POLLINATOR-MEDIATED INTERACTIONS OF FOUNDATION PLANTS IN THE MOJAVE DESERT

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# **Abstract**

Pollination facilitation is an indirect interaction whereby one plant species positively influences the reproductive success of another plant species through pollinators. This thesis contributes to the field of pollination facilitation using two approaches. First, we conducted a systematic review of the experimental pollination facilitation literature. We found that the field of pollination facilitation advanced seven mechanistic hypotheses which we synthesized into a conceptual framework to summarize the extent of mechanisms tested to date. Co-flowering interactions including the magnet species effect are the most frequently studied; however, the capacity for plants to facilitate the pollination of other plants through pathways that do not require co-blooming is an important research gap identified in this literature. We addressed several research gaps identified by the literature review. We tested the capacity for the dominant, foundation shrub *Larrea tridentata* to facilitate its annual understory. We separated blooming and non-floral interactions while incorporating the temporal dimension by tracking pollinator visitation to the understory as *L. tridentata* went through spring flowering phenology. *L. tridentata* interfered with the pollination of *Malacothrix glabrata* before it bloomed, and visitation was significantly reduced with blooming. *L. tridentata* supported plant and arthropod communities while creating locally stable microclimates demonstrating that positive and negative effects by foundation plants occur simultaneously. This project contributes to a better understanding of the underlying mechanisms driving interactions whole in a critically understudied arid environment.

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# **General Introduction**

# **Chapter One**

# Finding the bees knees: a conceptual framework and systematic review of the mechanisms of pollinator-mediated facilitation.

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## Abstract

Pollination facilitation is an indirect interaction whereby one plant species positively influences the reproductive success of another plant species through pollinators. A formal systematic review including 100 directly relevant papers was used to categorize the literature into a conceptual framework summarizing all mechanisms underlying pollination facilitation tested to date. We also summarized the spatial scale and grain size of each study, classified the theme, and recorded the ecosystem. Pollination facilitation research advanced seven major mechanistic hypotheses that can be synthesized into the following four umbrella mechanisms: trait-based effects, floral display size, floral diversity, and apparent pollination support. Co-flowering interactions including the magnet species effect are the most frequently studied; however, the capacity for plants to facilitate the pollination of other plants through pathways that do not require co-blooming is an important research gap identified in this literature. We propose that the term ‘apparent pollination support’ be used to describe pollination facilitation between plants through non co-blooming mechanisms. Most studies have been conducted using a relatively small spatial grain (< 1 m2) but there was evidence from all scales in most ecosystems of facilitation suggesting it may be more prevalent than previously assumed globally. Most studies (87.5%) that tested for facilitation at multiple scales reported scale dependence highlighting the need to explicitly consider spatial dimensions in future experiments on these topics. Invasion biology, agricultural science, mimicry systems, and conservation of rare plant species all examined pollination facilitation. Research gaps included the need to decouple mechanisms, explore the temporal dimensions and examine the relative importance of scale on the underlying processes that influence plant and pollinator community dynamics.

**Keywords**

Pollinator, facilitation, plant-plant, systematic review, scale dependence

## Introduction

Positive interactions between plant species, i.e. facilitation, are increasingly incorporated into ecological theory (Bertness and Callaway, 1994; Bruno et al., 2003; Callaway, 1995). Facilitation has been documented in most ecosystems as a fundamental process driving plant community structure and dynamics (Callaway, 1995). Pollinators provide critical ecosystem services, and there is increasing concern over their potentially global decline (Kearns et al., 1998; NRC, 2007). Recent estimates report that 87.5% of global angiosperms are animal pollinated (Ollerton et al., 2011). Therefore, understanding how plants interact via pollinators is necessary to understand the potential impacts of these declines. Co-flowering species of plants are common, and while there are a few salient examples of obligate plant-pollinator specialization, many species of plants share pollinators (Mitchell et al., 2009). Pollinator sharing leads to interactions between plants that can influence the reproductive success of one or both species forming a continuum of competitive to facilitative interactions (Rathcke, 1983). Competition between species for pollination profoundly influences the reproductive success of plants driving the evolution of floral morphology, phenology and reproductive strategies thereby integrating ecological and evolutionary perspectives (Mitchell et al., 2009). Mounting evidence shows that selection on reproductive plant traits and the development of ecological relationships are not driven exclusively by competition and that facilitation plays an important role.

Pollination facilitation influences many ecological and evolutionary processes. Facilitation has been demonstrated in plant mimicry systems (Benitez-Vieyra et al., 2007; Jersáková et al., 2009; Johnson et al., 2003; Peter and Johnson, 2008) and can promote the convergence of floral morphologies (Schemske, 1981). Facilitative interactions can also contribute to the evolution of complex mutualisms such as pollinator pollen placement mechanisms (Sun et al., 2011; Yang et al., 2013) and mitigate selection on mating traits that promote selfing (Moeller and Geber, 2005). Integrating pollinator mediated facilitation with current ecological theory will help to explain the coexistence of species with apparent niche overlaps (Moeller, 2004; Moeller and Geber, 2005) i.e. the joint use of resources by different species (Colwell and Futuyma, 1971) as well as the persistence of rare plants (Ghazoul, 2006; Moeller, 2004). Additionally, pollinator-mediated plant-plant interactions provide a framework for predicting the impact of invasive plant introduction on native plant communities (Bartomeus et al., 2008; Charlebois and Sargent, 2017; Molina-Montenegro et al., 2008; Morales and Traveset, 2009). Therefore, pollination facilitation has a wide-reaching and general capacity to serve as a model integrating ecological and evolutionary perspectives.

Pollinator mediated interactions are scale-dependent (Hegland and Kudo, 2014) meaning that the sign or strength of the interaction differs depending on the scale of observation. The recognition of spatial scale as a central concept to ecology has become well established (Levin, 1992; Sandel, 2015; Wiens, 1989), and increasingly, ecologists are explicitly incorporating spatial dimensions into their experimental design (Hegland and Kudo, 2014; Schmid et al., 2016; Spellman et al., 2016). Nonetheless, the current inconsistency in reporting in part stems from the terminology used by researchers (Sandel, 2015). Spatial scale as a descriptive measurement is distinct from the hierarchal, organizational levels frequently used by ecologists. Spatial scale is comprised of two components: grain, the size of the smallest unit of observation, and extent, the total sampling area (Scheiner et al., 2000; Turner, 1989). In field studies, grain and extent are often defined relative to the organism. Grain is often an individual or cluster of plants, and extent as a forest. Alternatively, they can be defined in absolute terms i.e. experimental plots. In both cases, these two scale components are finite measures that limit experimental resolution and therefore define the degree of generalization possible. It is not possible to infer patterns below measured grain size or above extent size (Wien, 1989). Scale of study has critical implications for applied ecology of plant-pollinator interactions and to experimental design because the mobility of animal pollinators increases the scale over which plants interact (Moeller, 2004). For example, some attractive plants facilitate their immediate neighbors while competing with others over a larger spatial scale (Hegland and Kudo, 2014; Schmid et al., 2016). Thus, a given scale can lead to erroneous conclusions when generalizing.

