service from its definitions to methodological alternatives.

### 4.1. Study gaps

#### 4.1.1. Location

Consistent with previous assessments (IPBES, 2016), studies of the pollination ES were mainly located in temperate industrialised countries, emphasising the need for data collection in multiplying studies in developing countries and under tropical climate. Over the past two years, new studies have been published in Latin America (*e.g.* Brazil (Elias et al., 2017; Hipólito et al., 2018, 2016; Ibarra-Isassi and Oliveira, 2018; Junqueira and Augusto, 2017; Nicodemo et al., 2018), Argentina (Geslin et al., 2013; Marrero et al., 2017; Tur et al., 2016), Costa Rica (Caudill et al., 2017; Galbraith et al., 2017), México (Landaverde-González et al., 2017), Columbia (Gutiérrez-Chacón et al., 2018)), Asia (Thailand (Narjes and Lippert, 2016), Philippines (Hass et al., 2018), tropical China (Liu et al., 2017)) and Africa (Burkina Faso (Stein et al., 2017)). Importantly, many crops highly dependent on animal pollination are produced under low latitudes including fruits (passion fruit, mango, avocado), nuts (Brazil nuts, macadamia, cashew nuts), spices (cardamom, nutmeg), cocoa and coffee (Klein et al., 2007). Also, the tropics are home to numerous flowering plants and pollinators with 94 % of the flowering plants being animal-pollinated vs. only 78 % in temperate zones (Ollerton et al., 2011). Additionally the decrease in pollinator richness and visitation rates with distance to semi-natural habitats has been observed to be faster in tropical than in temperate regions (Ricketts et al., 2008).

#### 4.1.2. Insects and plants

A limitation to numerous studies considering the dependence of crops towards animal pollination is their unique reference to the global synthesis by Klein et al. (2007), which might not always be adapted for local studies. Also, given prevailing instrumental approaches to ecosystem services

(Pascual et al., 2017), the majority of pollination studies focus on material benefits from food and feed plants. Numerous papers focus on the economic valuation of the pollination service with regional (Winfree et al., 2011) and global (Gallai et al., 2009) assessments (Breeze et al. (2016) for a review). Pollination studies definitely need to be extended to a broader range of plants to address other pollinator values. This goes from support for the production of honey, medicines and biofuels to their numerous immaterial contributions such as their role in maintaining biodiversity of wild flowering plants, the recreational value of beekeeping, their inspirational values and their major importance for indigenous people (IPBES, 2016).

The majority of studies focused on bees in a broad sense (*i.e.* wild bees, domestic honeybees and bumblebee) while other non-hymenopteran insect groups were largely neglected. The inclusion of more diverse groups is essential. It has been suggested in the United Kingdom that honeybees supply less than half of the pollination service demand (Breeze et al., 2011). According to IPBES (2016), it has been estimated that around 80 % of animal-pollinated crops are owed to the activity of 2 % of the wild bee species. Also managed pollinators are suspected of negative impacts on wild pollinators through competition for resources, of impeding wild plant reproduction and of propagating pathogens (Geldmann and González-Varo, 2018). Indeed, managed pollinator species such as *Apis mellifera* or *Bombus terrestris* are observed in direct and indirect competition with other pollinators and are the cause of major alterations of plant-pollinator networks (see Geslin et al. (2017) for a review). Thus studies centred on the pollination service should also consider non-hymenopteran insects such as hoverflies (Syrphidae) which can represent up to 40 % of flower visits (Rader et al., 2012). Other dipteran can represents up to 82 % of the abundance and 73 % of the species richness of observed dipteran (Orford et al., 2015). Some studies do focus on both bees and hoverflies (Albrecht et al., 2012; Arthur et al., 2010; Blaauw and Isaacs, 2014; Bommarco et al., 2012; Lucas et al., 2017), while rarer studies focus solely on hoverflies (Schirmel et al., 2018). Also, recent network analyses consider greater diversity of taxonomic groups and their interactions (Ballantyne et al., 2017; Deguines et al., 2016; Valdovinos et al., 2016).

Lastly, the reviewed articles dealing with insect observations or net captures focused on diurnal pollination, while nocturnal pollination may significantly contribute to pollination networks. A recent study showed that light pollution of a grassland decreased visitation rates and resulted in a fruit set reduction of *Cirsium oleraceum* (Knop et al., 2017). Appropriate methods would be required to accounting for nocturnal pollinator groups.

## **4.2. Synthesis**

### **4.2.1. Variability of definitions**

We identified four definitions for the pollination service that can be matched to two facets of the ecosystem service concept (Figure 1), and associated with two sets of methods. On one hand the presence of pollinators and pollen transfer capture pollination supply capacity. On the other hand, pollination success and harvest for human consumption depict pollination flow. Both facets are sometimes present in the same study, as in the European scale mapping of the pollination ES (Schulp et al., 2014). Our definitions are close to the five definitions of Liss et al. (2013) which match respectively pollination supply capacity in the case of pollinator abundance/diversity, pollen transfer and pollinator visitation, and pollination flow in the case of crop yield and plant fitness. Importantly, one should be careful before assimilating measures of pollination supply capacity and flow, as both facets are not always correlated. In our review, some articles reported both positive relationships and the absence of relationships. Such differences were observed across target crops (e.g. oilseed rape and beans (Garratt et al., 2014b); bilberry and lingonberry (Rodríguez and Kouki, 2015)). Direct indicators such as honeybee abundance had positive (Rogers et al., 2014) or neutral effects on pollination flow (Hevia et al., 2016; Mallinger and Gratton, 2015). This discrepancy could be due to the underlying ecological processes. Indicators of pollination capacity characterise pollinator communities (abundance, diversity) and flower visitation rates. However, it is well known that not all observed pollinators are effective pollinators of the studied plant and flower visitation rate is a poor proxy to estimate pollen transfer (*i.e.* the actual pollination function) (King et al., 2013). Thus, other indicators such as single visit pollen deposition, a measure of pollinator efficiency, might be more relevant to be compared to pollination flow indicators. Also indicators of pollination flow do not only depend on pollinators/the pollination function. Fruit and seed production are also affected by weather, abiotic conditions (for example micro-heterogeneity in soil characteristics), landscape characteristics, plant health and pests. Research clearly still needs to investigate relationships between pollination capacity and flow and, more particularly, possible method standardisation for rigorous comparisons.

