

# The role of disease in bee foraging ecology

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## Highlights

- Diseases have a central, but poorly understood role in bee foraging ecology
- Flowers are hubs for horizontal transmission of parasites within and between bee species
- Nutritional and non-nutritional pollen and nectar chemistry affects bee immunity and disease
- Diseases modify foraging behaviour by impairing foraging ability or changing floral preferences
- Parasites affect pollination services by reducing bee populations or changing foraging behaviour

## Abstract

Diseases have important but understudied effects on bee foraging ecology. Bees transmit and contract diseases on flowers, but floral traits including plant volatiles and inflorescence architecture may affect transmission. Diseases spill over from managed or invasive pollinators to native wild bee species, and impacts of emerging diseases are of particular concern, threatening pollinator populations and pollination services. Here we review how parasites can alter the foraging behaviour of bees by changing floral preferences and impairing foraging efficiency. We also consider how changes to pollinator behaviours alter or reduce pollination services. The availability of diverse floral resources can, however, ameliorate bee diseases and their impacts through better nutrition and antimicrobial effects of plant compounds in pollen and nectar.

30

## 31 **Introduction**

32 Bees, and the pollination services they provide, are threatened by a range of factors, including habitat  
33 loss, climate change, pesticides, and parasites [1],[2]. The impacts of parasites, and the diseases  
34 they cause, may be enhanced by interactions with other stressors [3]. Pesticides and decreasing floral  
35 resources can make bees more susceptible and less tolerant to diseases [4],[5], and global trade of  
36 managed pollinators has led to the spread of diseases into novel areas and hosts [2],[6]. Parasites  
37 can be transmitted and contracted by foraging bees on flowers [7], whereas the floral food rewards -  
38 pollen and nectar - that are consumed by bees may modulate disease severity, for example, through  
39 the antimicrobial compounds they contain [8],[9]. Foraging behaviour can also be impaired or altered  
40 by diseases (e.g. [10]), potentially affecting pollination services. Bee diseases and foraging ecology  
41 are thus intricately linked in a number of ways, and a better understanding of these relationships will  
42 be crucial to control the spread and negative effects of bee diseases. This review outlines the  
43 interactions between disease and foraging in bees, and highlights recent advances in this field as well  
44 as critical knowledge gaps.

45

## 46 **Foraging bees contract and transmit diseases on flowers**

47 Flowers act as hubs for the spread of diseases among visiting pollinators [7],[11],[12],[13]. Diseased  
48 bees can deposit parasites on flowers, for example, through defecation during foraging, or simple  
49 contact between contaminated bee and flower surfaces. Parasites may also be vectored by  
50 uninfected bees between flowers [13]. Subsequent flower visiting bees may then contract infections  
51 [7],[14]. Thus interactions at flowers present an important horizontal transmission route for bee  
52 diseases.

53 Emerging diseases spilling over from managed and naturalized honey bee and bumble bee colonies  
54 into native wild bee populations through shared flower use present a particular concern for pollinator  
55 conservation [15],[12],[16],[17]. For example, Deformed Wing Virus (DWV) and *Nosema ceranae*  
56 (Microsporidia) are both transmitted between honey bees and wild bumble bees, and can have high  
57 virulence in bumble bee hosts [12]. The detection of several viruses first described from honey bees  
58 in solitary bees, wasps, hoverflies, and moths suggests that some parasites may even be transmitted  
59 across broader taxonomic boundaries in the pollinator community [16],[18],[19]. However, it remains  
60 to be demonstrated if active and virulent viral infections can occur in these alternative hosts, as most  
61 studies to date have only screened for the presence, but not active replication of viruses, and effects  
62 on these alternative hosts remain unknown [19]. Global trade of honey bees has introduced bee  
63 parasites such as DWV strains into new areas where they were previously absent [6], which may  
64 threaten native pollinators. In South America, the invasive European bumble bee *Bombus terrestris*  
65 (introduced for greenhouse pollination in the 1990s) is likely to have spread the trypanosomatid gut  
66 parasite *Crithidia bombi* to native bumble bees, which may have contributed to the rapid decline of

67 these keystone species [20]. However, the epidemiological processes of disease spread among  
68 native and invasive pollinators, as well as disease impacts on wild pollinator populations are not well  
69 understood, and further research in this area is needed urgently [19]. Next generation sequencing  
70 methods have greatly facilitated the detection of novel pathogens and other microbial associates of  
71 bees [21],[22], and can in the future be employed to characterize plant-pollinator-pathogen webs via  
72 metabarcoding or metagenomics [23].