Although previously predicted to be a rare phenomenon (Feldman et al., 2004), there has been an increase in the publication of papers reporting facilitative interactions over the last three decades. Given this apparent prevalence a better understanding of the underlying mechanisms and potential outcomes of this interaction is needed. To this end, we conducted a formalized systematic review of the pollination facilitation literature published. Using the literature, we developed a typology for the research and classified all studies into this conceptual framework. The synthetic framework visualizes all the pathways tested in the literature where plants induce a response in pollinators leading to an increase in fitness for another plant species (Figure 1) describing a total of seven mechanistic hypotheses (Table 1). We focused on facilitation only because competition is comparatively well researched and mechanisms of facilitation are likely to be distinct from those underlying competition.

The primary goal of this review and conceptual framework was to link current research with ecological theory. Previous reviews of plant-plant facilitation have identified the need to understand indirect pathways (Filazzola and Lortie, 2014) and the individual mechanisms leading to facilitation (Brooker et al., 2008). The following specific objectives were addressed using this systematic review: to determine the frequency that each mechanism has been tested, to describe research gaps, to highlight the most common applications of pollination facilitation, and to assess the geographic and ecological scope of pollination facilitation studies. Pollination is an important ecosystem service therefore we examine the frequencies of publications within each to determine publication biases and ecosystem-specific gaps. In this systematic review, grain size and scale dependence in the primary literature were also synthesized to provide an estimate of the relative context and importance of pollinator facilitation at different scales and in effect to describe the potential scope that this set of mechanisms could be important to be pollinator communities*.*

## Conceptual framework

The seven hypotheses tested in the literature were classified into four umbrella mechanisms (Table 1). Pollination facilitation is an indirect interaction between plants mediated by the pollinator and the concepts were organized to reflect this plant-pollinator-plant interaction. The conceptual framework is comprised of trait-based effects, increasing floral display size, increasing floral diversity, and pollinator support as ‘umbrella’ mechanisms (Figure 1, A)*.* We use the umbrella term “trait-based effects” to include both the magnet species effect and mimicry and to reflect that these interactions are trait-mediated. In the magnet species effect, a particularly attractive plant species increases local pollinator abundances, thereby facilitating their co-blooming but often less attractive neighbors (Laverty, 1992; Thomson, 1978). The traits that magnet species exhibit are those that make a plant attractive to pollinators such as showy displays (Molina-Montenegro et al., 2008) or offering substantial resources (Johnson et al., 2003). The magnet species effect is not exclusively related to resources. For example, the sexually deceptive orchid *Ophrys fusca* acts as a magnet for a rewarding iris (Pellegrino et al., 2016) and tall-scaped *Primula farinosa* facilitate their short-scaped morphs (Toräng et al., 2006).In mimicry systems, less attractive plant species improve their fitness by mimicking a more preferred species (reviewed by Jersáková et al., 2009). In these cases, the trait is the resemblance to the model species. It can include mimicry of overall floral morphology (Carmona-Díaz and García-Franco, 2008), UV reflectance (Peter and Johnson, 2008), UV spectra and nectar content (Benitez-Vieyra et al., 2007). Facilitation due to the magnet species effect and mimicry is not commonly separated, and the degree of resemblance between the species is the major difference between these mechanisms (Carmona-Díaz and García-Franco, 2008). In both cases, the addition of another plant increases pollinator attraction disproportionate to the size of a display increase.

Facilitation can occur when plants growing together increase their combined floral display size by co-blooming (Feldman, 2006; Thomson, 1981). Many pollinators forage optimally (Pyke et al., 1977), and the nectar and pollen content of flowers influences their foraging decisions (Heinrich and Raven, 1972; Real, 1981). This leads to pollinators preferentially visiting larger displays (Chittka and Thomson, 2001; Thomson, 1981). There are two major ways to describe the size of a floral display: density i.e. the interplant distance and abundance, the total number of individuals (Kunin, 1997). Patch area and floral density interact to determine attractiveness for pollinators (Thomson, 1981). However, in many studies abundance and density are unavoidably confounded. Pollinator responses to floral display size are density-dependent (reviewed by Feldman, 2006). Per flower visitation rates are expected to increase with floral density until pollinators become ‘saturated’ by the overabundance of floral resources leading to a shift from facilitation to competition between plants (Rathcke, 1983). Pollinator densities mediate the shifting point (Ye et al., 2013).

When plants co-bloom, the increase in floral diversity can lead to improved pollination services by offering complementary resources to foragers (i.e. both pollen and nectar) or via sampling effort: more diverse displays may attract more diverse pollinators (Ghazoul, 2006), leading to the attraction of more effective pollinators. The umbrella term apparent pollination support includes all mechanisms for which co-blooming is not required. Sequential mutualisms arise when earlier blooming plants facilitate later blooming plants by increasing local pollinator abundance, or improving population longevity or stability (Waser and Real, 1979). We expand on this by including the mechanism of providing habitat for another plant’s pollinator (Hansen, 2007). This final mechanism is a novel extension to the literature because it does not require shared pollinators.

Each mechanism leads to either of two functional responses by pollinators (Figure 1, B): the change in behavior of individual pollinators or demography of pollinator populations. The conceptual framework by Moeller (2004) recognized two major responses by pollinators including aggregative (joint attraction) and numerical (joint maintenance) responses. We expand upon this; the most frequently documented behavioral response leading to facilitation is the joint attraction of pollinators (sensu Schemske 1981; Thomson 1978). There are other foraging-related behaviors that arise from context-dependent species preferences beyond attracting additional pollinators (Hersch and Roy, 2007). Pollinators can exert positive frequency dependent selection by preferentially visiting the most abundant plant. Thus plants can increase their fitness by co-blooming (Ghazoul, 2006; Toräng et al., 2008). Similarly, pollinators that show floral constancy, i.e. the tendency to facultatively specialize, can lead to facilitation between multiple species (Bobisud and Neuhaus, 1975) or among mimicry partners (Schiestl and Johnson, 2013). Some pollinators exhibit site-fidelity greater than floral constancy that leads to sequential facilitation of plants growing in that site (Ogilvie and Thomson, 2016). Demographic pollinator responses, sensitive to the local habitat or landscape (Grab et al., 2017; Jakobsson and Padron, 2014), can change the pollinator abundance, composition, or longevity thereby benefiting spatially or temporally associated plants. Both behavioral and demographic responses can improve the quality and quantity components of pollination (Figure 1, C). Visitation rates form the quantity component and conspecific pollen deposition is the quality component (Herrera, 1989). Increased visitation will not lead to increased fitness if excessive heterospecific pollen is deposited (Morales and Traveset, 2008). Furthermore, increased visitation is not necessary to increase conspecific deposition if more effective pollinators visit. This increase in conspecific deposition leads to increased seed set or viability (Figure 1, D).