### **4.2.2. Direct indicators and associated methods**

Each of the four pollination service definitions can be estimated by different indicators reflecting different facets of a same definition. Each indicator is associated to one or more estimation methods. Abundance and species richness are by far the more common indicators for pollinator presence. However functional diversity might be a more relevant indicator. Fruit and seed set have been observed to correlate with diversity of bee traits (Martins et al., 2015) or pollinator functional group richness rather than species richness (Albrecht et al., 2012). Functional traits found to be strongly

related to the pollination function include proboscis morphology (Ibanez, 2012) and body hairiness (Stavert et al., 2016). The trait matching mechanism (Bartomeus et al., 2016) underpins relationships between pollinator traits and flower traits. Thus, functional traits linked to flower properties (reflectance, morphology) or insect morphology (body size, mouth parts morphology) are related to visitation frequency or fruit set (Fornoff et al., 2016; Garibaldi et al., 2015; Ibanez, 2012). However these relationships may not always be predictive of detailed interactions (Bartomeus et al., 2018; Olito and Fox, 2015).

Captures were a common method for assessing insect abundance and diversity. Comparisons of pan traps and aerial netting results showed that aerial netting captured higher abundance and species richness of pollinating invertebrates (Popic et al., 2013). Moreover, the two methods only overlapped for 50 % of species composition, with 25 % of species captured only with either pan traps or aerial netting. Aerial netting may be more relevant than pan trapping for pollination studies as it directly samples insect-flower interactions and enables the analysis of pollen held by captured insects. Yet, combining both methods could maximise the assessment of pollinator diversity. The choice of observations over captures is considered as more respectful of biodiversity and aims to limit the impact of scientific studies. However Gezon et al. (2015) showed that repetitive captures – using pan traps or netting – did not impair the abundance, species richness and functional composition of wild bee groups. Nevertheless, insect captures and observations might not be reliable due to greater inter-annual variations at a site than inter-site variations, as observed in orchards (Russo et al., 2015). The estimation of the frequency of flower-visits per insects, a widely used and relatively simple variable, has been shown to be less relevant than measures of single-visit pollen deposition (SVD) *i.e.* the number of pollen grains deposited by one insect during one visit. Indeed, SVD was found to be much more relevant than visit-related indicators (frequency, duration, etc.) for estimating pollination effectiveness for 8 out of 13 plant species, as it allowed differentiating between flower visitors and pollinators (King et al., 2013). However, SVD measures require more time, work, equipment and skills with the necessity of isolating buds, collecting the flower after the first insect visit and counting pollen grains under a dissecting microscope.

Finally, Woodcock et al. (2014) advocate for the use of plant phytometers using seed set as pollination indicators instead of insect capture and identification, given that this method requires less field work, is more cost effective and more reliable.

#### **4.2.3. Indirect landscape indicators**

Landscape composition and configuration are often quantified as indirect indicators of the pollination service, or to assess nesting and feeding resources, for example for modelling the supply capacity of the pollination service (Lonsdorf et al., 2009; Schulp et al., 2014; Zulian et al., 2013).



Landscape composition quantified as the proportion of different land uses within in a given radius, is a common indicator. First negative effects on pollinators of agricultural land cover, considered as a measure of landscape simplification, are often reported (*e.g.* in Benjamin et al., 2014; Bommarco et al., 2012). Second the cover of (semi-)natural habitats (forest, grasslands or ponds) and the quantity and quality of hedgerows at both local and landscape scales often favour pollinators (Garratt et al., 2017; Holland et al., 2017; Stewart et al., 2017). In particular pollinator richness and abundance often decline with distance from a target crop to semi-natural habitats (*e.g.* Carvalheiro et al., 2010; Kremen et al., 2002; Ricketts et al., 2008). Landscape configuration also influences pollinators and the pollination service. Configurational heterogeneity measured as field border density (*i.e.* small field plots) positively impacted wild bee abundance and radish reproductive success (*i.e.* seed set) (Hass et al., 2018). However, some landscape elements have inconsistent consequences for pollinating insects. For instance mass flowering crops can either increase (Westphal et al., 2003) or decrease bumblebee abundance possibly due to a dilution effect (Holzschuh et al., 2016). Early flowering crops may also reduce bumblebee abundance and diversity because of possible competition with honeybees (Kallioniemi et al., 2017). Also landscape composition and configuration may affect different facets of bee diversity (Carrié et al., 2017).

Further indicators of habitat quality are also considered beyond basic landscape composition. First local feeding resources favour pollinating insects. These flower resources are estimated through flower abundance, diversity and flower traits related to nectar and pollen reward (Orford et al., 2016; Potts et al., 2003; Ricou et al., 2014). Second availability of local nesting substrate, frequently quantified by the proportion of bare ground or the presence of logs, also favours pollinators (Potts et al., 2003; Rodríguez and Kouki, 2015).

In order to integrate the pollinator community structure comprising different pollinator groups influenced by different scales and landscape elements, it is essential to either adjust the scale of the landscape analysis to focal species or to run multi-scale analysis. Indeed pollinating insects can differ in their responses to landscape structure depending on their ecological characteristics. For instance, while large and small bees responded similarly to the proportion of agricultural land at field scale (300 m), their response were opposite at landscape scale (1,500 m) (Benjamin et al., 2014). Different bee guilds have been observed to respond to the proportion of semi-natural habitat at different radii, due to habitat preferences linked to their nesting niche, while crop visitation preferences were related to bee sociality (Pisanty and Mandelik, 2015). Also richness and abundance of pollinating insects may respond to different scales: in an analysis of the pollination of *Lotus corniculatus* (L.) in peri-urban habitats wild bee richness increased with abundance of spontaneous flowers within gardens, but their abundance increased with landscape diversity within a 700 m radius (Pellissier et al., 2013). Lastly interactions among different mechanisms operating at different scales may mediate

effects on pollinators. For example effectiveness of agri-environmental management can be mitigated by the landscape context (Herbertsson et al., 2018; Scheper et al., 2013).