73 Floral traits such as floral morphology or chemistry could influence pollinator disease transmission,  
74 with flowering plants varying in their likelihood of spreading infections [7],[11]. For example, floral  
75 volatiles that provide broad spectrum antimicrobial protection for the flower can inhibit the survival on  
76 or colonisation of flowers by microorganisms [24], and so could equally kill bee parasites.  
77 Furthermore, architectural complexity in inflorescences was found to reduce *C. bombi* transmission in  
78 *B. terrestris* [7]. To date, there is little knowledge on the specific interactions of floral traits and bee  
79 disease transmission [11]. However, anthropogenic changes to plant communities, like introduction of  
80 invasive plants or loss of floral diversity via intensified land use, could alter transmission patterns with  
81 unknown consequences for bee health [11].

82

## 83 **The chemistry of bee forage impacts pollinator disease**

84 The chemistry of pollen and nectar varies in both primary metabolites (e.g., sugars, amino acids, and  
85 lipids) and the secondary compounds like flavonoids, terpenoids, and alkaloids [25]. These nutritional  
86 and non-nutritional chemical differences could modulate parasite susceptibility and disease severity of  
87 bees. For example, nutrition has been linked to bee immunocompetence. Bumble bees fed on a  
88 protein deprived diet containing no pollen showed a reduced immune response to *C. bombi* infections  
89 [26]. In honey bee workers, protein-rich pollen types resulted in higher individual (phenoloxidase  
90 activity) and social (glucose oxidase activity) immunocompetence [4]. Furthermore, honey bee larvae  
91 were more susceptible to *Aspergillus* opportunistic fungal pathogens when fed on poorer larval diets  
92 with monofloral pollen in comparison to polyfloral pollen [27].

93 Conversely, a diet with a high nutritional value can also benefit the parasite. Logan et al. [28] reported  
94 higher *C. bombi* levels in bumble bees and Jack et al. [29] reported higher *N. ceranae* spore loads in  
95 honey bees when both hosts were fed on pollen. In this case, the survival of honey bees fed on pollen  
96 was enhanced despite increased *N. ceranae* parasite load compared with pollen starved bees. This  
97 suggests that although a rich diet may improve conditions for parasites, it also increases the host's  
98 disease tolerance, which may be more important than parasite numbers alone [29].

99 The above studies did not directly manipulate individual chemical constituents of the experimental  
100 diets, making it difficult to determine what specific qualities of dietary variation influenced the different  
101 experimental outcomes. Pollen is chemically complex and highly variable between species, and the  
102 role of some pollen constituents like fatty acids, sterols, flavonoids, and alkaloids were neither  
103 investigated nor discussed. This important limitation will need to be addressed in future studies.