## Methods

### Systematic Review

To review the field of pollination facilitation, we used the search terms “pollinat\* facilitat\*” in ISI Web of Science (WoS) and SCOPUS in November 2017. Results from these searches were exported as bibtex files and are available within the associated repository. We also consulted book chapter bibliographies and did supplemental searches using Google Scholar to ensure that the literature was well represented within the WoS. Only primary, English language experimental research papers published since 1970 in peer-reviewed journals were included. The following inclusion criteria were used: 1) explicitly tested for pollination facilitation; 2) tested interspecific plant-plant interactions including a plant-mimic or object (e.g. hummingbird feeder, (Brockmeyer and Schaefer, 2012); 3) net facilitation was tested using at least one indicator of reproductive success (see Supporting Information, S1). We screened a total of 1501 papers by abstract and 268 full-text articles leading to the inclusion of a total of 100 papers in this review (Appendix A).

We classified the literature using our synthetic framework by the mechanistic hypotheses testable given the variables and experimental design utilized by the authors (Table S2). Articles were further reviewed for spatial scale, country and ecosystem of study, main methods, theme of study and spatial grain size was categorized. Small grain was defined as one individual plant or a plot 1m2 or less, medium between 1 m2 and 20 m2, large between 20 m2 and 500 m2, and very large greater than 500 m2. Scale dependence was defined as a significant change in the value of a variable or the importance of a model predictor variable when either the grain or extent was changed within the experiment. Studies were classified as broad if they were very large grained, had extents greater than 10000 m2, or self-reported as landscape scale; otherwise they were classified as narrow. Ecosystems were simplified to agricultural, alpine, wetland, beaches, experimental, forest, grassland, semi-arid, tropical forest and urban/disturbed.

### Data Analysis

When multiple ecosystems were tested within the same publication, they were treated as independent observations. Publications testing for interactions using multiple grain sizes were considered independent for grain size graphs and subsequent frequency testing. Multiple mechanisms could also be tested with the same publication, and they were classified independently for graphs and frequency testing. However, the mechanism by grain size analysis was restricted to single scale studies because it was necessary for them to be paired within a study. We tested the relative frequencies of each tested mechanism, grain size, and ecosystem using Pearson’s chi-squared tests (chisq.test function) in R version 3.4.2 (R Development Core Team, 2016). As a post hoc test we used the standardized residuals to compare the proportion of each grouping. We fit a linear model using the log-transformed publication count as the response and year as the predictor (lm function) in R version 3.4.2 (R Development Core Team, 2016) to test for a publication frequency increase over time.

## Results

A total of 100 papers reported testing for pollination facilitation (Figure S3). The number of papers published per year has increased exponentially since 1978 (Adjusted R2 = 0.6426, p < 0.0001). Studies from 27 countries have been published with the majority in the USA (Figure 2).

There were significant differences in the frequency of tested mechanisms (Figure 3, χ2 = 119.21, df = 6, n = 162, p < 0.0001). The majority of papers addressed the magnet species effect (64%). Pollinator support is an unstudied mechanistic pathway. Habitat provisioning and sequential mutualisms were examined in only five papers each. A single mechanism was tested within 47% of papers, two mechanisms in 42% of papers, and only one paper examined four potential mechanisms. The framework did not apply to one paper that tested for facilitation at a community level using a novel network approach (Tur et al, 2016).

The largest proportion (28.3%) of studies was conducted in grasslands or meadows (χ2 = 66.057, n = 106, df = 10, p < 0.0001). In most ecosystems, narrow scales were more frequently used, but in agricultural lands broader scales were more frequently tested (Figure 3). Alpine ecosystems, wetlands and tropical forests lacked studies that consider both scales within the same paper.

All but three studies reported spatial grain size, and these ranged from 0.009 m2 to 35900 m2. However, most reported grain qualitatively (55%) as either an individual plant, clump, or a number of stems. Pollination facilitation is tested most frequently (61% of studies) with a small spatial grain (< 1 m2). Very large grain sizes greater than 500 m2 were tested the least comprising only 3.8% of studies (χ2 = 151.74, n = 105, df = 5, p < 0.0001). Extent was not consistently reported preventing full quantitative scale reporting. Instead, we classified studies into the categories of narrow and broad. These two scales of study were well distributed between tested mechanisms (Figure 4). Sequential mutualisms were the exception and have not been studied at both broad and narrow scales within a given study. The mechanisms of pollination facilitation have been studied using a range of spatial grain sizes (Figure 5). A total of 25 studies tested for interactions at multiple scales or explicitly included spatial dimensions into the experimental design with 21 of them reporting scale-dependence.

Invasion biology was the most frequently theme addressed (29% of studies) followed by agriculture (12%), deceptive pollination (9%), conservation (6%), and rare species (5%). Most papers studied unidirectional or bidirectional interactions; only nine used a network approach to either directly study interactions or supplement more traditional testing.

The most frequent method of assessing reproductive success was tracking pollinator visitation rates (86% of studies). Of the 63 papers that used seed/fruit set as a response variable, 54 controlled for potential confounding effects of plant-plant interactions (Table S5). The methods include using potted plants (19), testing for pollen limitation by hand-pollination (18), and pollinator exclusion (6). Of the nine that did not, two were very large-scale agricultural experiments that tracked pollinator visitation. Of the remaining six, two measured both pollen deposition and visitation, one measured pollen deposition, one study measured visitation, and one tracked pollen dispersal with dyes. There was only one study with no supplemental measurements or controls.

## Discussion

This systematic review is the first formal synthesis of pollination facilitation providing an overview of the underlying mechanisms that have been tested to date. The conceptual framework proposed effectively classified the state of research of pollination facilitation based on the mechanistic pathways examined in the individual studies reviewed. This framework is nonetheless sufficiently flexible to included future novel hypotheses because of the use of umbrella terms that provide for the inclusion of additional mechanisms as they arise from future studies. Co-flowering interactions are the most frequently studied. The capacity for plants to facilitate the pollination of other plants through pathways that do not require co-blooming is an important research gap. Many studies do not explicitly differentiate between the mechanistic hypotheses. Another significant research gap is the study of joint multiple mechanisms. To better test the underlying drivers of pollinator mediated interactions and to integrate these findings into applied ecology, we need to study more than one mechanism in a given system preferably in the same experiment. Facilitative interactions between plants can increase under declining pollinator availability (Lazaro et al., 2014) highlighting the increasing importance to study these interactions as a means to better model resilience of pollinator and plant communities.

### Research gaps in pollination facilitation studies

In natural systems, multiple mechanisms of facilitation operate concurrently. There is always the potential for interactions between display size and other mechanisms of facilitation. These mechanisms can collectively inform applied ecology. For example, when the magnet species effect interacts with floral density, both the presence and density of the attractive species contribute to its effect on other species. In a simulated invasion, facilitation by *Taraxacum officinale* shifted to competition with high densities of the invader (Muñoz and Cavieres, 2008). This is applicable to applied invasion biology because it suggests for some species there is a density threshold at which an attractive plant can become a competitor. Seifan (2014) manipulated both the density and aggregation of attractive plants finding again a shift from facilitation to competition with increasing density, but also that at low densities, they were better facilitators when regularly spaced then aggregated. Magnet plants have the capacity to improve the self-sufficiency of restored ecosystems (Dixon, 2009). Thus better understanding interactions between attractiveness, density, and aggregation will improve restoration.

