

A review of the factors that influence pesticide residues in pollen and nectar: future research requirements for optimising the estimation of pollinator exposure

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1 **A review of the factors that influence pesticide residues in pollen and nectar:**
2 **future research requirements for optimising the estimation of pollinator**
3 **exposure**

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10 **Abstract**

11 In recent years, the impact of Plant Protection Products (PPPs) on insect pollinator decline has
12 stimulated significant amounts of research, as well as political and public interest. PPP residues have
13 been found in various bee-related matrices, resulting in governmental bodies worldwide releasing
14 guidance documents on methods for the assessment of the overall risk of PPPs to different bee
15 species. An essential part of these risk assessments are PPP residues found in pollen and nectar, as
16 they represent a key route of exposure. However, PPP residue values in these matrices exhibit large
17 variations and are not available for many PPPs and crop species combinations, which results in
18 inaccurate estimations and uncertainties in risk evaluation. Additionally, residue studies on pollen and
19 nectar are expensive and practically challenging. An extrapolation between different cropping
20 scenarios and PPPs is not yet justified, as the behaviour of PPPs in pollen and nectar is poorly
21 understood. Therefore, this review aims to contribute to a better knowledge and understanding of
22 the fate of PPP residues in pollen and nectar and to outline knowledge gaps and future research needs.
23 The literature suggests that four primary factors, the crop type, the application method, the
24 physicochemical properties of a compound and the environmental conditions have the greatest

25 influence on PPP residues in pollen and nectar. However, these factors consist of many sub-factors
26 and initial effects may be disguised by different sampling methodologies, impeding their exact
27 characterisation. Moreover, knowledge about these factors is ambiguous and restricted to a few
28 compounds and plant species. We propose that future research should concentrate on identifying
29 relationships and common features amongst various PPP applications and crops, as well as an overall
30 quantification of the described parameters; in order to enable a reliable estimation of PPP residues in
31 pollen, nectar and other bee matrices.

32 **Keywords**

33 Pesticides; Risk Assessments; Pollinator; Pollen and Nectar; Residues

34 **Capsule**

35 Pesticide residue values within pollen and nectar have potentially significant consequences for the
36 reliability of risk assessments for wild and managed bee populations, however, the reasons and
37 mechanisms underlying variations in residues are poorly understood and require greater
38 investigation.

39 **Introduction**

40 **Usage, benefits and drawbacks of Plant Protection Products**

41 The global population has increased rapidly, tripling since 1950 to a current total of 7.6 billion
42 (Population Reference Bureau 2017), and is predicted to expand to 9.6 billion by 2050 (UN 2017). This
43 growth has been facilitated by the intensification of crop production as a result of new developments
44 and innovations (Carvalho 2006; Johnson 2000). As a consequence, the daily food supply per capita
45 increased from 2196 kcal day⁻¹ in 1960 to 2884 kcal day⁻¹ in 2013, with cereal yields almost tripling in
46 the same time period (FaoStat 2017). Concurrent increases in production, use and trade of Plant
47 Protection Products (PPPs) indicate their contribution to these increases in food production (Atwood
48 and Paisley-Jones 2017; Gilland 2002; Tilman 1999; Tilman et al. 2001; Zhang et al. 2011). Today,

49 approximately 1000 active ingredients (a.i.s) (i.e. the components in PPPs which are active against
50 pests/plant diseases) are globally available (Lewis et al. 2016).

51 The predominant use of PPPs is in the agricultural sector to protect crops from weeds, fungal
52 pathogens and pests (Wilson and Tisdell 2001). Estimates suggest the losses in plant production
53 without PPPs would be up to 80% for some crops with potentially severe economic consequences
54 (Oerke and Dehne 2004; Oliveira et al. 2014; Pimentel 1997). Outside of the agricultural sector, PPPs
55 are a cost and labour efficient method for the protection and maintenance of public spaces, for
56 example weed control on railways and streets (Cooper and Dobson 2007). In the future, the targeted
57 use of PPPs could further grow in importance; consequences of globalisation and climate change are
58 predicted to change the distribution and life cycles of many pest species, which could render previous
59 control strategies ineffective (Hulme 2017; Rosenzweig et al. 2001). Therefore, there is a strong
60 argument to suggest that PPPs currently make a significant contribution to stable and reliable crop
61 yields, high food quality and the prevention of economic losses, which is a key factor in enabling the
62 global food system to continue to operate in its current format.

63 Nevertheless, PPPs are toxic chemicals and, in the absence of mitigation, some exposure to non-target
64 organisms and the ecosystem is inevitable. Due to their wide range of applications, PPP residues and
65 their metabolites can be found in many ecosystems, with the potential to cause various effects on
66 humans, soil and water organisms, birds, mammals and invertebrates (Mostafalou and Abdollahi
67 2017; Pimentel 2005; Tilman 1999).

68 **PPPs and insect pollinators**

69 In recent years, high overwintering losses of honey bee colonies and declines in populations of other
70 insect pollinator species in Europe and North America (Lee et al. 2015; Ollerton 2017; Potts et al.
71 2010b; Seitz et al. 2016) have raised concerns about the contribution of PPPs to these losses (IPBES
72 2016). Managed and wild pollinator species provide vital ecosystem services, particularly for agro-
73 ecosystems (Albrecht et al. 2012; Klein et al. 2007; Vanbergen et al. 2014; Veddeler et al. 2008) and

74 Gallai et al. (2009) calculated the total economic value of pollination worldwide to be € 153 billion. As
75 a result, the toxic effects of PPPs on pollinators, particularly neonicotinoids, has become the focus of
76 significant amounts of research, and political and public interest. There is a broad consensus amongst
77 researchers in the field that declines are the result of a combination of factors including habitat loss,
78 pests/diseases and PPPs (Goulson et al. 2015; IPBES 2016; Potts et al. 2010a). Whilst the overall role
79 of PPPs on pollinator declines is still debated, there is clear evidence for both the exposure of bees to
80 a range of chemical products via contact and oral exposure (e.g. Botias et al. 2017; Chauzat et al. 2010;
81 Johnson et al. 2010; Kiljanek et al. 2017; Tosi et al. 2018) and the toxicity of PPPs to bees in laboratory
82 toxicity studies (e.g. Kasiotis et al. 2014; Pettis et al. 2012; Sanchez-Bayo et al. 2017; Woodcock et al.
83 2017; Wu et al. 2011).

