# **General Introduction**

Interactions for pollination between plants directly involves reproductive success forming an interface between ecology and evolutionary biology that has captured the attention of biologists for more than 100 years. From an evolutionary perspective, mutualisms between plants and pollinators are adaptations evolved to meet the pollen dispersal needs of plants and the energy requirements of pollinators. These co-adaptations are at their most extreme within obligate mutualisms, e.g. between figs (*Ficus*) and wasps in the family *Agaonidae*, who are both pollinators and obligate seed parasites (Kjellberg et al, 2001; Cook et al, 2003). However, these strong examples of co-speciation are relatively rare. Plants frequently share pollinators (Waser 1996, Mitchell 2009) and pollination syndromes are dynamic (Waser, 1996). Plants can also affect the pollination of other plant species without sharing pollinators by providing habitat to another species’ pollinator (Hansen 2007) or by shading a neighbour (McKinney and Goodell, 2010). Plant-pollinator mutualisms physically take place within natural communities and are embedded within complex webs of interactions (Montoya). Therefore, plant-pollinator interactions are not only the outcome of co-evolution between the direct participants, they also reflect interactions within the surrounding community.

Competition has conceptually dominated the field of ecology for most of the last century. More recently, this dominance has been challenged and facilitation is now recognized as a fundamental process that contributes to function of plant communities (Bruno 2003, Callaway 1995). Pollinator-mediated facilitation is any interaction where one plant species positively influences the reproductive success of another plant species via pollinators. It is now recognized that these interactions form a continuum from competition to facilitation (Rathcke, 1983). This shift began with early theoretical work by Macior (1971) that suggested morphologically similar plants can maintain pollinator interest by increasing the ‘functional’ size of the floral display. This was followed up by Bobisud and Neuhaus (1975) who provided theoretical models showing facilitation can occur if pollinators do not distinguish between the plants. The first empirical support for pollinator-mediated facilitation was provided when hawkweeds (*Hieracium*) were shown to receive more visits in mixed stands than alone (Thomson, 1978). Laverty (1992) explained the facilitation of non-rewarding orchids by rewarding species with the magnet species effect, where a particularly attractive species facilitates its less attractive neighbours by increasing local pollinator abundances. Increases in floral diversity can result in facilitation demonstrating that morphological similarity is not a requirement for facilitation (Ghazoul, 2006). The majority of empirical evidence comes from pairwise interactions, however positive interactions can be diffuse and in some communities, positive pollinator mediated interaction may even dominate (Hegland, 2009).

Understanding the ecological and individual contexts that mediate the outcome of pollinator-mediated interactions is necessary research to address currently rising challenges in conservation and applied ecology. Pollination services are foundational to the self-sufficiency of ecosystems, but pollinators are undergoing a decline globally (Potts 2010, NRC 2007). Recent estimates report that 87.5% of global angiosperms are animal pollinated (Ollerton et al., 2011). Under declining pollinator availability competition between plants may intensify, potentially leading to competitive displacement or loss of species. Therefore, understanding how plants interact via pollinators is necessary to understand the potential impacts of these declines. Climate change is driving geographic shifts in species distributions leading to novel interactions between species (Hegland, 2009). The increasingly early onset of seasonal shifts may cause phenological mismatches between plants and their pollinators (Kudo 2013). Experimental evidence suggests that early flowering species have an increased risk of decreased visitation but that many species experienced no mismatch (Rafferty 2015). Mismatches are not an issue if another pollinator or interactor can fill its place (CaraDonna et al, 2017) Thus, understanding of the outcomes of pollinator sharing and how interactions shift with phenology will better help us understand the implications of shifting climates on pollination services. Another important source of novel interactions are introduced and invasive species. Interactions for pollination provide a conceptual framework to explain the impact of invasive plant species on the fitness of native species. One meta-analysis found that negative impacts of invasive species on the pollination of natives are more common (Morales and Traveset, 2009). However, another recent meta-analysis found that there are no negative overarching effects of invasives (Charlesbois and Sargent, 2017). This ‘evening out’ of interaction signs again highlights that interactions are a continuum from negative to positive, indicating the need to better understand underlying mechanisms.

In arid environments, shrubs can act as keystone facilitators, directly benefiting associated plants via multiple mechanistic pathways across all life stages (Filazzola and Lortie, 2014), such as stress amelioration, improved water and nutrient availability (Whitford et al, 1994) and seed trapping (Flores and Jurado, 2003). Shrubs can also act as foundation species, which positively influence the structure of the surrounding plant communities by creating locally stable conditions for other species (Ellison, 2005). Arthropod and plant communities are tightly linked, and interact with each other throughout their lifecycles. The benefits of foundation plants can scale up to other trophic levels including arthropods (Reid, 2012; Ruttan, 2016). For plants, the shift from vegetative growth to reproductive growth is a major life-history step and the shift in life stage by a foundational plant can potentially cascade through beneficiary communities.