Biodiversity continues to decline with human expansion (Butchart et al., 2010). Therefore, understanding the influence of floral diversity and display size jointly is important to for predicting the impacts of this decline. Experiments along gradients of fragmentation could provide a convenient and applicable system, particularly if pollinator populations are sampled. For example, along an urban diversity gradient, flower rich urban areas supported richer bee communities, leading to improved seed set for focal plant species (Theodorou et al., 2017). Incorporating pollinator identity is important to a better understanding of the mechanisms, as well as for predicting the impact of pollinator declines. For example, network analysis of island plant-pollinator visitation networks has shown that invasion intensity influenced the behavior of *Apis mellifera*, leading to community wide simplification of interactions despite having no negative influence on native seed set (Kaiser-Bunbury et al., 2011). Network approaches are labor and resource intensive but when combined with manipulative experiments will provide community-level and highly explanatory results.

Apparent pollination support is the least studied mechanism of pollination facilitation. It is the most likely to generate novel hypotheses because co-flowering is not a requirement. The study of pollination support in the literature takes two distinct streams including sequential mutualism (temporal facilitation) and habitat provisioning. Competition can shift to facilitation as floral phenologies diverge if shared pollinator populations are supported leading to a ‘sequential mutualism’, i.e. facilitation follows competitive interactions (Moeller, 2004; Waser and Real, 1979). Sequential mutualisms are likely an outcome rather than a cause of phenological divergence (Waser and Real, 1979) particularly because sequential flowering is not exclusively maintained by competition. This form of mutualism can also be maintained by herbivory (Brody, 1997). Alternatively, earlier blooming plants such as mass flowering crops can create resource pulses for pollinators that support later blooming plants (Grab et al., 2017). This effect had been termed ‘temporal spillover’ in agricultural studies (Riedinger et al., 2014). Evidence for temporal facilitation has also been found in invasive/native pairs (Ferrero et al., 2013), agricultural systems (Grab et al., 2017), and experimental arrays (Ogilvie and Thomson, 2016). Temporally separated mutualisms are generally predicted to be widespread (Waser and Real, 1979). Inclusion of the temporal dimension increases the complexity of interactions and presents considerable difficulty to experimental design. However, integrating the temporal dimension is likely critical in applied contexts because of the capacity for support. For example, the rare plant *Symphyotrichum* *sericeum* shares pollinators with earlier blooming plants (Robson, 2012) suggesting that conservation efforts to support the pollination of some rare plants need to consider both the immediate neighbors but also earlier blooming interacting plants. There is widespread potential for pollination facilitation to inform applied conservation practices.

Habitat loss is one of the most important drivers of wild bee abundance and diversity declines (Brown and Paxton, 2009; Potts et al., 2010). The mechanisms of habitat provisioning are thus critical to the conservation of both pollinator and plant populations. Cavity-nesting bees including *Megachile* leafcutter bees, *Hylaeus*, *Ceratina* (Michener, 2000) and agriculturally important *Osmia* bees (Cane et al., 2007) use pithy stems and dead wood as nesting sites, but this pathway for facilitation is likely trait-mediated (i.e. pithiness) rather than species-specific. Accordingly, habitat provisioning is addressed at a community level by agricultural studies showing that proximity to hedgerows (Dainese et al., 2017) and semi-natural lands (Norfolk et al., 2016) benefits crop pollination. In natural ecosystems, the only published example of facilitation by habitat provisioning is species-specific. The *Pandanus* shrub provides habitat for the gecko *Phelsuma cepediana* which is the main pollinator of *Trochetia blackburniana* (Hansen et al., 2007), and this shrub is a species of conservation concern in Mauritius. Shrubs of *T. blackburnia* experienced better pollination growing near *Pandanus*. The frequency that this mechanism functions is needed to better inform targets for conservation. Potential relationships can include facilitation by plants that act as hosts to pollinating Lepidoptera or within any system where the larva of a generalist pollinator requires a specific host plant. Plants growing in harsh environments benefit from close association to nurse plants due to abiotic stress amelioration (Filazzola and Lortie, 2014). Pollination facilitation has not been tested in arctic or desert ecosystems. Overall, pollination facilitation in harsh environments is a research gap. Pollination facilitation is very understudied in these harsh environments and can be a very important pathway to both conservation and agriculture.

Mensurative experiments that use seed-set or fruit-set as a response variable may be confounded by pollinator independent plant-plant interactions (Lachmuth et al., 2018). This review found the majority of experimental designs controlled for these sources of micro-environmental variation. Several authors have used methods to measure the presence of these interactions in tandem with tracking pollinator visits or pollen transfer. For example, Kaiser-Bunbury (2011) used the ratio of native to invasive flowers as a proxy for plant-plant competition. Molina-Montenegro (2008) corrected for potential bottom-up facilitation by measuring nitrogen and water availability, as well as visitation rates and seed output. The majority of papers overall use pollinator visitation as a response variable, which directly addresses pollinator behavioral or demographic responses. However, increased visitation does not always lead to increased seed set. For example, pollen deposition can be facilitated but not visitation rates (Muir and Vamosi, 2015) if more effective pollinators visit. Plants can simultaneously compete and facilitate different portions of the pollination process. In orchids, different interaction signs for pollinator attraction, pollen removal and pollen deposition have been reported concurrently (Duffy and Stout, 2011). It is not known how the mechanisms underlying the interaction influences the quality and quantity aspects of pollination. However, it is unlikely there is a consistent, overarching mechanistic influence because pollinator behavioral and demographic response to each mechanism depend on the identity of the interactors, as well as the context. The continued publications of papers that measure multiple metrics of reproduction will allow for future quantitative analyses as to the strength of interaction operating on each part of the pollination framework and enable this to be tested rigorously.

### Scale dependent effects are highly variable

The outcome of scale-dependency was highly variable across the pollination facilitation literature reviewed here. Facilitation typically decreased with distance likely because the influence of a plant cannot extend beyond the foraging range of its pollinators. For example, facilitation occurs at only very short distances from the invasives *Lupinus* (Jakobsson et al., 2015) and *Brassica nigra* (Bruckman and Campbell, 2016) suggesting that these invasives have little overall effect on pollinations in these systems. In almond orchards, floral abundance under trees is positively associated with their seed set while floral abundance within the landscape is not (Norfolk et al., 2016). Conversely, the invasive *Ranunculus ficaria* has a stronger magnet effect when present at the landscape scale suggesting presence in landscape is more important than local floral abundances some systems (Masters and Emery, 2015). Facilitation shifting to competition with increasing scale was reported in several systems including insect-pollinated red clover (Hegland and Kudo, 2014) and nectar-feeding birds within a fynbos ecosystem (Schmid et al., 2016). Scale dependence can arise at least in part from underlying mechanisms. Spatial scale dependence can manifest as magnet plants first influence the probability of a pollinator entering a patch, and then within the patch influence the pollinator’s choices between individual flowers (Seifan et al., 2014). These effects can lead to relatively small-scale facilitation between neighbors but competition between patches. Floral abundance is likely important at larger scales because it relates to the total pollen and nectar resource content of a community, and therefore to the carrying capacity of pollinator populations, and density may be more important at smaller scales because it is related to individuals’ foraging habits and preferences; these hypotheses are yet to be tested. The perception of floral display size by pollinators differs at multiple scales because at small scales increases in density are attractive to pollinators but at larger scales, as density increases, the displays become more diluted relative to pollinator abundances (Rathcke, 1983), and increases in display size become less visible. These perceptual biases by pollinators can lead to changes in interaction sign with increasing scale. Understanding the underlying mechanisms of scale-dependency is important to the effective experimental design of studies looking at pollination interactions. For instance, a recent meta-analysis found that the distance between control and neighboring plants influences the sign of an interaction more than the identity of the interactors (Charlebois and Sargent, 2017). A quantitative estimate of grain and extent is needed for pollinator mediated interaction studies because changes in strength and sign of interactions have been reported to change with scale and without measures in spatial dimensions we cannot effectively model its importance. Pollinator mediated facilitation has been nonetheless reported across a wide range of spatial grain sizes and in a variety of ecosystems. This suggests that these interactions are prevalent and are not restricted to small scales.