84 Overall, there is a difficult trade-off between permitting the use of products upon which modern
85 agriculture relies for the protection of crops and maintaining vital environmental goods and services,
86 which themselves have an important role in sustainable food production. Therefore, in order to ensure
87 the safety of PPPs, complex and highly regulated processes of environmental risk assessments have
88 been developed.

89 With respect to pollinators, the European Food Safety Authority (EFSA 2013) published a Guidance
90 Document on the risk assessment of PPPs on bees (including honey bees, *Apis mellifera* L.,
91 Bumblebees, *Bombus spp.* and solitary bee species), to outline a process by which PPPs can be
92 evaluated for their potential risks in causing unacceptable harm to bees. Similar approaches have been
93 published in the US, Canada and Brazil (Cham et al. 2017; USEPA 2014). An important component in
94 these approaches are PPP residue levels in pollen and nectar. They represent a key route of exposure
95 for pollinators as, in many species, all life stages feed to some extent upon these food sources (Rortais
96 et al. 2017; Villa et al. 2000). However, knowledge to enable a more accurate prediction of PPP
97 residues in pollen and nectar is limited and a number of barriers, which are discussed in more detail
98 in the next section, inhibit a clear assessment of residue levels used in risk estimation.

99 **Aim of the review**

100 In this review our aim was to identify and compile existing literature data on the behaviour and fate
101 of residues in pollen and nectar following PPP applications, and outline the manifold parameters which
102 appear to influence these residues. In doing so we identify knowledge gaps concerning the variability
103 of PPP residue values in pollen or nectar and highlight future research needs, in order to enable a
104 precise prediction of residue levels for pollinator risk assessments in future and to encourage, initiate
105 and facilitate further research in this field.

106 **Pollinator risk assessments and evidence base**

107 **Current methodological approaches for pollinator risk assessments**

108 Current approaches for pollinator risk assessments (e.g. Cham et al. 2017; EFSA 2013; USEPA 2014)
109 pursue similar strategies and methodologies. In general, effect studies (e.g. laboratory adult acute oral
110 toxicity studies, larvae toxicity studies) and exposure estimates (contact or oral) are combined in a
111 tiered approach to assess the risk of PPPs to pollinators, ranging from very conservative estimates to
112 more realistic scenarios. While the latter requires high data input and more extensive studies, in the
113 lower, more conservative tiers, worst-case default values can be applied. Theoretically, such an
114 approach allows for more rapid and cost-effective initial assessments that are robust enough to
115 separate those PPPs that pose a potential risk to bees from those that can be considered of low risk.
116 To assess the risk from oral exposure of bees to PPPs, the guidance documents (Cham et al. 2017;
117 EFSA 2013; USEPA 2014) provide general default residue values in pollen and nectar for different
118 application scenarios, which aim to be protective. If the assessment fails in lower tiers and risk
119 mitigation is not possible, the guidance documents cited above suggest a refinement of the
120 assessment in higher tiers, for example by using representative “real” PPP residue values in pollen or
121 nectar or compound and crop specific data, which can be further refined by conducting field trials.

122 **Barriers associated with PPP residues in bee products and their implementation in risk assessments**

123 A recent proposal made in reference to EFSA's risk assessment from the European Crop Protection
124 Authority (ECPA 2017), which represents the industrial sector, concluded that the current guidance is
125 over-conservative and that even substances known to be non-toxic to bees fail at lower tiers. They
126 assert that, in most cases, a higher tier refinement is required. In order to facilitate higher tier
127 assessments, oral exposure estimates must be refined using representative residue data (Cham et al.
128 2017; EFSA 2013; USEPA 2014). However, data on residue levels in floral resources vary widely and
129 are unknown for many PPPs and crop species (EFSA 2013; Lundin et al. 2015). Table 1 provides a brief
130 overview of PPP residue data recorded in pollen from spray applications, illustrating the variation of
131 PPP residues from different active ingredients and in different crops. These data are taken from a
132 recent meta-study (Kyriakopoulou et al. 2017) and from the pollinator risk assessment published by
133 EFSA (2013), both providing a comprehensive overview and summary of data on the available residue
134 data in bee-relevant matrices and products, which were gathered from Draft Assessment Reports
135 (DARs), literature and peer reviews of active ingredients.

136 Overall, there is wide variation in residues, with differences not only between various active
137 ingredients and crop combinations, but also within each of these groups. For instance, aggregated
138 residues from various PPPs vary considerably not only within *Brassica* pollen, but also from uses of
139 individual PPPs, such as teflubenzuron on *Brassica*. Similar findings can be observed for residues in
140 nectar (Table S1).

141 Both publications highlighted the fact that the available studies differed considerably in design,
142 sampling timing, sampling methodology and application scenarios, or lacked data for certain types of
143 active ingredients. Thus residue data is difficult to compare. Overall, knowledge about PPP residues in
144 pollen or nectar is fragmentary and only a small proportion of treatments and crops have been taken
145 into account, with the majority of residue values provided for neonicotinoids and oilseed rape (OSR)
146 (*Brassica napus* L.). Pollinator risk evaluation is therefore based on extrapolated residue data and as a
147 consequence, on an incomplete dataset. However, the knowledge regarding PPP residues present in

148 pollen and nectar is too limited to allow extrapolations or conclusions to be drawn from those crops
149 where data are available.

150 Yet, if risk assessments are based on residue values that are not representative for the treatment
151 scenario and cropping system, the risk posed from PPPs to pollinators might be incorrectly estimated
152 (Lundin et al. 2015), resulting in false negatives (i.e. misuses of concern), or in false positives, which
153 may result in unnecessary higher tier testing. The currently available data sets can neither mitigate
154 the variability and incompleteness, nor rationalise how this should be addressed in risk assessments
155 or why these variations in PPP residues occur.