The overarching objective of this thesis is to examine the mechanisms of pollination facilitation and test the importance of foundation plants interact on their respective communities. For the first chapter, I conducted a systematic review of the experimental, pollination facilitation literature. I extracted and catalogued the extent of mechanisms tested by previous researchers to create a literature driven conceptual framework. I also summarized the scales of study, ecosystem and ecological themes to determine major research gaps. I found there is a need to examine multiple mechanisms jointly and that interactions that do not require co-blooming are understudied. hmm The second chapter is an experimental approach to measuring interactions between the ecologically dominant shrub species *L. tridentata* and the commonly co-blooming annual *Malacothrix glabrata.* By disentangling blooming and non-blooming pathways as *L. tridentata* shifts through natural phenology, I quantified their contributions to the net observed interactions. I also assessed if *L. tridentata* acts as a foundation species in this system by sampling plant and arthropod communities, and testing the shrubs ability to create milder microclimates. These projects contribute to a better understanding of the underlying mechanisms controlling these interactions, from across a wide spread of literature but also in a critically understudied desert ecosystem. The maintenance of pollination mutualisms is an important aspect of conservation and therefore of management, and these findings can be used to inform best management practices within arid regions. Sure. Good. Sometimes committees recommend stating a general hypothesis for whole thesis then link to this in the synthesis section after chapters.

# **Synthesis and General Conclusions**

Personal note – you switch between I and we. I love we but it is your thesis. To save edits later, even for general sections, I recommend avoid altogether and remove first person.

Topic sentence first linking to overararching objective you developed. Frame context very briefly.

Start with synthesis chapter findings first to that this section matches order of thesis?

The direct and indirect interactions of *Larrea tridentata* and its associated plant, arthropod and pollinator communities were examined within a diverse shrub and succulent desert scrub ecosystem located in the Mojave National Preserve. We used a mechanistic approach to address these topics, first theoretically and then empirically. Mechanistic approaches in community ecology are defined as the integration of individual-ecological concepts into the creation of theoretical frameworks (Schoener, 1986). Thus, we conducted a systematic review of the pollinator-mediated facilitation literature. We organized seven, mechanistic hypotheses of pollination facilitation under four umbrella terms: increasing floral display size, trait-based effects, increasing floral diversity and apparent pollination support. Within the conceptual framework developed herein, the individual concepts synthesized are exclusively from the perspective of the plant. Yah is is ok – I would be a bit more enthusiastic here – ie a total of 7 mechanistic hypothesis described all the lit on topic etc.. you know a bit more positive-bias on what was found. Not a celebration, haha, but a clear statement of what was achieved then maybe link to implication very briefly here but develop later. So, this first paragraph would be like the first paragraph of a Discussion in a paper.

Restate H and big purpose.

Why we care about it.

Were H & Preds supported and what was achieved.

Then end with implications of the body of work as whole.

Then next two-three paragraphs do a bit of a deeper dive linking WHOLE body of work, ideally both chapters at once, to a. other work. B. gaps, or c. implications with citations.

The behavioural responses of pollinators can also be defined in terms of individual concepts, however these are rarely examined empirically. Within the framework, pollinator responses were separated broadly into behavioural and population responses. Facilitation through population responses has rarely been studied and has been excluded from meta-analyses despite its high potential in natural systems (Jackobsson and Padron, 2014). One of few papers integrating the pollinators responses was Jackobsson and Padron (2014). They separated facilitation from the magnet species effect and through effects on population sizes and found the invasive Lupinus facilitated via pollinator population growth. Ghazoul (2005) proposed several behavioural responses by pollinators that could lead to facilitation via diversity effects including the competitive displacement of a pollinators to the less desirable plant, however this has still not been tested. In this study, one of the potential drivers of the decrease in visitation rates when *L. tridentata* blooming was the competitive displacement of syrphid flies by bees. Future work should consider how pollinator competition leads to plant facilitation or competition. Integrating pollinator identity and behavioural ecology is the next step towards a fully mechanistic understanding of the framework. Ok get what you are doing. Could be a bit more profoundly stated.