## Conclusions

Positive interspecific and intraspecific interactions between plants for pollinators can dominate in some plants communities (Hegland et al., 2008; Tur et al., 2016) and were relatively ubiquitous here. The scope of pollinator mediated facilitation is thus relatively broad encompassing most major ecosystems. Most pollinator mediated facilitation experiments to date use only a small spatial grain. This suggests that scale dependence can be a serious issue in these studies. It has been suggested that pollination as an ecosystem service operates on a local scale and at the ecological levels of the individual and population (Andersson et al., 2015). This review further suggests that pollination also operates on a community level for plants and their animal pollinators. The mechanisms categorized here likely do not function in isolation, and experiments that examine more than one pathway concurrently are needed. Furthermore, distributional asynchrony can result from shifts in the spatial distribution of species under climate change scenarios (Hegland et al., 2009) and this can lead to novel interactions between plants and pollinators highlighting the increasing need to understand the underlying drivers. Studies of pollinator-mediated facilitation must now begin to explore the relative importance of scale, temporal interactions, and the relative changes in one mechanism over another with these changes.

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## Figures and Tables

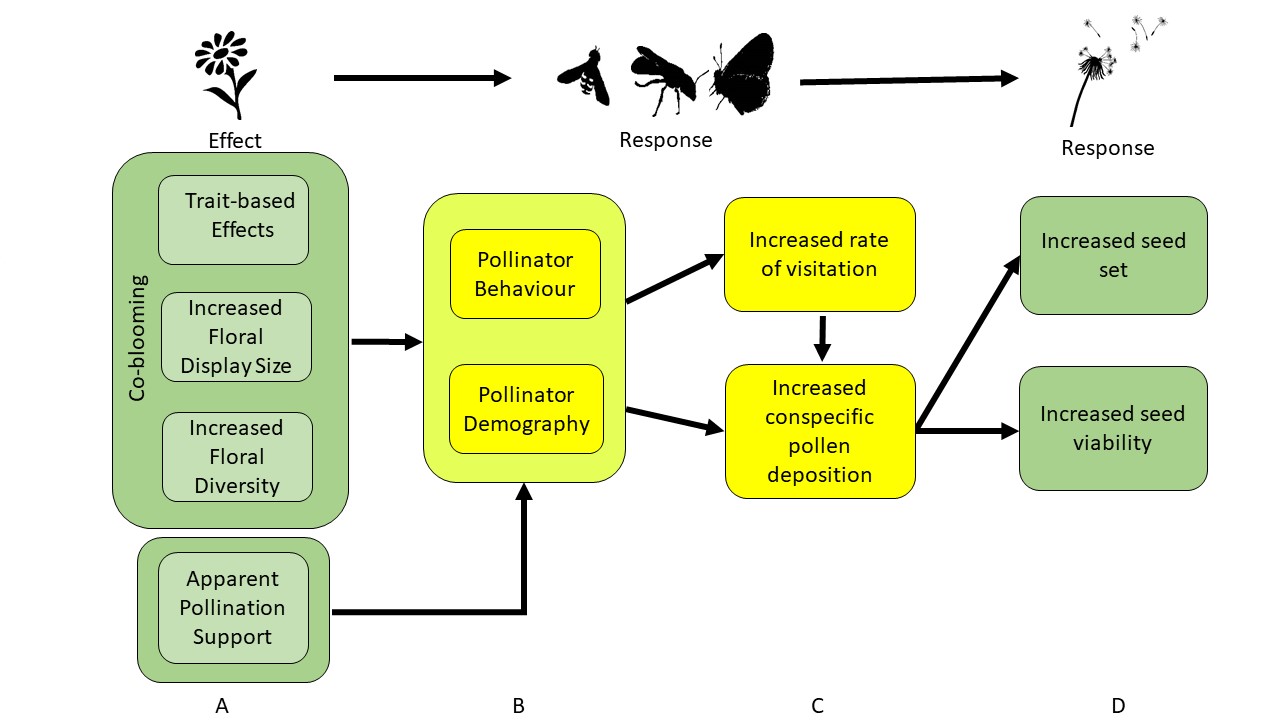


Figure 1: A conceptual framework to model the mechanisms and hypotheses associated with pollinator-mediated facilitation. The concepts were extracted from a systematic review of 100 studies on this topic. The seven mechanistic hypotheses tested within the literature can be categorized into four umbrella hypotheses. Refer to Table 1 for a description of the seven mechanistic hypotheses. Each mechanism (A) can lead to a behavioral or demographic responses (B) that increases pollinator visitation or conspecific pollen deposition (C) that leads to an increase in fitness for another plant species (D).

Table 1: A summary of the mechanistic hypotheses generated by a systematic review of the pollination facilitation literature, a concise definition for each, the proposed umbrella mechanism under which it falls and examples of reference articles.

|  |  |  |  |
| --- | --- | --- | --- |
| Mechanism | Description | Umbrella mechanism applicable | Key Paper(s) |
| Magnet Species Effect | Attractive plant increases pollination success of less attractive neighbors disproportionate to the size of the shared floral display | Trait Based Effect | Thomson 1978, Laverty 1992 |
| Mimicry | Mutualistic (Mullerian) or  unilateral (Batesian) facilitation between two or more species that share similar display patterns or colors | Trait Based Effect | Peter and Johnson, 2008  Jeraskova, 2009 |
| Floral Neighborhood Abundance | Increased pollination services due combining floral display and therefore increasing number of flowers | Floral Display Size | Thomson 1981 |
| Floral Neighborhood Density | Increased pollination success by combining floral display and therefore decreasing overall interplant distance | Floral Display Size | Rathcke, 1983  Feldman 2006 |
| Diversity | Improved pollination services due to growing in more diverse floral stands or area | Diversity | Ghazoul 2006 |
| Sequential Mutualism | Earlier blooming plants attract, maintain or increase pollinator population that then pollinates later blooming plant | Pollinator Support | Waser and Real 1979  Ogilvie and Thomson 2016 |
| Habitat Provisioning | One or more plants provide habitat for the pollinators of another plant | Pollinator Support | Hansen, 2007 |