156 **PPP residue studies in pollen and nectar**

157 Extensive studies are needed to derive reliable PPP residue values in pollen and nectar. However, the
158 exact determination of residues in bee-attractive plants is expensive and time consuming. Relatively
159 large volumes of the target matrices are required for the chemical analyses needed to quantify the
160 PPP residues, but pollen and nectar are typically produced only in small quantities. Furthermore,
161 numerous active substances, crop species and application scenarios must be considered. The ECPA
162 (2017) claimed that, in order to meet the requirements of the EFSA guidance document (EFSA 2013),
163 for a single product used on five different bee-attractive crops, up to 75 residue studies would need
164 to be conducted, with associated costs of approximately € 7.5m. Consequently, the development and
165 registration of new products and innovations, in addition to the re-authorisation of already approved
166 PPPs, are likely to incur large costs, which may limit the availability of PPPs. According to the ECPA,
167 minor use crops are most likely to be affected, which are often economically important for their
168 growers and for crop diversity, but not of significant importance to the industry to justify high costs
169 for research and development.

170 Furthermore, with new insights and findings becoming apparent and a better comprehension of risks
171 posed by PPPs in recent decades, it is likely that regulatory requirements will be further increased and
172 adapted and that applicants for active ingredient and PPP registrations, PPP producers and responsible

173 authorities will need to deliver more detailed data regarding the fate of PPPs in plant matrices
174 important to pollinators.

175 Thus, to ensure the accurate protection of pollinators and to permit scope for developments in crop
176 protection, methods need to be devised to enable an accurate estimation of PPP residues in pollen
177 and other bee-important matrices that require reduced effort and expenditure. In order to achieve
178 this, a better knowledge and understanding of the fate of PPP residues in pollen and nectar is
179 necessary. The identification of patterns and relationships of PPP residues within the plant and
180 between different species may provide an opportunity to identify better methods for accurate
181 estimation of residue levels for diverse PPPs and cultivation methods. However, little is understood
182 about the behaviour and relationship of residues in floral resources, which can be altered and
183 influenced by numerous factors.

184

185 **Factors influencing PPP residues in pollen, nectar and other related matrices**

186 An assessment of the literature suggests that there are four primary factors which could influence the
187 level of PPP residues in pollen and nectar and other related matrices: i) crop related parameters ii)
188 discrepancies in PPP application method, timing and dose rate iii) physicochemical properties of the
189 active ingredient and iv) environmental conditions. These primary factors consist in turn of several
190 sub-factors which can all potentially contribute to variable PPP residues in pollen or related crop
191 matrices. The first two factors listed are considered more often in the literature, since they are
192 tangible and relatively easy to determine under constant conditions. By contrast, the effects of
193 environmental conditions are more difficult to isolate, as they can, for example, influence the chemical
194 properties of an active ingredient, as well as the development and physiology of a plant. Hence, there
195 are a wide range of factors influencing PPP residue levels in pollinator relevant matrices, which are
196 strongly interdependent and form a complex system. Another factor which can unintentionally
197 influence the results of PPP residue levels in pollen and nectar is the sampling methodology. For

198 instance, OSR flowers are often collected and then incubated for a certain time period and
199 temperature to facilitate pollen release (e.g. Botias et al. 2015). The loss of water might result in higher
200 PPP concentrations, but conversely the high temperatures can initiate a dissipation of PPP residues.
201 In other studies pollen is collected by grinding the anthers to powder (e.g. Jiang et al. 2018), collecting
202 pollen in boxes as it falls naturally from plants (Schmuck et al. 2001) or by using bees (e.g. Choudhary
203 and Sharma 2008). These discrepancies in sampling are often not scrutinised in studies but might
204 influence the comparability of results.

205 **General findings**

206 Although high variability is typically observed in PPP residues in pollen and nectar, there are some
207 instances that permit comparisons among a wide range of PPPs/crop systems. Kyriakopoulou et al.
208 (2017) detected statistically significant differences among sampling matrices, with the residue levels
209 in both pollen and nectar being highest when extracted directly from flowers than from bees. Such
210 differences could be caused by dilution effects, when bees mix pollen from untreated and treated
211 crops (Bonmatin et al. 2015; Rolke et al. 2016). In many studies a dilution effect, cross contamination
212 from other fields (e.g. Kunz et al. 2015) or chemical alterations cannot be excluded when pollen and
213 nectar is collected by free flying bees and it is often difficult to directly link the residues found to the
214 previous PPP treatment, unless studies are conducted using bee-sampled pollen collected from
215 tunnelled crops (i.e. no alternative sources of pollen are available).

216 Furthermore, Kyriakopoulou et al. (2017) detected higher residues in pollen than in nectar, a
217 phenomenon which has been reported in several other studies, which employ a range of treatment
218 regimens (e.g. Choudhary and Sharma 2008; Cowles and Eitzer 2017; Dively and Kamel 2012; EFSA
219 2012; Goulson 2013; Jiang et al. 2018). Reasons for this difference have not been investigated thus
220 far; however, several possible mechanisms can be proposed. If bee- collected matrices are analysed,
221 the effect could be caused by the partial metabolism of residues in nectar within the bees (Gong and
222 Diao 2017; Sanchez-Bayo and Goka 2014). However, similar results have also been reported from

223 samples taken directly from the plant. Cowles and Eitzer (2017) suggested a relationship between
224 residue levels in pollen and nectar and whether nectaries and anthers are supplied by phloem or
225 xylem. Choudhary and Sharma (2008) presumed analytical impediments, for example the active
226 ingredient could form conjugates with sugars in nectar, thus becoming difficult to extract, or that, due
227 to morphological differences, there may be differences in either the initial levels of PPPs or in their
228 rates of degradation. Overall, the meta-analysis by Kyriakopoulou et al. (2017) found a strong
229 correlation between the residue levels in pollen and nectar, though none of the individual studies
230 included in the meta- analysis has directly compared this parameter thus far.