104 Plant secondary metabolites have a range of ecological functions, including defence against microbial  
105 disease. Although the chemistry of pollen and nectar is of increasing interest [25], knowledge of the  
106 diversity of these secondary compounds and their antimicrobial properties against bee diseases is  
107 limited. The best evidence to date that nectar secondary compounds reduce disease load in bees  
108 comes from several studies of *C. bombi* in bumble bees. Manson et al. [30] showed that gelsemine  
109 (an alkaloid found in the nectar of *Gelsemium sempervirens*) reduced *C. bombi* infection levels in *B.*  
110 *impatiens*. Richardson et al. [8] later found four out of eight secondary nectar compounds to inhibit *C.*  
111 *bombi* in the same host. Baracchi et al. [31] showed that nicotine delayed the development of *C.*  
112 *bombi* infections in a second host species, *B. terrestris*. Such effects can occur under biologically-  
113 realistic dosage levels, for example, in Richardson et al. [8] the monoterpene thymol was fed at 0.2  
114 ppm in sugar water, whereas it naturally occurs in thyme nectar at concentrations of up to 8.2 ppm,  
115 sufficient to inhibit *C. bombi* in vitro [9]. The eco-evolutionary interactions between plant compounds  
116 and bee parasites are however likely considerably more complex than this, and have only been  
117 studied in a few cases. Palmer-Young et al. [9] showed that *C. bombi* strains differed more than 4-fold  
118 in their EC<sub>50</sub> values for thymol and anabasine. *C. bombi* strains could also readily evolve increased  
119 resistance to thymol in vitro within a 6 week period [32]. Importantly, under natural conditions,  
120 parasites will not be exposed to single plant compounds within the host, but chemical mixtures from  
121 the bee diet. Different plant metabolites may then act additively or synergistically in inhibiting  
122 parasites, although this has been shown only using compounds at above naturally occurring  
123 concentrations [33].

124 In addition to direct effects, secondary plant compounds can indirectly affect bee diseases by  
125 modulating the immune system or gut microbiome. Mao et al. [34] showed that *p*-coumaric acid, a  
126 phenylpropanoid found in nectar and pollen, enabled upregulation of two antimicrobial peptides  
127 (abaecin and defensin) in honey bees, and Negri et al. [35] found an improved cellular immune  
128 response in honey bees feeding on abscisic acid, a terpenoid present in nectar of some species. A  
129 potential, but unstudied, path for secondary metabolites to indirectly affect bee parasites is through  
130 modulation of the bee gut microbiome, the composition of which has been shown to play an important  
131 role in parasite susceptibility [22],[36]. Given the complex interactions between plant compounds,  
132 microorganisms, and hosts, to understand the outcome for bee health it will be necessary to  
133 complement controlled laboratory experiments elucidating underlying mechanisms with field or semi-  
134 field (e.g. greenhouse) trials under more natural conditions. These studies should investigate fitness  
135 consequences of phytochemical dietary differences for healthy or diseased bees by manipulating the  
136 plant composition of the foraging environment or supplementing free flying bee colonies with target  
137 phytochemicals. Studies will also have to be extended beyond the bumble bee – *C. bombi* system, as  
138 patterns found in this interaction may not translate to other pathogens (e.g. viruses, *Nosema*) and  
139 hosts.

140 Besides naturally occurring plant compounds, bees are also exposed to agricultural pesticides during  
141 foraging. Neonicotinoid insecticides can suppress the immune system of honey bees [37], and  
142 increase the risk and severity of parasitic infections with *N. ceranae* and DWV [5],[38]. The interaction

143 of pesticides and other anthropogenic stressors with diseases increases the pressure on pollinator  
144 populations [2],[3].

145 Ultimately, a biodiverse floral landscape and the resulting dietary alternatives for bees may have an  
146 important beneficial effect for bee disease resistance and tolerance by improving nutrition and  
147 availability of beneficial secondary compounds. Polyfloral diets increase immune function and  
148 decrease disease loads in honey bees [4],[39], and the different secondary compounds in nectar may  
149 act synergistically against parasites (e.g., *C. bombi* in bumble bees [33],[40]). One of the best and  
150 most practical methods to improve pollinator health may therefore be to ensure the availability of  
151 diverse and health promoting floral resources in urban, agricultural, and natural landscapes.

152

### 153 **Diseases affect foraging behaviour**

154 Just as the foraging of bees impacts pathogen susceptibility and transmission, the pathogens can  
155 influence the behaviour of foraging bees. For example, Fouks & Lattorff [41] found that bumble bees  
156 avoided flowers artificially inoculated with the parasite *C. bombi*. Bacteria in nectar can also deter  
157 honey bees and bumble bees from feeding [42],[43]. It remains to be seen how and to what extent  
158 bees can detect pathogens while foraging, but these studies suggest bees may be able to reduce  
159 exposure to pathogens by altering foraging choices.