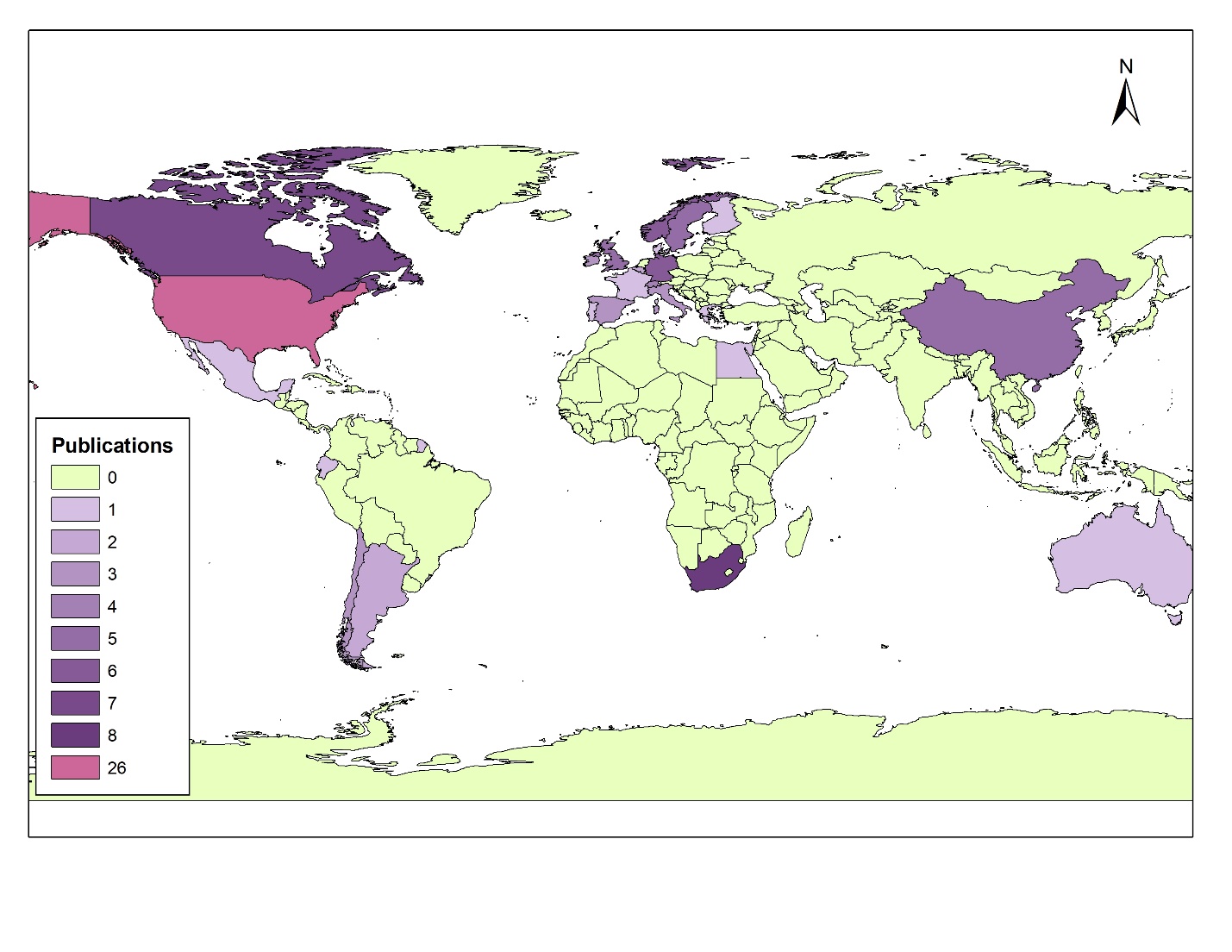


Figure 2: A map showing geographic distribution of studies testing for pollination facilitation. The islands Seychelles and Mauritius each have one publication but are not visible on this map.

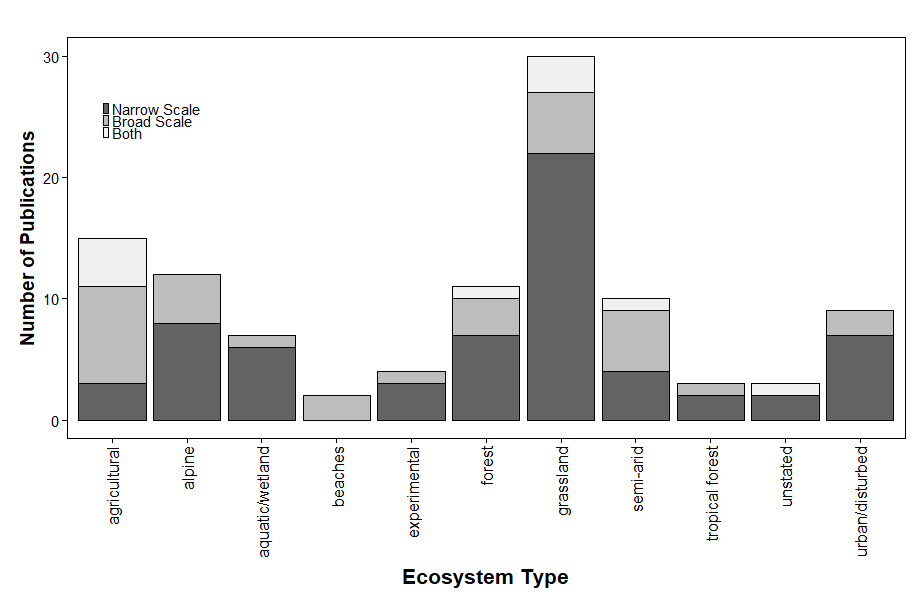


Figure 3: The frequency of pollination facilitation studies tested in each ecosystem type and their corresponding scale of study.

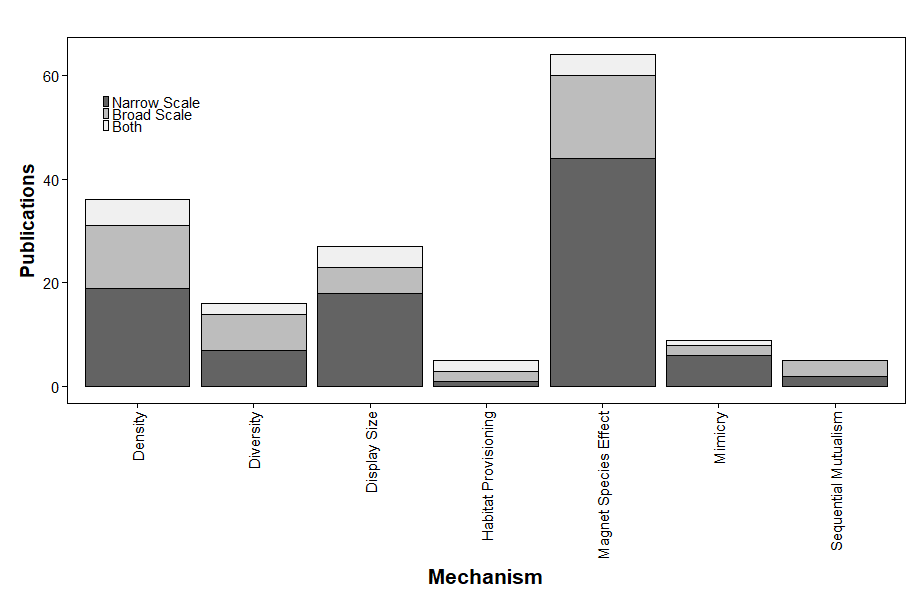


Figure 4: The number of studies testing each mechanism and their corresponding scale of study.