231 **Crop related parameters**

232 Although few crop species are considered in studies on PPP residues in pollen and nectar, there is
233 evidence that crop traits have an influence on the residue levels in bee-important matrices.
234 Differences in residue levels in various plant parts can be explained by a dilution effect with plant
235 growth (more biomass) (Holland et al. 1996), plant height (Kleier 1994) and even plant age (Bonmatin
236 et al. 2015), for example when PPPs have the ability to be adsorbed to plant compounds like lignin
237 (Fujisawa et al. 2002). Overall, these effects are strongly related to the physicochemical properties of
238 a compound (see section below for full discussion on the effects of physicochemical properties). Soil
239 treatments of the systemic compound imidacloprid demonstrated that there is a clear gradient with
240 respect to residue levels from the leaves at the bottom of the plant up to the leaves at the top of the
241 plant, and eventually to the flowers and pollen (Alsayeda et al. 2007; Bonmatin et al. 2005; Johnson
242 2012; Laurent and Rathahao 2003; Stoner and Eitzer 2012).

243 This raises questions as to whether conclusions drawn from the PPP residue levels found in foliage can
244 be applied to those in pollen/nectar and whether crops with lower biomass exhibit higher residue
245 levels in leaves and consequently in pollen or nectar. Balfour et al. (2016) found that neonicotinoid
246 concentrations in the tissues of flowering maize (*Zea mays* L.) and OSR are negatively correlated with

247 plant mass, however, they did not directly compare these results with pollen and nectar collected
248 from the same plots.

249 Dively and Kamel (2012) found a strong correlation of imidacloprid residues in squash (*Cucurbita pepo*
250 L.) between leaves and pollen, and leaves and nectar ($r = 0.94$ and $r = 0.88$, respectively; $p < 0.001$)
251 following different soil application treatments. This, however, was analysed only during the course of
252 one year and the trend was not replicated for metabolites of imidacloprid or other investigated
253 neonicotinoids. Dively and Kamel (2012) suggested that the diverse chemical properties of the
254 investigated compounds, mainly the solubility, were the reason for a varying uptake and translocation
255 rate, and consequently higher residue levels of other neonicotinoids. However, the differences in
256 residue levels could also be due to the fact that they randomly selected leaves for analysis during their
257 study. Considering the dilution effect and gradient, different results might have been found by using
258 leaves of similar size and position on the plant. Such an approach was employed by Jiang et al. (2018),
259 who collected only newly expanded leaves of cotton (*Gossypium* sp.) over a one-month period.
260 Although no correlations were observed in nectar, correlations between imidacloprid and
261 thiamethoxam residues in leaves and pollen ($r = 0.88$ and $r = 0.90$, respectively; $P < 0.001$) were found.
262 However, it is unclear whether these observations also apply for other crops, other PPPs (i.e. those
263 with non-systemic properties) and different application scenarios.

264 Demonstrating similarities between species has proven to be problematic, with even varieties of the
265 same species resulting in different residue levels. This was demonstrated by Bonmatin et al. (2003),
266 who investigated several sunflower (*Helianthus annuus* L.) varieties after a seed treatment with
267 imidacloprid. The final concentration in flowers was dependent on the variety, with ranges from 2.7
268 $\mu\text{g g}^{-1}$ up to 7 $\mu\text{g g}^{-1}$. The authors did not provide any information about habitus or other species-
269 specific characteristics, but an acropetal decrease of residues in foliage, as described above, was
270 detected for all varieties. In addition, during the formation of the capitula of the sunflower there was
271 a sudden increase in imidacloprid residue levels in the upper parts of the plants. Similar findings were

272 reported by Laurent and Rathahao (2003), analysing different parts of sunflowers. Moreover, PPP
273 concentrations in pollen were similar to those found in the floret dish. It can therefore be concluded
274 that the pollen was contaminated by the late shift of PPP residues in sunflowers. The authors
275 presumed a remobilisation process, in which compounds accumulated in older leaves were
276 transferred towards the upper part of plants during the reproductive stage. However, imidacloprid is
277 a xylem-mobile PPP; hence, it should not re-translocate (Sur and Stork 2003).

278 Laurent and Rathahao (2003) provided another explanation for the phenomenon, suggesting that it
279 was a consequence of the differential root system of sunflowers. This consists of fascicular roots,
280 which grow horizontally in the superficial layer of the soil, and a deeper root system; thus, various soil
281 levels can be penetrated. Sunflowers are particularly capable of recovering PPP residues from soils,
282 which can be attributed to this extensive root system (Bonmatin et al. 2003; Mitton et al. 2016).
283 Consequently, the more pronounced root system of an older plant can take up more PPPs from the
284 soil, leading to an increase of residues during the flowering period. The root system is also an
285 important parameter concerning the PPP uptake from soil in other species, for example from the
286 *Cucurbita* family (Otani et al. 2007). For instance, cucumbers (*Cucumis sativus*) grafted with high
287 uptake root stocks could recover up to 70% more dieldrin (an organochlorine insecticide) than those
288 with a low uptake root stock (Otani and Seike 2007), giving a further explanation as to why different
289 varieties exhibit different residue levels from soil treatments. Regarding the ability of different root
290 systems to shift the PPP residues in plants, plant density and whether experiments are conducted in
291 field or pots might also be important parameters to understand the variability of residues in flowers
292 and should be considered in soil-applied PPP residue studies.

293 Obviously, these observations are less relevant for foliar-sprayed or non-systemic PPPs (see section
294 below for full discussion of the effects of application method). The PPP's chemical properties, the
295 morphology and the structure of the leaves, flowers and cuticle determine the uptake rate of the
296 product and hence the likelihood of translocation to pollen or nectar (DiTomaso 1999; Kirkwood 1999;

297 Price and Anderson 1985). For example, a hairy or waxy leaf structure affects the retention time of
298 chemicals on the surface (Yu et al. 2009); this can alter the uptake rate of the PPPs and hence the
299 chemicals' exposure to environmental conditions. Therefore, even under similar conditions, different
300 plant species will show different residue levels and behaviour. Kyriakopoulou et al. (2017) found
301 species-related differences in pollen and nectar residues. In particular, OSR showed the highest
302 residue values in comparison to other plants. However, there were more data available for OSR and
303 the majority of other species was summarised to one group. Therefore, there is limited confidence as
304 to whether OSR genuinely is a crop which accumulates a high level of PPP residues in pollen or nectar.
305 For a summary of this section and problems regarding pollinator risk assessments see Figure 1.