#### 4.3. Method selection and alternative options

##### 4.3.1. Selecting fit for purpose methods

Given the diversity of definitions, indicators and methods, proposing a unique method for the biophysical quantification of the pollination service estimation would clearly be counter-productive, also because of the inherent complexity raising from an interaction of two highly diverse taxonomic groups (pollinator-dependent plants and pollinating organisms). Instead, we provide here guidelines for an appropriate method selection amongst existing methods. We note here that this may not be as helpful to pollination specialists. The decision tree was rather aimed at scholars or practitioners with more limited experience who are considering the pollination ES as part of assessments or monitoring of multiple services, *e.g.* in environmental impact or restoration studies. The choice for a given pollination study should be guided by both the study question and availability of human, time, equipment and financial resources (Figure 8). Method selection is first based on the study focus and constraints. This is an essential decision since, as noted above, the relationship between pollination supply capacity and flow is unclear. If plant reproductive success – *i.e.* the *pollination success* definition, or yield characteristics – *i.e.* the *harvest for human consumption* definition, are targeted, variables and methods associated with the pollination flow definitions, and associated measures should be selected as direct indicators of effective plant pollination. If pollinating insects are the main topic of interest, the variables and the methods identified as direct indicators of pollination supply capacity would be more relevant (Figure 8). For example, to estimate the visit frequencies of respectively grapefruit and mangoes, [Chacoff and Aizen \(2006\)](#) and [Carvalho et al. \(2012\)](#) made observations of pollinator visits on flowers. To compare pollinator communities between landscapes, [Baldock et al. \(2015\)](#) used net captures, as did [Winfree et al. \(2015\)](#) to determine whether each of richness or abundance of wild bees participate more to pollination service delivery. As for trap captures, these methods were for example used to explore the effects of orchard ground cover on pollinator communities (Saunders et al., 2013) and to estimate the impacts of coffee plantation management on bee communities (Jha and Vandermeer, 2010). These methods can be complemented by analyses of community composition and structure (Bennett and Isaacs, 2014; Carrié et al., 2017; Potts et al., 2006). Whether focusing on supply capacity (insect-based indicators) or flow (plant-based indicators), as a second step a set of variables and methods should be made depending on the study constraints and available resources (Figure 8). Precise field-identification of pollinators requires advanced naturalist skills and thus cannot be performed by everyone. As for insect captures and laboratory identification, identification can be entrusted/subcontracted to

entities. Flower isolation for estimation of insect participation to their reproductive success will require more visits than insect observations but less field time. This step of flower isolation was for example used to determine the consequences of wild flower plantings on the pollination service flow in blueberry fields (Blaauw and Isaacs, 2014). It was also applied to compare different pollination treatments in order to estimate the effects of wild bee pollination on tomato production (Potter and LeBuhn, 2015). Methods to estimate the pollen load of individual insects or the single visit deposition are not included in this decision tree as they were only used in a minority of the reviewed articles. For measuring plant reproductive success, while seed/fruit count and scaling require few specific skills, they are labour intensive and require long hours spent in the laboratory (Figure 8). These methods were for example applied to measure the impact of insect pollination on the seed number and weight of spring oil seed rape (Bommarco et al., 2012) or to estimate the influence of field size on blueberry fruit set and berry weight (Isaacs and Kirk, 2010). To go further, some studies analyse more particularly some qualities important for human consumption, such as the benefit of insect pollination for size and shape of apples (Garratt et al., 2014a) or the consequences of management practices on the mass of marketable fresh mangoes (Carvalho et al., 2012). Thus, each level of definitions and each indicator have their resources (human, time, equipment) constraints.

Feeding and nesting resources indicators may also be considered as proxies to estimate pollination supply capacity. In this case indirect indicators based on habitat and landscape characteristics would be selected. Landscape characterisation requires aerial photography and/or precise cartography of the studied area, as well as remote-sensing interpretation and/or geographic analysis skills. This combination of abilities, time and data make these analyses not available to everyone.

#### **4.3.2. Alternative methods**

Alternative methods to the common methods analysed in this study exist. First citizen-science networks are increasingly popular in order to monitor pollination services in (peri-)urban ecosystems. For example, the monitoring of reproductive success of *Vicia faba* L. in the UK (Birkin and Goulson, 2015) and of *Lotus corniculatus* in France have been successful programs for monitoring pollinator communities as they are known to reflect the richness and abundance of bumblebee morphospecies (Pellissier et al., 2013). At a larger scale, insect observation networks based on citizen-science are developed and can be used to summarise the distribution of pollinating insect at a national level. For example the French program Spipoll (<http://www.spipoll.org/>) estimates the occurrence frequency of observed taxa (Deguines et al., 2016, 2012). Also, pollination supply capacity could be estimated through standardised rapid biodiversity assessment methods aiming to assess arthropod diversity.

These methods are based on insect trapping and include a specific protocol to estimate pollinator diversity (Obrist and Duelli, 2010). Second, recent methods rest on technological advances such as video surveillance to monitor pollinator visitation (Phillips and Gardiner, 2015), or a recently developed procedure to monitor flower-visiting animals through the use of digital camera and automated data processing, reducing manpower needs (Steen, 2017). Recent advances in remote sensing have also been applied to estimate pollination. Optical flower traits have been linked with different pollination syndromes – wind, self and insect pollination (Feilhauer et al., 2016). Recently, Clec’h et al. (2018) tried to link remotely sensed data (land cover, distance to forest, elevation, NDVI, etc.) with field measurements of the richness of *Sphingidae* moths as an indicator of pollination capacity. Lastly, using Internet big data, Bahlai and Landis (2016) investigated the relationships between field measured flower attractiveness and the abundance of images showing this plant species and beneficial insects.

#### **4.3.3. Towards method standardisation**

This review highlighted the high diversity of existing methods used to estimate the pollination service, for instance in the assessment of ecological impacts or restoration. Our results highlight the necessity of moving towards comparable indicators and standardised methods. Such common methods could especially facilitate meta-analyses of comparable indicators across studies. As an example, in the current state of knowledge a robust analysis of wild bee decline across ecosystems and climatic conditions is limited by available data sets where similar indicators (*e.g.* species richness, total abundance) have been quantified using highly different methods (*e.g.* net sampling and pan traps). An experiment by Popic et al. (2013) demonstrated that these methods result in incomparable values. For that, and in the context of current and future global changes, it becomes necessary to converge towards standardized methods, in order to conduct comparable studies across the world able to report changes in pollinator communities but also in yields of animal-pollinated crops in different countries. This would raise awareness about current problems and promote pollinator-management practices at a large scale. Moreover, comparable indicators and standard methods would facilitate the modelling of the pollination ES, thanks to broader and more standardised data sets which could be used to calibrate such models. A first attempt towards this is provided by TESSA, a toolbox of methods for estimating ecosystem services. TESSA presents a standard method with different complexity levels allowing to estimate both ecosystem supply capacity of the pollination service and its flow (Peh et al., 2017). Besides the significant effort of presenting standardized methods, such platforms could support data collection for analysing the relationships between indicators of pollination service supply capacity and flow.