160 On the other hand, once bees are infected, diseases may have a range of effects on foraging  
161 behaviour. Schmid-Hempel & Schmid-Hempel [44] were the first to document an association between  
162 parasite infections and bee foraging behaviour in the field. *B. pascuorum* workers parasitized by  
163 conopid flies were found foraging significantly more often on *Stachys officinalis* than on *Prunella*  
164 *grandiflora* when compared to unparasitized individuals. Additional field studies revealed that conopid  
165 and *C. bombi* parasitized bumble bees were less likely to collect pollen for their colony [45],[46]. A  
166 number of experimental studies have later found detrimental effects of diseases on various aspects  
167 related to the bees' foraging ability. In bumble bees, *C. bombi* reduces foraging speed and the ability  
168 to learn floral reward associations and novel flower handling motor patterns [47],[48],[49],[50]. Honey  
169 bees infected with *N. ceranae* have reduced homing ability and conduct shorter search flights  
170 [51],[52], and honey bees forage less and carry less pollen under increased *Nosema apis* infections  
171 [10]. Similarly, DWV infections reduced flight distance and duration in honey bees [53]. Furthermore,  
172 DWV and *N. ceranae* infected honey bee workers started foraging at an earlier age [54], potentially  
173 through impacts on juvenile hormone levels [55]. An earlier onset of foraging in infected bees could  
174 benefit the parasites by increasing horizontal transmission on flowers [54], but direct evidence for an  
175 evolved manipulation of pollinator foraging behaviour by parasites is lacking. As a consequence of  
176 these various effects, infected bees may be less efficient foragers [10],[45],[56] with negative  
177 consequences for individual and colony survival and reproduction.

178 Bees could also obtain fitness benefits through actively changing their foraging behaviour when  
179 infected, in essence self-medicating by preferentially visiting plants with disease ameliorating

180 compounds. Self-medication behaviour has been suggested in other animals [57], including several  
181 insect species [58]. For a behaviour to be classified as true self-medication, de Roode et al. [57]  
182 outlined five criteria to be fulfilled: 1.) Application or ingestion of a chemical compound or third  
183 species; 2.) Initiation of the behaviour by parasite infection; 3.) Increased fitness of the infected  
184 individual or its genetic kin by the behaviour; 4.) Costliness of the behaviour to uninfected individuals;  
185 5.) Relevance of the behaviour in natural environments (beyond e.g. artificial diets in the laboratory).  
186 For honey bees, increased resin collecting was observed in chalkbrood fungus (*Ascosphaera apis*)  
187 challenged hives, and experimentally applying bee-collected resin (propolis) to the interior of the hive  
188 reduced chalkbrood infection levels [59]. Stingless bees similarly collect antimicrobial resins [60],[61],  
189 but it is unknown if this behaviour is increased or altered by parasite infections. Under laboratory  
190 conditions, honey bees preferred honey with higher antimicrobial activity (sunflower honey) over less  
191 active honeys under *N. ceranae* infections, and feeding sunflower honey led to a slight reduction in *N.*  
192 *ceranae* spore counts [62]. In the field, Richardson et al. [50] showed that bumble bees naturally  
193 infected with *C. bombi* increased foraging for nectar with experimentally increased iridoid glycoside  
194 concentrations, compounds that had previously been shown to reduce *Crithidia* infection levels [8].  
195 However, as the association between *C. bombi* infections and iridoid glycoside foraging in this study  
196 was correlational, and not based on experimental manipulation, it remains unclear if this behaviour  
197 was caused by the infection, or other external factors caused individuals to both be infected and  
198 change foraging. In conclusion, these studies suggest that criteria 1, 2, and 5 for self-medication  
199 mentioned above have been fulfilled for honey bees, and suggestive evidence has been obtained for  
200 bumble bees as well. Crucially, fitness effects, i.e., a fitness benefit of the behaviours under infection  
201 and costs to uninfected individuals (criteria 3 & 4) remain to be demonstrated directly. A reduction in  
202 parasite numbers (see [8],[62]) may result in fitness benefits, but, as pointed out by de Roode et al.  
203 [57], is not a central criterion for demonstrating self-medication. Harmful effects of ingested  
204 compounds could negate any benefit of decreased parasite numbers, and conversely, if  
205 phytochemicals increase disease tolerance, unaltered parasite counts could still result in host fitness  
206 benefits [57]. Experimental tests looking at fitness benefits of foraging behaviour changes under  
207 infection are therefore needed to determine if bees are truly self-medicating.