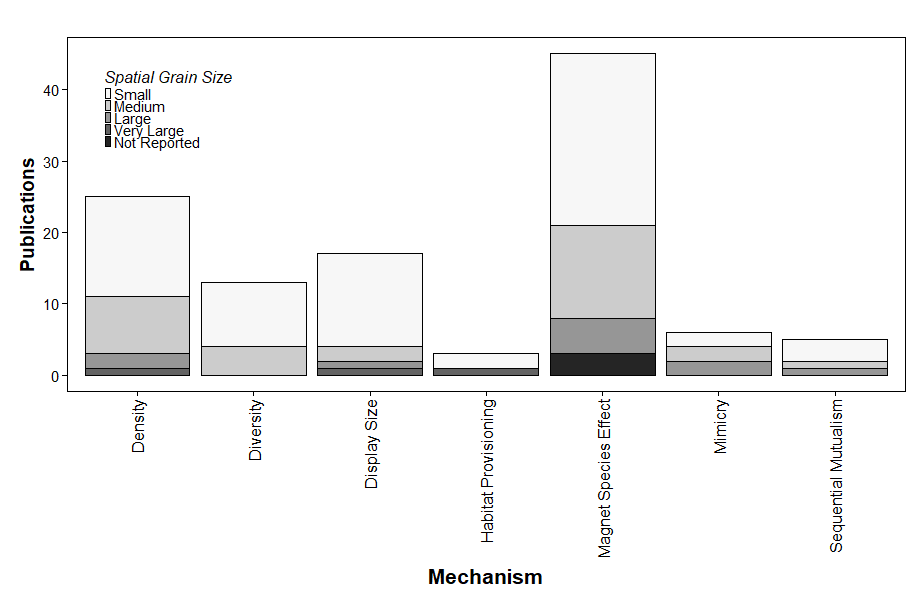


Figure 5: The number of associated studies based on spatial grain size and each testable mechanism.

## Supplemental Information

S1: Criteria for measuring reproductive success

1. Measured rates of pollinator visitation to flowers
   1. Observed in-situ
   2. Observed by technology
   3. Collected from flowers
2. Quantified pollen deposition to stigmas of beneficiary
   1. Conspecific pollen deposition
   2. Release from pollen limitation
      1. Hand pollination experiments
3. Measured seed production
   1. Per fruit
   2. Per plant
4. Measured fruit production

S2: Criteria for defining mechanistic hypotheses based upon predictor variables.

Magnet species effect – Presence/absence of a certain species, species specific effect controlled for beyond abundance/diversity.

Abundance – used heterospecific or combined floral abundance as predictor

Density – used heterospecific or combined floral density as predictor. Includes aggregation.

Mimicry – tested for facilitation between similar appearing species by author’s definition or in some cases authors tested for degree of similarity using floral traits

Sequential Mutualism – earlier blooming plants facilitate later blooming plants or other temporal effect

Habitat Provisioning – Provided habitat to known pollinator (Hansen 2007), alternatively author’s referred to semi-natural areas as wild bee habitats, such as hedgerows, grasslands and meadows as these areas provide nesting sites to pollinator populations.

Diversity: Use floral diversity as a predictor variable

Full-text articles assessed for eligibility (n = 268)

(n = )

Papers obtained through database searching (Web of Science) and Scopus November, 2017 Keywords:

Pollinat\* facilitat\*

(n = 1490)

Identification

Papers obtained from other sources, such as book chapter bibliographies, google scholar and WOS alerts (n = 11)

Records excluded for:

Relevance

(n = 1232)

Eligibility

Records screened by abstract or summary (n = 1501)

Full-text articles excluded:

Not explicitly testing facilitation (n = 96)

Not testing interspecific interactions (n = 27)

Not plant-plant (n = 20)

Unable to obtain (n = 5) Conference abstract (n =2) Review (n = 7)

Not english (n = 11)

n = 168

Screening

Include in synthesis (n = 100)

Extracted data:

Ecosystem

Grain size, extent size

Response variables measured

Scale (fine/broad)

Theme

Multi-scale, Scale dependence

Methods

Included

S3: PRISMA diagram (Moher et al, 2009) of workflow for pollination facilitation systematic review describes the identification of relevant studies.

S4: Tables showing frequency of ecosystems tested, theme of study and mechanism of study. Standardized residuals signify how much a value contributes to the overall chi-squared value. Significance at the 95% level is assessed at values > 1.96 and < 1.96. Some authors report experiments with multiple ecosystems or address multiple mechanism within a single paper so papers may be counted more than once.

* 1. Ecosystems tested.

|  |  |  |
| --- | --- | --- |
| Ecosystem | Frequency | Standardized Residuals |
| Agricultural | 15 | 1.81 |
| Alpine | 12 | 0.79 |
| Aquatic/wetland | 7 | -0.89 |
| Beaches | 2 | -2.5 |
| Experimental | 4 | -1.90 |
| Forest | 11 | 0.46 |
| Grassland | 30 | **6.88** |
| Semi-arid | 10 | 0.12 |
| Tropical forest | 3 | **-2.24** |
| Unstated | 3 | **-2.24** |
| Urban/disturbed | 9 | -0.21 |

* 1. Ecological themes of studies.

|  |  |  |
| --- | --- | --- |
| Theme | Frequency | Standardized residuals |
| Agriculture | 12 | **3.02** |
| Community ecology theory | 4 | -0.56 |
| Conservation | 6 | 0.33 |
| Deceptive pollination | 9 | 1.67 |
| Diversity | 1 | -1.91 |
| Floral traits selection | 1 | -1.91 |
| Foundation plants | 2 | -1.46 |
| Invasive species | 29 | **10.63** |
| Mating systems | 1 | -1.91 |
| Mechanical pollen isolation | 1 | -1.91 |
| Mimicry | 4 | -0.56 |
| Niche theory | 1 | -1.91 |
| Pollination theory | 1 | -1.91 |
| Rare plants | 5 | -0.12 |
| Relatedness | 2 | -1.46 |
| Stress gradient | 1 | -1.91 |
| Species coexistence | 5 | -1.12 |
| Urban ecology | 2 | -1.46 |
| No theme | 13 | **3.46** |

|  |  |  |
| --- | --- | --- |
| Mechanism | Frequency | Standardized residuals |
| Floral density | 36 | **2.89** |
| Diversity | 16 | -1.60 |
| Floral abundance | 27 | 0.86 |
| Habitat Provisioning | 5 | **-4.07** |
| Magnet species effect | 64 | **9.17** |
| Mimicry | 9 | **-3.18** |
| Sequential Mutualism | 5 | **-4.07** |