## 5. Conclusion

This review underlined the multiple facets of definitions of the pollination service, and associated indicators which can be sometimes estimated by common methods. Frequent indicators and associated methods address different questions, confirming the importance of properly defining the conceptual and methodological frameworks for each pollination study. By helping researchers and practitioners to choose relevant methods for their study objectives given their resource and time constraints, we hope to facilitate the integration of the pollination service into management and land-use planning. Importantly emerging alternative methods may further help in this endeavour. The in depth analysis of relationships between indicators of the pollination service supply capacity – *i.e.* insect diversity indicators – and indicators of the pollination service flow – *i.e.* indicators of plant reproductive success, stands as a priority for improved coherence. To progress towards methodological standardisation, further research should also aim at better understanding plant-pollinator networks, investigating plant and pollinator specialisation, plant dependency to pollinator-pollination and the pollination efficiency of pollinators.

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**Figure 1:** Conceptualisation of the pollination ecosystem service adapted from Martín-López et al. (2014). Green boxes and arrows represent Ecosystem components; blue boxes and arrows represent socio-system components; red terms and arrows represent ES; purple elements represent ES values (based on the IPBES framework (Pascual et al., 2017)) and resulting decisions/actions on ecosystems; the black box and arrows represent drivers of ecosystem state and of ES flow.

**Figure 2:** Characterisation of the pollination studies' context. Results presented here are proportion of total occurrences. When the number of articles is different of the number of occurrences it is that some articles had more than one occurrence. MFC stands for mass 'flowering crop'. Climbing plants is for a study on passion fruits which is a climbing plant and not a fruit tree. The group of focus insects "bees" combines studies focusing at the same time on wild bees and domestic honeybees and sometimes bumblebees.

**Figure 3:** Proportion of pollination studies **carried out** in different countries across continents. For example, the yellow colour indicates that between 2.5 and 5 % of the studies included in this review were carried out in each of the countries coloured in yellow: Canada, Brazil, Sweden and Australia. (Source: [http://thematicmapping.org/downloads/world\\_borders.php](http://thematicmapping.org/downloads/world_borders.php)).

**Figure 4:** Proportion of articles using 0 to 4 pollination definitions and proportion of co-occurrences of the different definitions. The number of articles may differ from the number of occurrences when some articles had more than one occurrence.

**Figure 5:** Indicators (green boxes and bar graphs) and their associated estimation methods (red boxes and red bar graphs) for the two definitions of the pollination service supply capacity: *presence of pollinators* and *pollen transfer* (blue boxes). Each definition is related to its indicators by a black arrow. Indicators are related to their associated estimation methods by black arrows. For each indicator and estimation methods, bar plots present proportion of occurrences of each modality are represented in the bar plots, thus the number at the side of each bar is expressed in percentage. The number of articles may differ from the number of occurrences when some articles had more than one occurrence because of the presence of more than one modality. Descriptions of the different modalities are detailed in Table 1 for indicators and Table 2 for estimation methods. The central three-part graphs represent the estimation methods common to the abundance/diversity indicators of the *presence of pollinators* definition and to the visit frequency of the *pollen transfer* definition: the left panel presents the proportion of occurrences for the *presence of pollinators* definition; the right panel presents the proportion of occurrences for the *pollen transfer* definition and the central panel presents the proportion of occurrences for both definitions gathered. The article numbers on the left of the three-part graphs represent the number of articles applying the methods related to pollinator observation and capture.

**Figure 6:** Indicators (green boxes and bar graphs) and their associated estimation methods (red boxes and red bar graphs) for the two definitions of the pollination service flow: *pollination success* and *harvest for human consumption* (blue boxes). Each definition is related to its indicators by a black arrow. Indicators are related to their associated estimation methods by black arrows. For each indicator and estimation methods, bar plots present the proportion of occurrences of each modality, thus, expressed as percentage. The number of articles may differ from the number of occurrences when some articles had more than one occurrence because of the presence of more than one modality. Descriptions of the different modalities are detailed in Table 1 for indicators and Table 2 for estimation methods. The central three-part graphs represent the estimation methods common to the measured variables of *pollination success* and *harvest for human consumption*: the left panel presents the proportion of occurrences for the *pollination success* definition; the right panel presents the proportion of occurrences for the *harvest for human consumption* definition and the central panel presents the proportion of occurrences for both definitions gathered. For the step of *pollen manipulation* related to both definitions, the proportion corresponds to the percentage of articles involving this experiment step amongst related the two definitions

1171 which number are on the bar graph itself. Repro.-obs. and Repro.-an. stand respectively for observation of reproduction  
1172 and analysis of reproduction.

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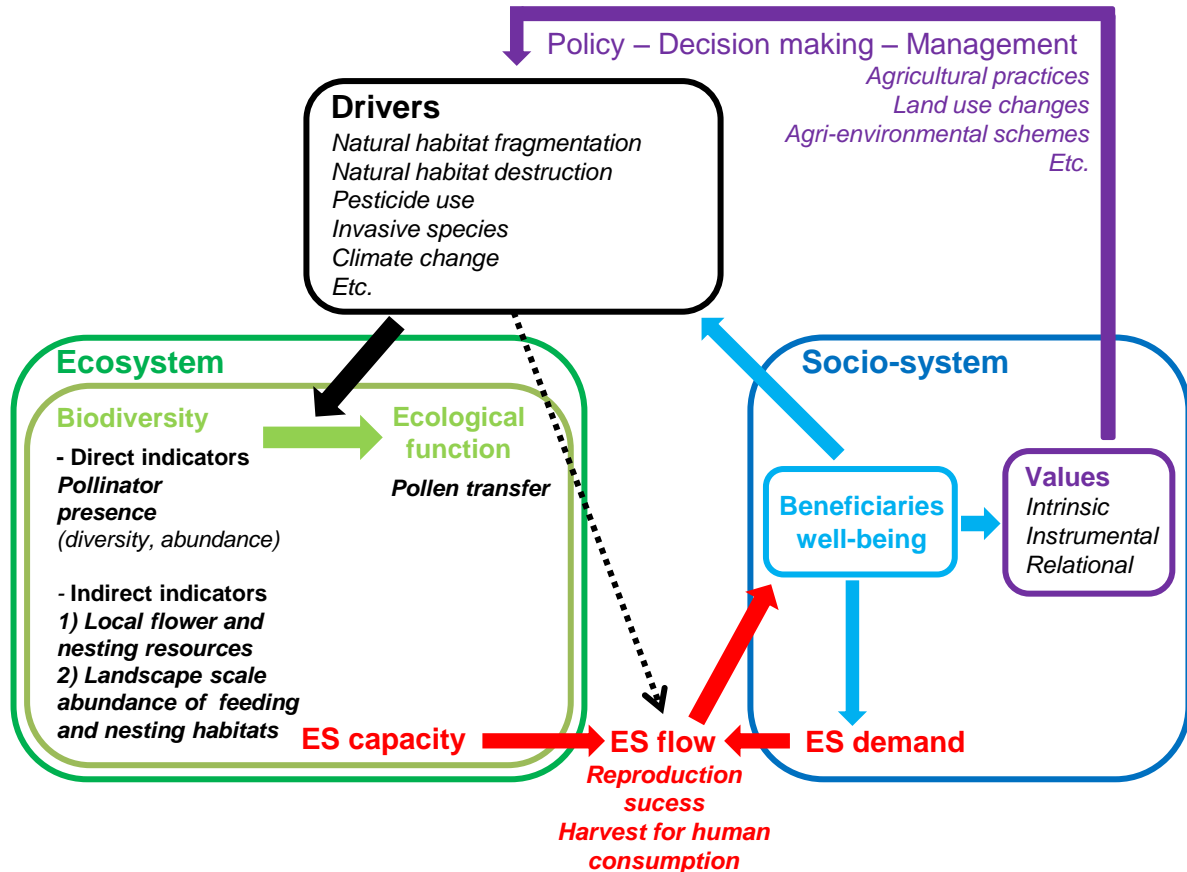
1174 **Figure 7:** Proportion of occurrences of variables linked to the habitat and landscape characteristics. The number of articles  
1175 may differ from the number of occurrences when some articles had more than one occurrence.