Stress-gradient hypothesis – has SGH been developed in thesis? If not, interesting idea to introduce here. Strengths – yup applies, limitations – may say why did you not link sooner. I propose sure – link entire thesis to it if you want. predicts that positive interactions are more common in harsh environments (Bertness and Callaway, 1994). Stress can be due abiotic factors such as ie. heat or salinity or resource scarcity, ie. droughts. When two organisms share a fundament resource whose scarceness is the stressor, it is predicted that facilitation can only occur when neighbours increases the availability of this resource (Callaway 2007, Maestre and Cortina, 2004, Maestre et al, 2009). Pollen limitation is an external factor that negatively influences the reproductive capacity of plants (Rhodes, 2001) and can thus be considered a stress that leads to inhibited seed production. Floral displays are the method by which plants attract pollinators, thus when a magnet plant attracts more pollinators to an area it is increasing local resources for neighbours. However, this review revealed that neither desert nor arctic ecosystems have been studied in these contexts. Meta-analyses show that most sexually producing plants are pollen-limited (Larson and Barrett, 1999, Knight et al, 2005) and that the alpine is no more or less limited than more temperate lowlands (Raul Garcia-Comacho, 2009). This suggests the potential ubiquity of pollinator-mediated facilitation, but overall evidence is completely lacking harsh environments. We confirmed the role of *L. tridentata* as a foundation plant within this system. As expected for a beneficiary shrub in a harsh environment, it facilitated understory annuals while stabilizing microclimates – AND did its role change with stress and thus support SGH?, a prominent mechanism underlying nurse-protégé studies (Filazzola and Lortie, 2014). Pollinator-mediated facilitation was not measured between *L. tridentata* and *M. glabrata*, so this project still provides no evidence of pollination facilitation in desert ecosystems. Indirect interactions>??? Another big idea – might save for another paragraph. are mediated by organisms rather than the abiotic environment, therefore unless the harshness of an ecosystem directly leads to pollen limitation i.e. inhibits pollinators, it is unlikely that pollination facilitation would be more commonly found in them.

So you introduced SGH and also indirect interactions – each could be a paragraph here, brief, that is ‘tested’ with your two thesis chapters.

Understanding the function of communities through both time and space is a fundamental goal of community ecology. Any interaction is observed within a snapshot of time and space, and interaction networks are treated as stable, static entities (Poisot, 2015). Our review revealed that incorporating interaction pathways – aha – third big idea – functional ecology. Sure you can do that here too. that do not require co-blooming into experimental design is important because they operate concurrently with those that require co-blooming. This prediction was confirmed by our empirical experiment which demonstrated an intensification of competitive interactions when blooming. The difference in pollination rates between microsites was very small when *L. tridentata* was blooming, and pollen deposition showed no difference between microsites. Without incorporating the temporal dimensions, the conclusions would be different and the ‘snapshot’ would not reflect these important interactions. Interactions are dynamic and networks frequently ‘rewire’ (CaraDonna et al, 2017). Competition between plants can influence linkage of plant-pollinator interactions (Carstensen et al 2014). When a dominant plant blooms, it may induce a large scale rewiring within the community. Cornucopia plants (sensu Mosquin 1971) continuously bloom for long periods, produce an abundance of nectar or pollen resources and are thus important to pollinators. Both the ecological function of *L. tridentata* and pollinator responses suggest that *L. tridentata* is a cornucopia species in this system, and our results suggest that pollinators switched to it when it entered a full bloom. Thus, a future model system for investigating how plants can rewire pollination networks and influence interaction turnover is cornucopia species. Good.

Ok fourth big idea. Maybe state at the beginning of this entire section that you will frame all thesis work into a total of 4 major themes in community ecology research then go ahead and do this.

Scale dependence can arise from the underlying mechanisms of pollinator-mediated interactions, as discussed in Chapter 1. There was a significant decrease in pollinator visitation to *M. glabrata* with shrub blooming at both microsites, suggesting that the influence of *L. tridentata* extends beyond its canopy and bring up questions of spatial scale. Pollinators are mobile foragers whose range dictates the independence of microsites. Without knowing the identity and foraging scales of the pollinators a priori, it is not possible to know at which scales to incorporate into experimental design. This could be solved fairly simply over time by using some pilot experiments that measure the average interaction distance by using UV dyes and mapping how far away the dye is deposited. A second level then would be capturing pollinators to see if they are carrying this UV pollen. An unexpected finding of this project was that heterospecific pollen increased with distance from *L. tridentata*. This shows that proximity with other plants may influence the number of interactors or its position within network topology. Ok..

The shrub species tested had simultaneous positive effects on an annual plant community through increase in relative abundance and climate buffering while decreasing pollination effects. In this case, there may be a trade-off between facilitation for abundance early in life and pollination later. The evolution of staggered floral phenology is hypothesized to minimize competition between co-blooming plants for pollination (Mosquin 1971). *L. tridentata* and *M. glabrata* overlap at the beginning and ends of their phenology (Jennings, 2001). This separation may have evolved to minimize this trade-off. In the Mojave National Preserve, *M. glabrata* forms morphologically distinguishable populations (Andre, pcom 2017) which could be due divergence or phenotypic plasticity. A first, observational step would be determining if variation in *M. glabrata* phenology is influenced by the presence or phenology of flowering shrubs. The results of this study reveal an interesting system for modelling life-history tradeoffs. This work highlights that though species may be benefactors with a positive role within an ecosystem, the effect they have is net and the outcome of both positive and negative interactions. Hmm?

Cut.