## 208 **Are diseases reducing pollination services?**

209 Diseases may reduce pollination services by foraging bees in two ways. Firstly, pollinator population  
210 declines resulting from diseases could lead directly to reduced pollination services owing to fewer  
211 floral visits, negatively affecting food production [2]. Consequently, the global spread of diseases from  
212 managed pollinators into wild bee populations is of special concern [6],[63], and better trade  
213 regulations are needed to halt the national and international spread of pathogens through the  
214 distribution and trade in managed pollinator species [2],[63].

215 Secondly, an important but poorly understood open question is whether diseased bees intrinsically  
216 deliver sub-optimal pollination services. Given that various pathogens have been observed to impair  
217 the foraging ability of bees (see discussion above), it would seem likely that pollination services are  
218 also altered or impaired. Gillespie & Adler [64], for example, found a negative correlation between

219 *Nosema* infection rates in bumble bees at different field sites, and seed set of *Trifolium* and *Solanum*  
220 plants. Lach et al. [10] found that honey bees infected with *N. apis* collected less pollen, and infection  
221 intensity was negatively correlated with the amount of pollen grains carried on the body of foragers,  
222 suggesting a lower efficiency of highly infected workers as pollinators. In contrast, higher *C. bombi*  
223 disease loads by bumble bees in urban compared to rural environments did not result in reduced  
224 pollination, which instead only depended on the amounts of visits a flower received [65].

225 Shifts in the floral preferences of infected bees may impact pollination services [66]. For example,  
226 *Crithidia* infected bumble bees foraged more and transferred more pollen on *Chelone glabra* flowers  
227 with higher iridoid glycoside concentration, compounds previously found to reduce *Crithidia* infections  
228 [50]. Potentially, this change in pollinator preference under infection would increase pollination  
229 services for plants with higher amounts of nectar iridoid glycosides, but would lower pollination of  
230 those plants for which these compounds were at low concentration or absent [50]. Conopid fly  
231 infected bumble bees switched more often between plant species while foraging [66], whereas  
232 tracheal mite infections increased flower constancy [47]. This suggests that depending on the specific  
233 interaction, bee parasites could both increase and decrease within-species pollen transfer between  
234 flowers. Certainly, much more detailed experimental work is needed to understand the potential  
235 impacts of diseases on pollination services.

236

## 237 **Conclusion**

238 Diseases are an important, but still poorly understood factor in bee foraging ecology. Foraging for  
239 pollen and nectar exposes bees to a multitude of parasites that are horizontally transmitted via  
240 flowers. A better understanding of the epidemiology of disease spread in foraging pollinators and the  
241 role of floral traits in influencing transmission is needed if we are to develop effective interventions to  
242 reduce the impact of disease on pollinators. The varying nutritional and non-nutritional plant chemistry  
243 of pollen and nectar can affect bee diseases, either by directly inhibiting parasites through  
244 antimicrobial compounds, or indirectly by influencing host nutritional state, immune function, and the  
245 microbiome. Parasites can alter bee foraging behaviour, either through adaptive or non-adaptive  
246 impacts of the parasite on bee behaviour, or through bees detecting and avoiding infected flowers.  
247 Infected bees in turn could potentially self-medicate by visiting plants with disease-ameliorating pollen  
248 and nectar phytochemistry. Both the reduction of pollinator populations and the change in foraging  
249 behaviour due to diseases may result in reduced or altered pollination service, highlighting an urgent  
250 need to better understand the relation between foraging and bee disease.

251

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256

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412 concentrations. As these secondary compounds were previously shown to have some activity against  
413 *C. bombi*, this may benefit diseased bees. As a consequence of the changed foraging preferences,  
414 male-phase flowers with higher iridoid glycoside nectar levels donate more pollen and have increased  
415 fitness.