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1177 **Figure 8:** Decision tree to guide for the choice of appropriate pollination estimation methods, considering the focus  
1178 element of the pollination system and the means constraints.

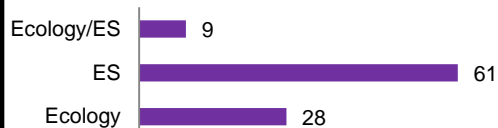
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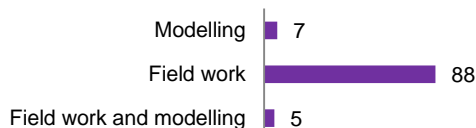
### Field of study

On 131 articles



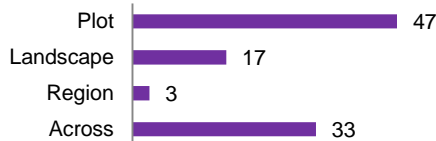
### Method types

On 131 articles



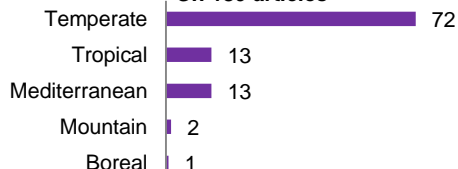
### Scale of study

On 131 articles



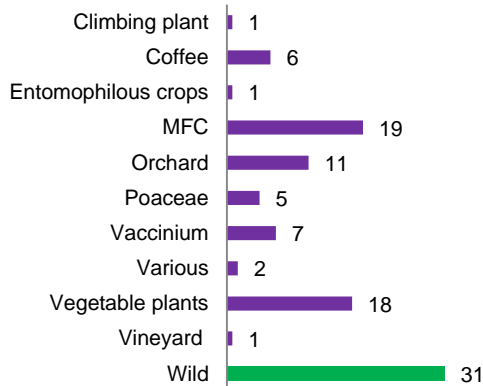
### Climate of study

On 130 articles



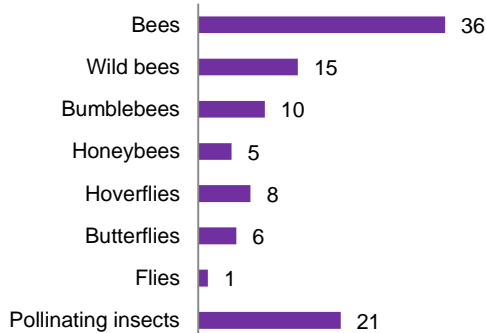
### Focus plant

131 occurrences on 117 articles



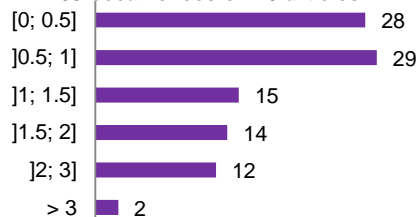
### Focus insect group

145 occurrences on 126 articles



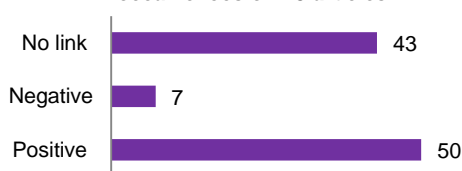
### Radius of landscape study (km)

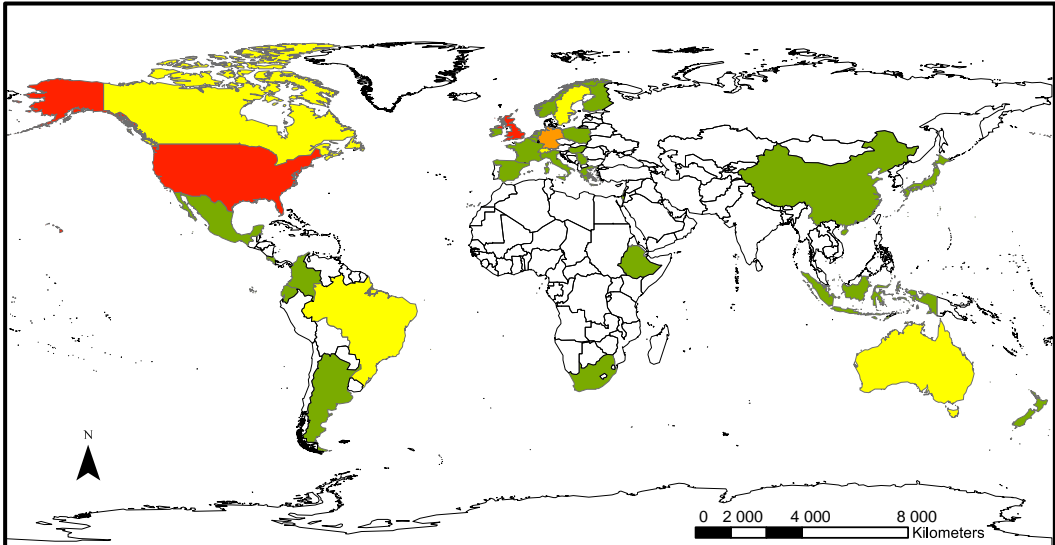
169 occurrences on 49 articles



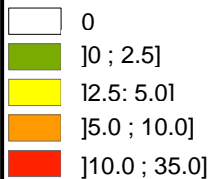
### Relationship between potential and realised pollination