306

307 **Application Method, Application Timing, Dose Rate**

308 The application method, timing of the application and the dose rate of an applied PPP are strongly
309 interdependent. For example, by using a seed treatment, the longest possible time period between
310 application and flowering of the plant is attained. In contrast, many fungicides are sprayed directly
311 onto the plant shortly before or during flowering, especially when they have been assessed as non-
312 harmful for bees. Furthermore, seed dressings often contain less active ingredient per hectare and
313 therefore may be considered to be more environmentally friendly. This is reflected in the residue
314 levels of foliar applications and seed dressings reviewed by EFSA (2012, 2013), with residues from seed
315 dressings being substantially lower than from spray applications. Evidence regarding the effect of dose
316 rate on PPP residues in pollen was provided by Bonmatin et al. (2005), who used three different doses
317 of the systemic active ingredient imidacloprid, applied as a seed dressing to sunflower seed. The
318 concentration of imidacloprid in the capitula of several varieties became higher when the dose rate
319 was increased. Furthermore, the ascent of imidacloprid during flowering (see section above) was more
320 pronounced when the doses of the seed dressing were high. However, studies directly comparing the
321 effect on residues in pollen and nectar at different dose rates of foliar applied or non-systemic PPPs

322 are scarce, although it is possible to discern a certain trend from the detailed values provided by EFSA
323 (2012), indicating that higher dose rates cause higher residues in pollen and nectar.

324 Yet, it cannot be concluded that a high application of PPPs naturally results in a high exposure for bees
325 or in high residues in relation to the dose rate. Choudhary and Sharma (2008) applied a range of PPPs
326 to mustard (*Brassica juncea* Czern.) using foliar application, each with a defined dose rate, and showed
327 that PPPs applied at higher rates indeed tend to result in higher residues in pollen and nectar (Table
328 2). Interestingly, RUDs - the residue unit employed in risk assessments to account for different dose
329 rates (RUD = concentration in nectar/ pollen (mg kg^{-1}) at an application rate of 1 kg ha^{-1} or 1 mg seed^{-1}) - exhibited an opposing trend in this experiment. Lambda-cyhalothrin afforded the highest PPP
330 residues relative to the dose rate and endosulfan, though applied at the highest dose, afforded the
331 lowest residues with respect to the dose. Thus, the ratio of residues from different PPPs relative to
332 the dose rate is not equal for all compounds, it is rather influenced by other factors, for example the
333 different chemical properties of the active ingredients, which are responsible for varying uptake and
334 accumulation in floral parts.
335

336 Nevertheless, Byrne et al. (2014) observed higher residues in nectar with a doubled dose rate
337 compared to the normal dose rate when treating citrus trees with a soil drench application of
338 imidacloprid. This effect was reinforced at later sampling dates, i.e. with a longer time period between
339 application and flowering. It is assumed that a longer time period between application and flowering
340 results in lower residues because of the dilution, metabolism and dissipation in plants. For
341 imidacloprid, however, to a certain extent the contrary was shown. Whether this effect is similar to
342 that described by Bonmatin et al. (2003) and Laurent and Rathahao (2003) in the above section is not
343 verifiable. It does, however, illustrate that the timing of the application can have a significant impact
344 on residue levels in pollen and nectar. These findings can also be important when comparing varieties
345 and cropping systems. For instance, Pohorecka et al. (2012) found substantially lower residues of
346 thiamethoxam in bee foraging products from winter OSR than spring OSR. It is hypothesised that the

347 longer time period between treatment and bloom of winter OSR led to a higher degradation of the
348 active ingredient.

349 Cowles and Eitzer (2017) also detected late imidacloprid accumulation in sunflower pollen, but under
350 different experimental conditions. Their extensive experimental setup considered three
351 neonicotinoids, applied at different times with different application methods to sunflower and swamp
352 milkweed (*Asclepias incarnata* L.). Again, a low rate imidacloprid soil drench application was the only
353 scenario (application rate, method, and insecticide) found to result in increasing concentrations as the
354 time post-application increased; which meant a soil drench application performed 10 weeks prior to
355 bloom was the only timing for this application scenario that exceeded the designated “toxicity
356 threshold” for bees in pollen concentrations at the lowest dose rate. In contrast, dinotefuran soil
357 drench applications led to higher residues when they were applied closer to the blooming period. The
358 authors concluded that dinotefuran has a better solubility and higher mobility than imidacloprid and
359 therefore the uptake is faster, whereas the uptake of imidacloprid takes longer and so residues
360 accumulate later in pollen. This finding might be especially important for the estimation of residues in
361 crops with a pronounced short or long life cycle and shows that the physicochemical properties of a
362 compound must always be taken into account (see section below for full discussion of physicochemical
363 properties).

364 Cowles and Eitzer (2017) demonstrated that higher application rates resulted in higher residues in
365 pollen and nectar, depending on the chemical applied. However, the method of application had the
366 strongest influence on pollen and nectar residue levels. Soil drench applications resulted overall in
367 higher residues than the foliar applications, even if both were applied only two weeks before bloom.
368 This indicates that, even though the uptake via leaves is good, it cannot be compared with the uptake
369 and transport via the roots and should be considered separately for the assessment of residues in
370 floral matrices. In contrast to these findings, the tables provided by EFSA (2012, 2013) indicate that
371 residue values from foliar applications are higher compared to soil treatments. However, those tables

372 only consider seed dressings, which contain significantly less active ingredient than soil drenches or
373 foliar sprays. Furthermore, many residue values for foliar applications are derived from applications
374 performed during bloom or shortly before, whereas the latest foliar application in Cowles' and Eitzer's
375 experiment was applied two weeks before bloom.