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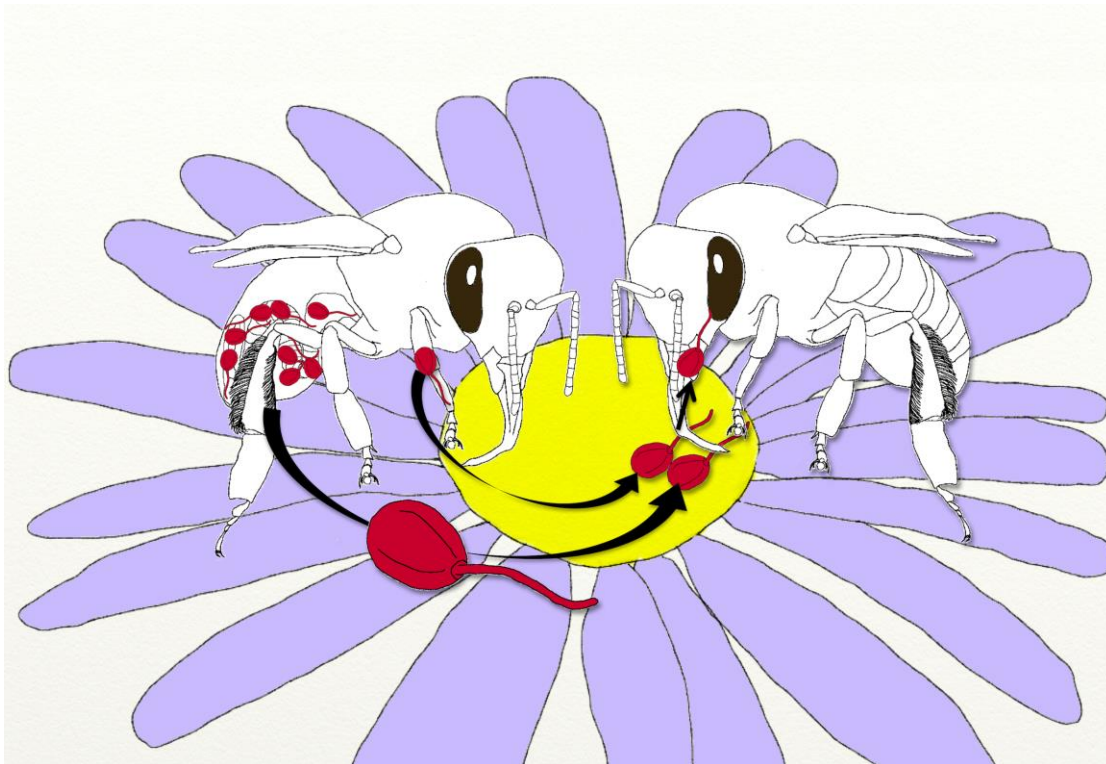
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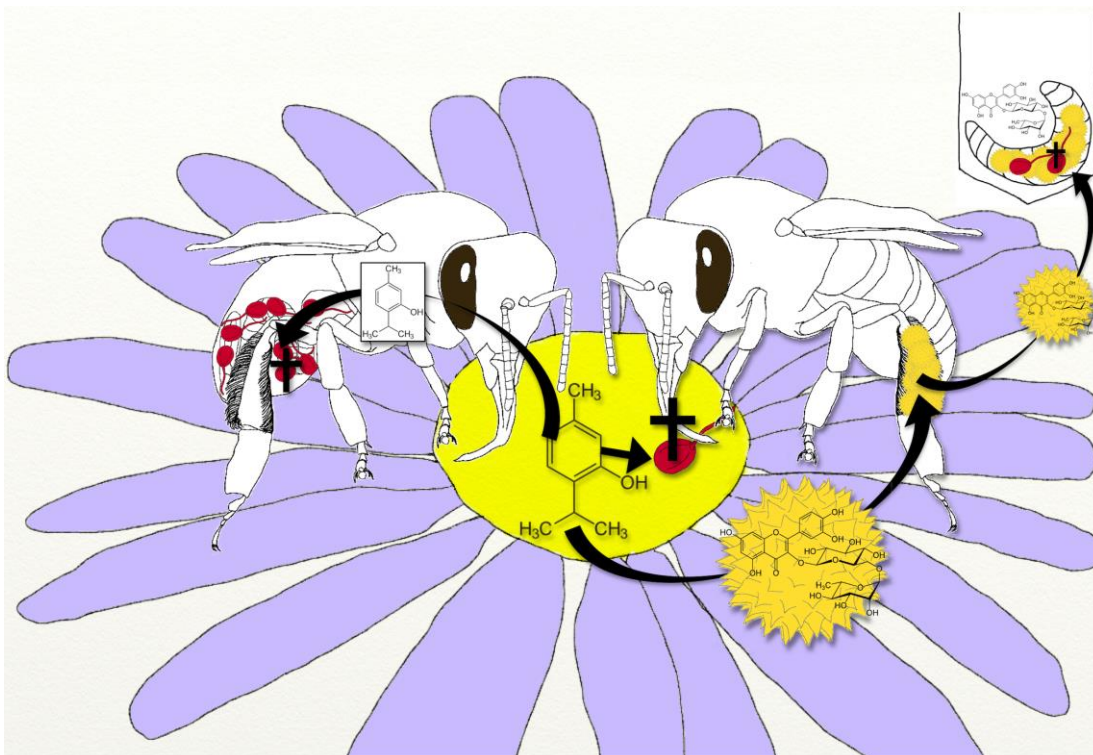
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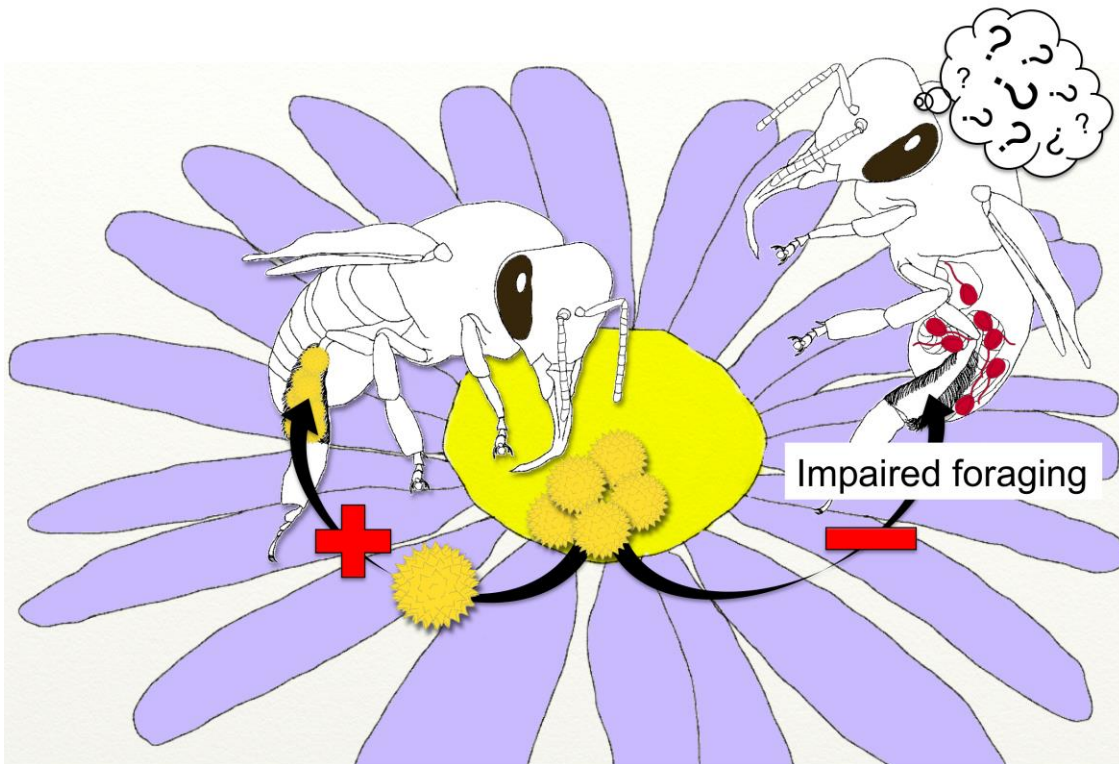
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478 Figure 1: Bees transmit and contract parasites on flowers. Parasites can be excreted by infected  
 479 foraging bees onto flowers, or vectored on the bees' surface between flowers. Subsequently visiting  
 480 bees of the same or different species may then ingest parasites while foraging, and become infected.