42 occurrences on 23 articles





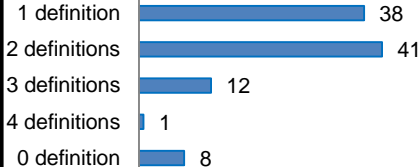
### Legend





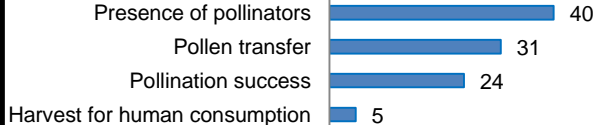
## Number of definitions

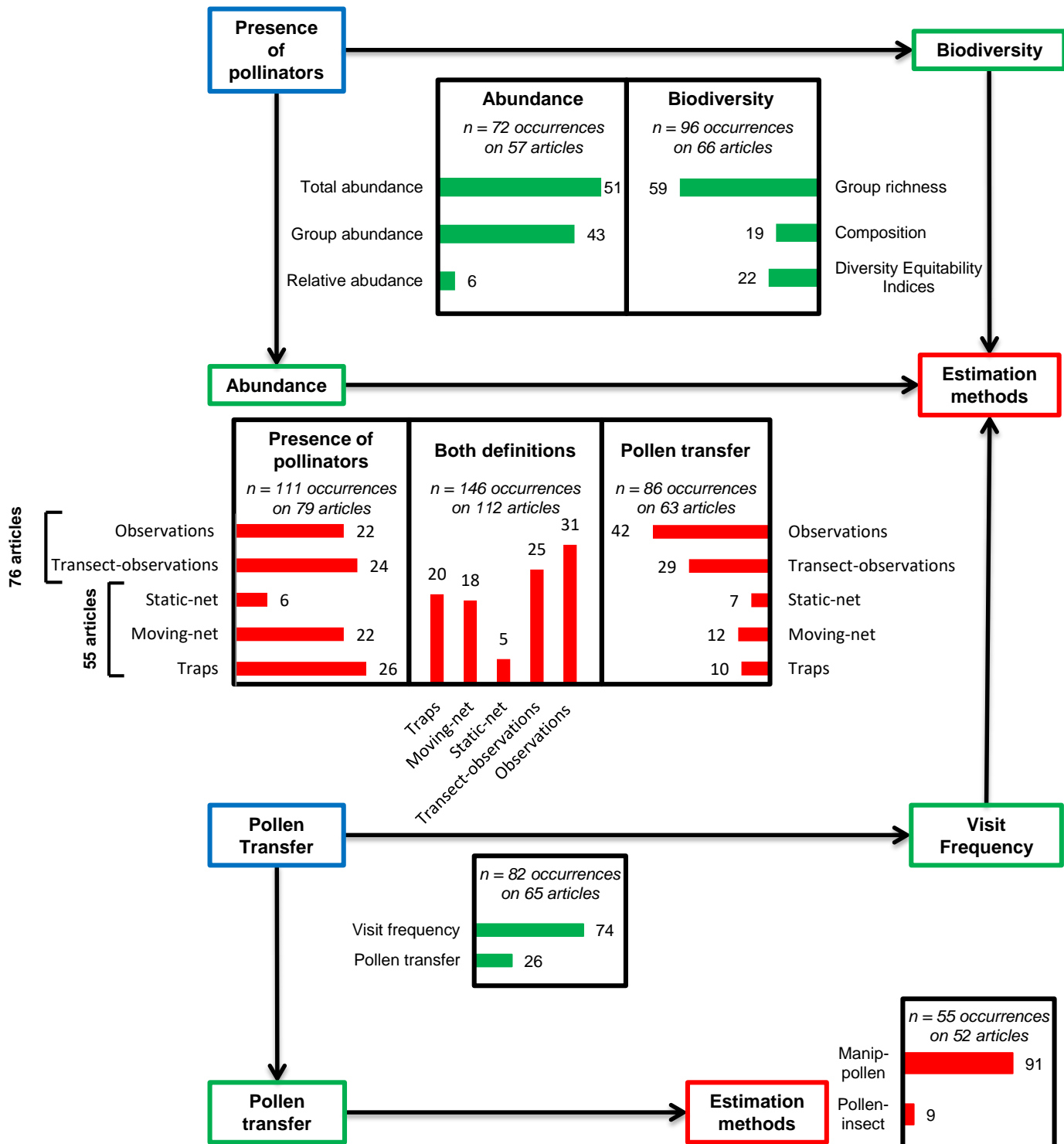
*On 131 articles*

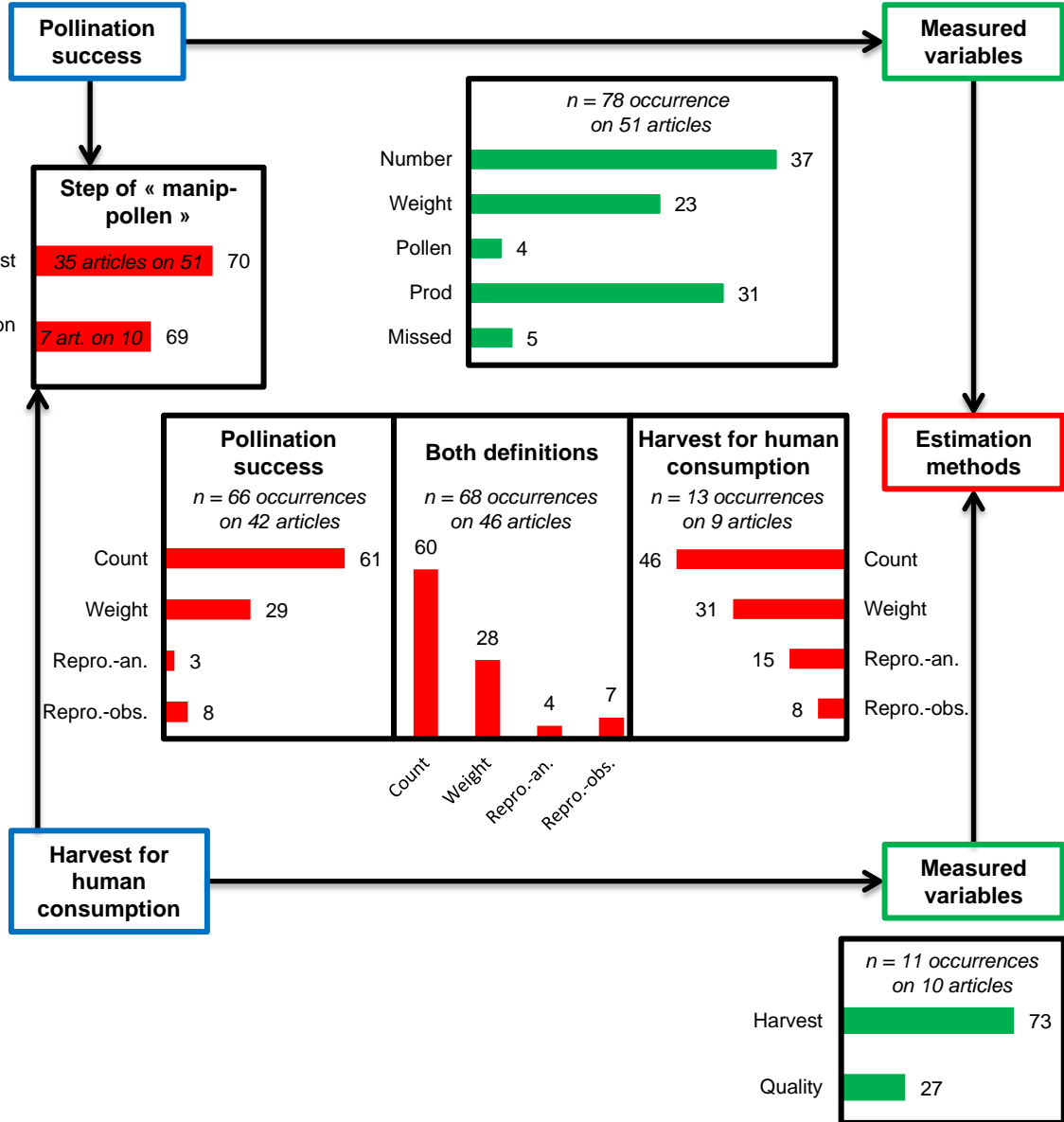


## Different definitions

*211 occurrences on 131 articles*

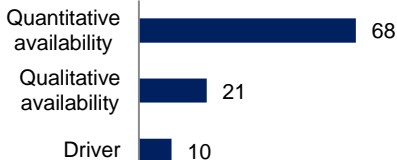






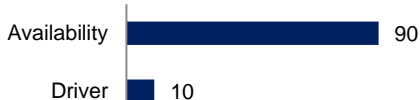
### Feeding resources

**136 occurrences on 98 articles**



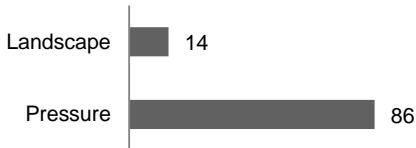