376 Dively and Kamel (2012) showed that foliar-applied neonicotinoids in squash resulted in higher
377 residues in pollen compared to a soil drip and drench application, especially when squash was sprayed
378 at full bloom. In contrast, the PPP residues from foliar applications in nectar were lower after a spray
379 application or did not differ from soil drench and drip irrigation. This leads to the assumption that
380 systemic PPPs are provided over a longer period from the inside of the plant and thus have a greater
381 probability to accumulate and express in nectar. Dively and Kamel found the lowest residue levels
382 from imidacloprid bedding tray soil applications. This was the most distant application method relative
383 to bloom and no increase in residues could be observed. However, the dose rate was very low
384 compared to the other treatment regimes. In total, contrary to Cowles and Eitzer's (2017) experiment,
385 the timing of the application and dose rate seemed to play a more important role than the application
386 method, confirming the assumption that applications closer to bloom result in higher residues. Both
387 Kubik et al. (1999) and Wallner (2009) showed that there is a lag period between the application of
388 fungicides and the maximum residue level in pollen, although the compounds were sprayed directly
389 onto the plant before and during bloom in cherry trees and OSR, respectively. More studies with
390 different PPPs are necessary to confirm these results, especially for foliar applications (Figure 2).
391 Overall, it can be concluded that there is a strong interdependence between the time available for the
392 accumulation of the compound and the time for dissipation, metabolism and translocation in the
393 plant, influenced by the chemical properties of a PPP and the application method.

394 **Physicochemical Properties**

395 A detailed knowledge about the physical and chemical properties of a chemical compound is a
396 necessary prerequisite to understand its general behaviour in metabolism, analytical methods,

397 formulations, and the environment (Tsipi et al. 2015). Therefore, these parameters are usually studied
398 under well-defined conditions and are required for the registration of a PPP. Physicochemical
399 properties determine the uptake of a compound into the plant, its translocation, as well as its
400 dissipation and metabolisation in the plant and the environment.

401 For PPPs applied before bloom, it can be assumed that every parameter influencing the uptake of a
402 compound and its acropetal translocation will influence the residues in floral resources. Some key
403 physicochemical properties include the solubility in water, the partition coefficient octanol/water (\log
404 K_{ow}), the dissociation coefficient (pK_a), the molecular size of a compound, the root concentration factor
405 and the transpiration stream concentration factor. These properties can be altered by additives and
406 vary depending on the formulation type (Bonmatin et al. 2015; Farha et al. 2016; Hsu and Kleier 1996;
407 Trapp 2004).

408 Overall, PPPs can be classified according to their behaviour in and on plants. Non-systemic or contact
409 compounds are not distributed in the plant and will probably cause only residues in floral matrices if
410 the flower or pollen comes directly into contact with the PPP. On the contrary, translaminar PPPs are
411 taken up and redistributed from one face of a leaf to the opposite face of a leaf, an important
412 parameter for many fungicides (Klittich et al. 2008), whereas systemic PPPs are distributed within the
413 whole plant, either acropetally via the transpiration stream to older leaves in xylem or in both,
414 acropetal and basipetal directions to new growth in the phloem sap. The most common way for the
415 translocation of (non-ionised) plant systemic insecticides is the unidirectional acropetal translocation
416 in xylem (Wyss and Bolsinger 1997).

417 One key parameter describing PPP translocation for non-ionised compounds in the plant is the
418 partition coefficient octanol/water ($\log K_{ow}$). It describes the compound's lipophilicity and its ability to
419 move through bio membranes; thus it determines the uptake of a PPP through the leaf cuticle and its
420 distribution within the plant (Briggs and Bromilow 1994; Kirkwood 1999; Klittich et al. 2008; Wang and
421 Liu 2007).

422 In general, compounds with a $\log K_{ow} < 0$ are considered to be hydrophilic and compounds with a \log
423 $K_{ow} > 0$ lipophilic (Wang and Liu 2007). Lipophilic compounds tend to cross bio membranes but are
424 partitioned into lipophilic tissue along the symplastic pathway (Sicbaldi et al. 1997). Therefore, the
425 optimum uptake and translocation in xylem occurs for non-ionised PPPs with intermediate $\log K_{ow}$
426 values of 1–3. Translaminar distributed compounds can show $\log K_{ow}$ values up to 4.5. Highly polar and
427 highly non-polar compounds are poorly translocated within a plant (Bromilow and Chamberlain 1989;
428 Bromilow and Chamberlain 1995; Sicbaldi et al. 1997; Vryzas 2016).

429 Non-ionised compounds with a lower $\log K_{ow}$ can also be distributed in the phloem sap, though
430 entering the symplast is impeded (Bromilow et al. 1987). In contrast, more lipophilic compounds can
431 readily enter the phloem, but also easily move between xylem and phloem. However, as the xylem is
432 moving faster than the phloem, compounds are eventually translocated in the xylem (Peterson and
433 Edgington 1976; Wyss and Bolsinger 1997).

434 In general, most phloem-mobile compounds appear to be weak acids (Trapp 2004) and their
435 translocation is highly dependent on a favourable combination of $\log K_{ow}$ and the dissociation
436 coefficient (pK_a) (Wyss and Bolsinger 1997). The pK_a describes the acid strength and ability of a
437 compound to dissociate; it can be regarded as the pH at which a particular acid or base group is 50%
438 ionised (Bromilow and Chamberlain 1995). Plant compartments exhibit different pH values across
439 membranes, ranging from pH 5 in the apoplast to pH 8 in the phloem sap (Chamberlain et al. 1998).

440 Accordingly, a weak acid will appear at low pH in its un-dissociated state, having the ability to easily
441 enter the symplast. Once in the symplast, due to the higher pH, it dissociates and is not able to cross
442 back through the membranes (i.e. the ion trap theory) (Briggs et al. 1987; Bromilow and Chamberlain
443 1995; Chamberlain et al. 1998; Pessaraki 2014; Tyree et al. 1979).