* 1. Mechanism tested

Table S5: Methods that authors used to control for confounding effects of plant-plant interactions and environmental variation. Methods are exclusive here but in a few cases multiple methods were used, papers were assigned to the most frequent method.

|  |  |
| --- | --- |
| Method Used | N |
| Potted plants | 19 |
| Pollen supplementation to measure pollen limitation | 18 |
| Pollinator exclusion to determine degree of self and subsequent seed set | 6 |
| Focal plant removal | 2 |
| Floral removal to maintain equal densities | 1 |
| Measured micro-environmental variables (e.g. nitrogen availability) | 3 |
| Measured genetic quality of offspring to determine distance of outcrossing | 1 |
| Focal plant translocations | 1 |
| Spatial separation of plants & measured distance | 2 |
| Individuals within a consistent monoculture (agricultural study distance to hedgerows measured) | 1 |
| **Total** | **54** |

# **Appendix**

## List of studied included in systematic review

A list of all studies included in this systematic review from the Web of Science and SCOPUS using the term pollinat\* facilitat\* and supplemental searches using Google Scholar.

Albrecht, M., Ramis, M.R., Traveset, A., 2016. Pollinator-mediated impacts of alien invasive plants on the pollination of native plants: the role of spatial scale and distinct behaviour among pollinator guilds. Biological Invasions 18, 1801-1812.

Alexandersson, R., Agren, J., 1996. Population size, pollinator visitation and fruit production in the deceptive orchid *Calypso bulbosa* Oecologia 107, :533-540.

Bartomeus, I., Vila, M., Santamaria, L., 2008. Contrasting effects of invasive plants in plant-pollinator networks. Oecologia 155, 761-770.

Benitez-Vieyra, S., Hempel de Ibarra, N., Wertlen, A.M., Cocucci, A.A., 2007. How to look like a mallow: evidence of floral mimicry between *Turneraceae* and *Malvaceae*. Proc Biol Sci 274, 2239-2248.

Brockmeyer, T., Schaefer, H.M., 2012. Do nectar feeders in Andean nature reserves affect flower visitation by hummingbirds? Basic and Applied Ecology 13, 294-300.

Brookes, B., Small, E., Lefkovitch, L.P., Damman, H., Fairey, D.T., 1994. Attractiveness of alfalfa (*Medicago satiua L*.) to wild pollinators in relation to wildflower. Canadian Journal of Plant Science, 779-783.

Brown, J., York, A., 2017. Fire, food and sexual deception in the neighbourhood of some Australian orchids. Austral Ecology 42, 468-478.

Bruckman, D., Campbell, D.R., 2016. Pollination of a native plant changes with distance and density of invasive plants in a simulated biological invasion. Am J Bot 103, 1458-1465.

Bruninga-Socolar, Crone, E.E., Winfree, R., 2016. The role of floral density in determining bee foraging behavior a natural experiment. Natural Areas Journal 36.

Caraballo-Ortiz, M.A., Santiago-Valentín, E., Carlo, T.A., 2011. Flower number and distance to neighbours affect the fecundity of *Goetzea elegans* (*Solanaceae*). Journal of Tropical Ecology 27, 521-528.

Carmona-Díaz, G., García-Franco, J.G., 2008. Reproductive success in the Mexican rewardless *Oncidium cosymbephorum* (*Orchidaceae*) facilitated by the oil-rewarding *Malpighia glabra* (*Malpighiaceae*). Plant Ecology 203, 253-261.

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Carvalheiro, L.G., Seymour, C.L., Nicolson, S.W., Veldtman, R., Clough, Y., 2012. Creating patches of native flowers facilitates crop pollination in large agricultural fields: mango as a case study. Journal of Applied Ecology 49, 1373-1383.

Carvallo, G.O., Medel, R., Navarro, L., 2013. Assessing the effects of native plants on the pollination of an exotic herb, the blueweed *Echium vulgare* (*Boraginaceae*). Arthropod-Plant Interactions 7, 475-484.

Chung, Y.A., Burkle, L.A., Knight, T.M., 2014. Minimal effects of an invasive flowering shrub on the pollinator community of native forbs. PLoS One 9, e109088.

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Da Silva, E.M., King, V.M., Russell-Mercier, J.L., Sargent, R.D., 2013. Evidence for pollen limitation of a native plant in invaded communities. Oecologia 172, 469-476.

Dainese, M., Montecchiari, S., Sitzia, T., Sigura, M., Marini, L., 2017. High cover of hedgerows in the landscape supports multiple ecosystem services in Mediterranean cereal fields. Journal of Applied Ecology 54, 380-388.

de Waal, C., Anderson, B., Ellis, A.G., Bartomeus, I., 2015. Relative density and dispersion pattern of two southern African *Asteraceae* affect fecundity through heterospecific interference and mate availability, not pollinator visitation rate. Journal of Ecology 103, 513-525.

Dietzsch, A.C., Stanley, D.A., Stout, J.C., 2011. Relative abundance of an invasive alien plant affects native pollination processes. Oecologia 167, 469-479.

Duffy, K.J., Johnson, S.D., 2017. Effects of distance from models on the fitness of floral mimics. Plant Biology, 438-443.

Duffy, K.J., Stout, J.C., 2008. The effects of plant density and nectar reward on bee visitation to the endangered orchid *Spiranthes romanzoffiana*. Acta Oecologica 34, 131-138.

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Feldman, T.S., 2008. The plot thickens: does low density affect visitation and reproductive success in a perennial herb, and are these effects altered in the presence of a co-flowering species? Oecologia 156, 807-817.

Ferrero, V., Castro, S., Costa, J., Acuña, P., Navarro, L., Loureiro, J., 2013. Effect of invader removal: pollinators stay but some native plants miss their new friend. Biological Invasions 15, 2347-2358.

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Flanagan, R.J., Mitchell, R.J., Karron, J.D., 2010. Increased relative abundance of an invasive competitor for pollination, *Lythrum salicaria*, reduces seed number in *Mimulus ringens*. Oecologia 164, 445-454.

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Ha, M.K., Ivey, C.T., 2017. Pollinator-mediated interactions in experimental arrays vary with neighbor identity. Am J Bot 104, 252-260.

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Hegland, S.J., Grytnes, J.-A., Totland, Ø., 2008. The relative importance of positive and negative interactions for pollinator attraction in a plant community. Ecological Research 24, 929-936.

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Holzschuh, A., Dudenhöffer, J.-H., Tscharntke, T., 2012. Landscapes with wild bee habitats enhance pollination, fruit set and yield of sweet cherry. Biological Conservation 153, 101-107.

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# **Chapter 2:** Disentangling the drivers of pollinator-mediated interactions between creosote bush (Larrea tridentata) and desert dandelion (Malacothrix glabrata).