### Nesting resources

**80 occurrences on 75 articles**



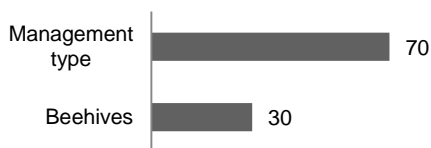
### Landscape characteristics

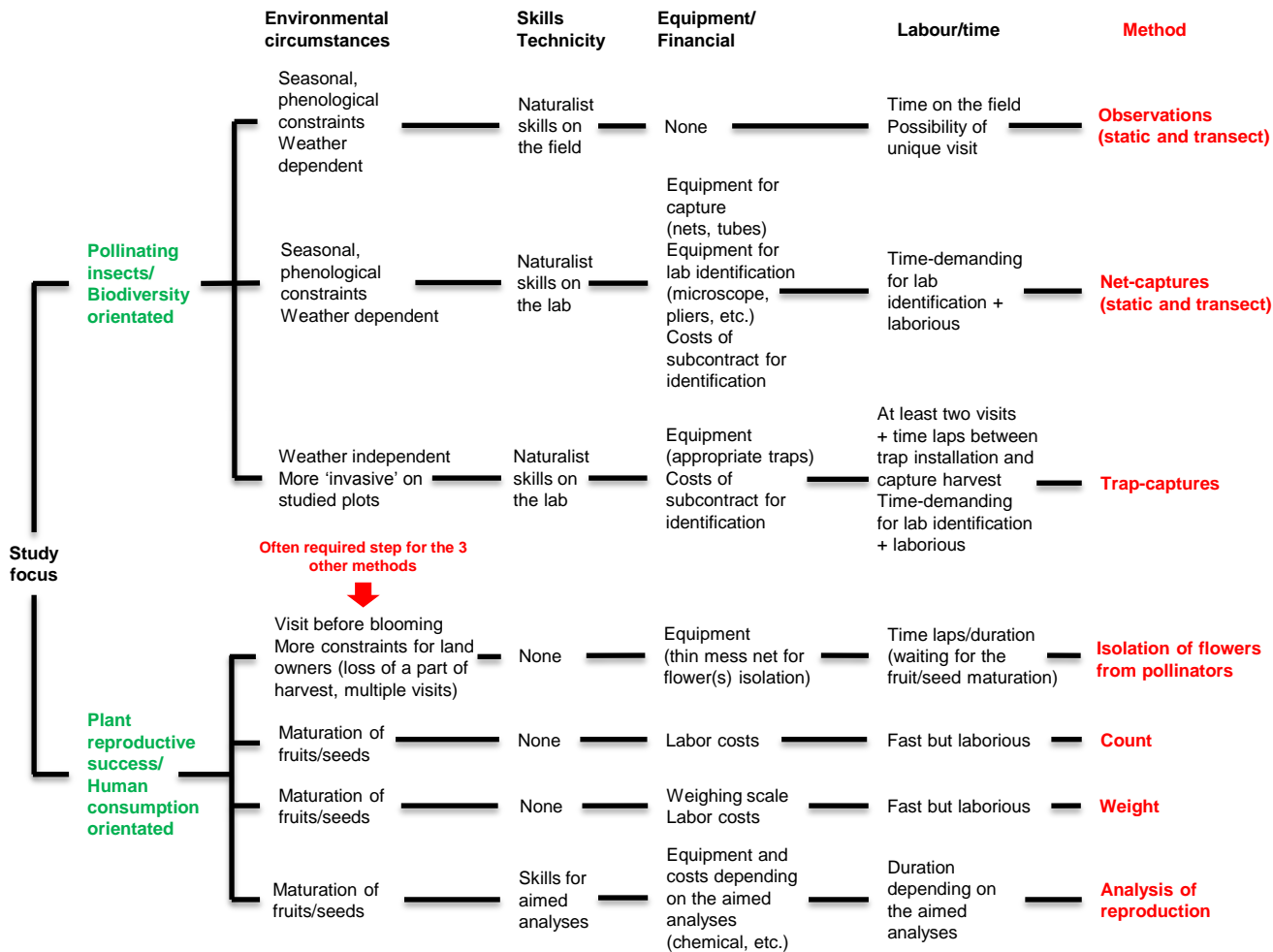
**72 occurrences on 64 articles**



### Management

**37 occurrences on 31 articles**





**Table 1:** Classification of pollination variables and associated indicators according to pollination definitions. The third column lists indicator denominations used in the rest of the paper.