444 It is understood that pollen and nectar, as part of reproductive organs, are a sink for photosynthetic
445 products, even though nectaries can be supplied by phloem and xylem depending on the crop and
446 variety (Heil 2011; Pacini et al. 2016; Wist and Davis 2006). However, many PPPs already found in
447 these matrices, mainly insecticides and fungicides, are considered to be more xylem-mobile according

448 to their physicochemical properties. Thus, an acropetal movement in the plant is conceivable but the
449 exact mechanism as to how these chemicals are transferred into the pollen is not yet understood.

450 Aajoud et al. (2008) demonstrated that the low transpiration stream of different parts of a sunflower
451 head cannot be responsible for all of the fipronil residues found in this tissue. Although fipronil is more
452 likely to move in xylem due to its high $\log K_{ow}$ (= 4.0), Aajoud et al. showed under laboratory conditions
453 that fipronil is transported from sources (older leaves) to sinks (growing parts). In general, for non-
454 ionised compounds like fipronil or neonicotinoids the ion trap theory does not apply and the active
455 ingredient can move freely between phloem and xylem according to its bio membrane permeability
456 (Sur and Stork 2003). Aajoud et al. (2008) suggested that both xylem and phloem pathways are
457 involved in the transfer of fipronil to the flower head. Transfer via xylem from the roots to the leaves
458 has been previously demonstrated and depends upon the rate of leaf transpiration, in addition to the
459 compound concentration in the xylem, whereas the phloem pathway seems to be an influencing factor
460 in the translocation to the flower parts and hence to pollen or nectar.

461 Another explanation for unexpected phloem transport is that biotransformation in plants can alter
462 the compounds' properties. For example, due to its physicochemical parameters, imidacloprid is
463 transported in xylem and accumulates in leaves, but some of its metabolites (e.g. 6-chloronicotinic
464 acid) were shown to have properties which are potentially phloem-mobile (Buchholz and Nauen 2002;
465 Chamberlain et al. 1995; Nauen et al. 1999). Furthermore, transformed compounds can form
466 conjugates with glucose, isomaltose and amino acids, which could change the translocation pathway
467 (Jiang et al. 2009; Oliver and Hewitt 2014; Sur and Stork 2003; Wu et al. 2012).

468 These findings could perhaps explain the increase in imidacloprid in upper plant parts, as described in
469 the earlier section about crop-related parameters, and rationalise the presence of PPP residues in
470 physiological sinks like pollen and nectar. Nevertheless, these conclusions might not apply for
471 compounds with other physicochemical properties, especially for PPPs which are considered to be
472 non-systemic.

473 In pollen residue studies, physicochemical properties are often mentioned to describe and explain the
474 reason for differences in residue levels but, to our knowledge, no study has tried to link these PPP
475 characteristics experimentally to the residues found in pollen or other matrices. Kyriakopoulou et al.
476 (2017) found weak correlations between the residue levels in nectar and the solubility in water,
477 although Bromilow and Chamberlain (1995) considered water solubility as a rather poor guide to
478 systemic behaviour. Thorbek and Hyder (2006) used artificial neural networks to examine the
479 relationship between physicochemical properties of different PPPs and residues in food products. In
480 their opinion, the physicochemical properties and the crop type explained up to 50% of the variation.
481 Thorbek and Hyder concluded that these properties control important aspects of the processes
482 leading to residues in food commodities. These findings may be transferred to the residue occurrence
483 in bee-important plant matrices.

484 In general, the uptake of PPPs and their half lives in plants are very well studied, primarily because risk
485 assessments on human exposure or their environmental fate are required for the registration of PPPs,
486 as well as the setting of Maximum Residue Levels (MRLs). However, the process determining the
487 residues in bee-important matrices is not well understood, and more research is required to link the
488 physicochemical properties of a compound to the translocation to pollen or nectar and to the fate and
489 dissipation after the application of a PPP (Figure 3).

490 **Environmental conditions**

491 PPPs applied to a crop enter a complex system, which is greatly influenced by its surrounding
492 environment and underlying manifold interactions. These variations are reflected in the fluctuating
493 PPP residues reported in pollen or nectar, especially in field experiments. Laurent and Rathahao (2003)
494 reported significantly higher variations in pollen residues in a lysimeter experiment compared to
495 greenhouse experiments. Jiang et al. (2018) experienced varying residue fluctuations across the
496 course of one month in field experiments and Rolke et al. (2016) observed high variations even within
497 different sub-areas of one field. Even small-scale weather incidents can change the result of a chemical

498 treatment, for example when the compound is washed off the leaves by rain shortly after application.
499 Additionally, plant growth and physiology are dependent on the surrounding conditions and will
500 influence the behaviour of the compound. This of course makes the comparability of PPP residues in
501 pollen or nectar from different studies difficult, although the environmental fate of all kinds of PPPs
502 are well studied.

503 Key parameters influencing both the chemical fate and the plant are water and temperature.
504 Physicochemical properties are usually assessed under defined laboratory conditions and are
505 therefore likely to change under varying conditions (Hornsby et al. 1995; Tsipi et al. 2015). For
506 example, cuticle permeability was shown to increase rapidly with increasing temperatures (Baur et al.
507 1997; Baur and Schönherr 1995). Degradation processes in soil, vegetation and air are all accelerated
508 at higher temperatures (Bloomfield et al. 2006), whereas colder temperatures limit biological and
509 chemical reaction activities, resulting in longer half-lives and slower dissipation rates (Farha et al.
510 2016). Humidity can increase compound uptake into leaves (Hull 1970; Ramsey et al. 2002), while rain
511 can lead to wash-off and leaching (Hunsche et al. 2007; Radolinski et al. 2018) and water stress was
512 shown to affect the distribution of systemic insecticides in plant leaves (Stamm et al. 2016). Soil
513 conditions are affected by temperature and water availability; organic matter content, microbial life
514 and clay content play a key role in the fate and uptake of soil applied PPPs (Cessna et al. 2017; Di et
515 al. 1998; Gevao et al. 2000; Zhang et al. 2018). PPPs with a long half-life in soil or exposed to conditions
516 that prevent a breakdown in soil are more likely to be taken up during flowering. The transport of
517 xylem-mobile compounds is, inter alia, dependent on the transpiration stream. Therefore,
518 environmental conditions and plant species which enable a high transpiration will enhance acropetal
519 movement and consequently the likelihood of translocation of PPP residues to pollen or nectar.