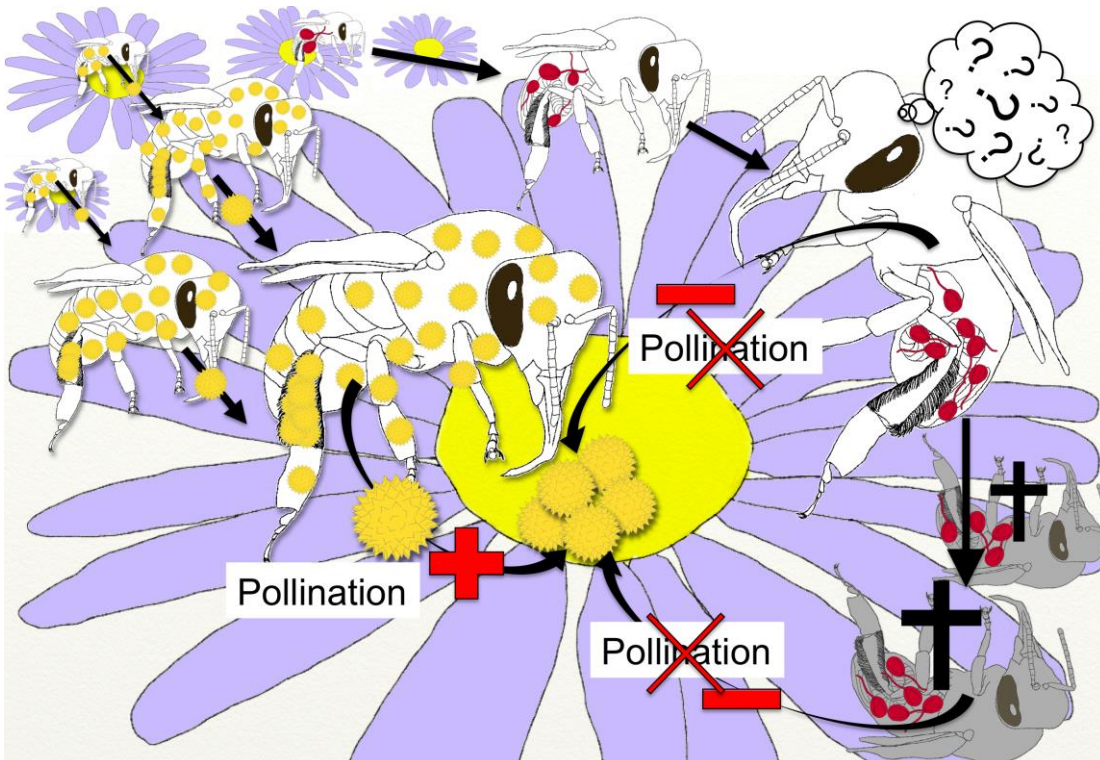
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482 Figure 2: Flower chemistry affects bee diseases. For example, antimicrobial plant metabolites on  
 483 flowers may kill bee pathogens and reduce floral transmission, and compounds in pollen and nectar  
 484 can inhibit diseases in the gut of foraging bees or in larvae in the nest.



485

486 Figure 3: Diseases modify foraging behaviour of bees. Infected bees can be less efficient foragers for  
 487 example due to less pollen collecting, or a reduced ability to learn floral reward associations and novel  
 488 flower handling motor patterns.



489

490 Figure 4: Diseases may reduce pollination services due to a reduction in bee populations or by  
 491 affecting foraging behaviour, reducing pollen transfer between conspecific plants.