Associated definition	Variables and associated indicators	Denomination
<b>Presence of pollinators</b>	<b><i>Biodiversity</i></b>	
	Specific/morpho-species/functional groups richness, etc.	<b>Group richness</b>
	Pollinator community composition	<b>Composition</b>
	Diversity (Shannon index, Simpson index, $\beta$ diversity), equitability, similarity measures between pollinator communities	<b>Diversity Equitability Indices (DEI)</b>
	<b><i>Abundance</i></b>	
	Total abundance/density	<b>Total abundance</b>
	Taxa abundance/density (species, group, size, etc.)	<b>Group abundance</b>
	Relative abundance (of different taxa)	<b>Relative abundance</b>
<b>Pollen transfer</b>	Visit number/Visit rate/Visit frequency	<b>Visit frequency</b>
	Pollen transfer efficiency Pollen deposit on stigma per visit Pollen quantity held by one individual Pollen quantity taken per visit	<b>Pollen transfer</b>
<b>Pollination success</b>	Pollen grain number with developed pollen tube	<b>Pollen</b>
	Seed/fruit number (unit, per plant, per pod, etc.)	<b>Number</b>
	Fruit/seed mass (fresh or dry)	<b>Weight</b>
	Seed/fruit production (% of flowers becoming fruits, % viable seeds)	<b>Prod</b>
	Number of aborted seeds/fruits	<b>Missed</b>
<b>Harvest for human consumption</b>	Harvest (production per surface unit)	<b>Harvest</b>
	Seed/fruit quality (shape, relevant properties in their consumption)	<b>Quality</b>

**Table 2:** Classification of the estimation methods associated with the different pollination-related variables.

Typology	Estimation methods
<b>Observations</b>	
<b>Transect-observations</b>	Transects with insect count done walking (for a given time/speed) (count of the visit number, the number of flower visited, total number of flowers). The same approach is applied on circular plots or on a spiral.
<b>Observations</b>	Plot observation with a focus on the whole surface or on focal plant(s) during a given time In some large flowers: observations with cameras Follow one individual and count how many flower it visited during a given time and the proportion of the target plant(s) visited on 10 visits Focal observation of one species to note its feeding preferences
<b>Captures</b>	
<b>Moving-net</b>	Transects with captures done with a net or an insect vacuum along a given distance (in a given time)
<b>Static-net</b>	Captures with a net or an insect vacuum during a given time or a given number of net strokes, not along a transect
<b>Traps</b>	Pan traps (of different colours (white, yellow, blue), with different configurations and different durations (from 24h to more than 96h)) Other traps (with interception windows, in nest shape, etc.)
<b>Pollen analysis</b>	
<b>Manip-pollen</b>	Experimental designs implying pollinator exclusion at least during a part of the flowering or some hand-pollination Flower isolation: - pollinator exclusion when flowers are at a bud state and then flower presentation to an insect or waiting a first visit and after isolation: removing the stigmas (pollen grain count (all pollen combined or separation of hetero- and conspecific pollen) or counting the obtained number of seeds/fruits)-complete pollinator exclusion (sometimes completed with hand-pollination)
<b>Pollen-insect</b>	Insect captures for: count of pollen grain number on different body parts, estimation of the pollen load.
<b>Harvest</b>	
<b>Count</b>	Count of the number of pollen grains developing pollen tube/of fruits/of seeds
<b>Weighing</b>	Fruit/seed weighing (fresh or dry)
<b>Observation of reproduction</b>	Observation of reproduction: Number of aborted/malformed fruit/seed
<b>Analysis of reproduction</b>	Analysis of reproduction: Quality analysis of fruits/seeds (chemical analysis, analysis of shape, etc.) Final harvest
<b>Pollinator manipulation</b>	
<b>Pollinator manipulation</b>	Modification of the pollinator community composition Modification of beehives' configuration
<b>Citizen science</b>	
<b>Citizen science</b>	Use of citizen science for data collection
<b>Literature data</b>	
<b>Literature data</b>	Use of data/information available on historical data bases or publications

**Table 3:** Typology of the most common habitat variables.

Typology	Variables
<b>Habitat - feeding resources</b>	
<b>Quantitative availability</b>	Floral/foraging habitat resources: density of flowers/of species flowering/of entomophilous plants, proportion of flower cover, flower abundance Density of flowers of the target plant Proportion of the (semi)-natural habitat in the surroundings, distance from the closest (semi-)natural patch Hedgerow/field margins presence/absence/quality Surface of crop needing insect pollination
<b>Qualitative availability</b>	Nectar presence/quantity/quality Specific richness of flowering plants
<b>Driver</b>	Proportion of bare soil Proportion of impervious surface Grazing, mowing
<b>Habitat – nesting resources</b>	
<b>Quantitative availability</b>	Proportion of the (semi)-natural habitat in the surroundings, distance from the closest (semi-)natural patch Hedgerow/field margins presence/absence/quality Proportion of bare soil
<b>Driver</b>	Proportion of impervious surface Soil compaction

**Table 4:** Typology of the most common co-variables of pollination studies.

Typology	Variables
<b>Landscape characteristics</b>	
<b>Pressure</b>	Fragmentation/Isolation (of the studied plot compared to (semi-) natural area) Fire regime (most of all in Mediterranean landscapes) Land use (gradient of intensity of land use: more or less agricultural/urban area; intensity of anthropic impact on ecosystems)
<b>Landscape</b>	Landscape metrics: area/density/edge; shape; connectivity; configuration; complexity; diversity Linear elements
<b>Management</b>	
<b>Management type</b>	Organic/conventional agriculture Different degrees of management (forest management more or less interventionist) Applied treatments (fertilizers, pesticides, etc.)
<b>Beehives</b>	Beehive presence