520 In general, flowers are also exposed to these conditions, however, they may show a different
521 susceptibility to environmental conditions and a different uptake compared to the rest of the plant,
522 due to the different structure and often hydrophilic properties of their surface (Baker and Hunt 1981;

523 Koch et al. 2008). Furthermore, flower opening, the dispersal of pollen, as well as the amount and
524 composition of pollen and nectar produced is dependent on the surrounding environment, especially
525 temperature and humidity (Heil 2011; Pacini et al. 2006; Vidal et al. 2006). PPPs applied during or
526 shortly before bloom will contact the flowers directly and the presence of residues is therefore likely
527 at least in pollen, even for compounds with a short half-life. All factors favouring a fast dissipation or
528 degradation can thus decrease the residues in pollen or nectar. Choudhary and Sharma (2008)
529 recorded a general faster dissipation of PPP residues in pollen than in nectar depending on the active
530 ingredient. They attributed this faster degradation to the fact that pollen is more exposed to
531 environmental conditions than the nectaries, which are typically deeply embedded within the flower.
532 Consequently, the presentation of pollen, the arrangement of anthers and nectaries within the flower
533 and their protection by flower petals could influence the impact of environmental conditions on
534 residue behaviour in pollen and nectar. For example, compounds with a relatively low photo stability,
535 such as pyrethroids, might dissipate faster in pollen grains presented openly to pollinators, compared
536 to residues in nectar. None of the available studies considered or compared the influence of
537 environmental conditions on PPP residues in pollen or nectar (Fig. 4). However, a field study conducted
538 in consecutive years detected correlations in PPP residues from one year to another, despite varying
539 environmental conditions (Dively and Kamel 2012). Nevertheless, the factors acting in different
540 environments on PPPs availability in floral resources are complex and not well understood. [Different
541 climates and soils, for example across Europe, are currently accounted for in risk assessments for bees
542 by conducting residue trials at multiple sites across broad geographic regions. However,
543 environmental influences are not understood well enough to allow an extrapolation or comparison
544 between different sites and may require further attention depending on the mode of application and
545 properties of the active ingredient \(e.g. soil uses with systemic compounds, UV stability\). Controlled-
546 environment studies looking at the effect of for example temperature on residues could provide
547 further insights.](#)

548

549 **Conclusions**

550 Overall, PPP residues in bee-important plant matrices are subject to manifold influences and many
551 parameters can potentially impact their level and residence time in pollen or nectar. Several plant-
552 related parameters, such as species and variety (including morphology), habitus and structure, were
553 identified as contributing factors to the variation observed in PPP residue levels in pollen or nectar.
554 Furthermore, the application mode, especially the dose rate and the timing of the application, were
555 considered as a key source of residue variations. Nevertheless, the highest variations can probably be
556 explained by the physicochemical properties of different compounds and, above all, by the influence
557 of environmental conditions. However, we also demonstrate that studies which focus on these
558 influencing factors are scarce and the complex processes which determine the residue level in bee-
559 important matrices are not well understood (Fig. 1-4).

560 Thus far, research has typically concentrated on the influences of the broad application areas of
561 neonicotinoids, thereby mainly on soil applications, which are not representative of most other
562 insecticides. Investigations into the variability of non-systemic products in floral resources is notably
563 neglected in research, whilst further research into residues of fungicides and herbicides in pollen and
564 nectar is also required.

565 It is questionable whether the currently available data sets on residue levels can mitigate the
566 described variability and whether they are representative enough to be used for conducting reliable
567 risk assessments on pollinators. More wide-ranging and well replicated studies, which reflect different
568 cropping scenarios, are necessary to obtain reliable residue levels in these specific matrices. In
569 addition, PPPs are designed to have the best possible uptake rate and retention time on and in the
570 plant to be effective against pests and to simultaneously avoid environmental pollution. This conflicts
571 with the aim to achieve low residues in pollen or nectar. Therefore, application modes and
572 circumstances in which PPP residues in flower parts are low or dissipate fast should be clarified.

573 It would be extremely difficult to assess the fate in pollen or nectar for all active ingredients, in all bee-
574 important plants and under different climates. Therefore, methods are needed which enable an
575 accurate estimation and extrapolation of PPP residues in these ecologically important matrices, which
576 are also able to consider the numerous influences they are exposed to. In order to enable this,
577 comparable results are required, which do not just reflect a snapshot of a single randomly selected
578 field area and environmental conditions, but also reveal a broader knowledge which can be
579 transferred to further situations.

580 This can only be achieved by improving the understanding of residue behaviour and their dynamics in
581 these complex tissues. A fundamental challenge for future research will be to quantify the effects of
582 different dynamics and interacting factors on PPP residue levels. Future research should aim to
583 investigate relationships, interdependences and common features amongst various PPP applications,
584 which may allow conclusions to be drawn on residues in pollen and nectar and, as a result, permit
585 suitable systems to be identified which can act as model scenarios or be consulted for worst-case
586 estimations, enabling all other scenarios to be adequately covered.

587 Achievement of this will permit risk assessments to be conducted with considerably less effort and
588 expenditure, whilst simultaneously enabling rapid and accurate assessment of the risks for pollinators
589 posed by PPPs.

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594 **Conflict of interest**

595 We wish to draw attention to the fact that the corresponding author's PhD project is funded by
596 Syngenta Ltd, a company manufacturing and selling plant protection products. Furthermore, some of
597 the co-authors are employed by Syngenta.

598 **Bibliography**

- 599 Aajoud, A., Raveton, M., Azrou-Isghi, D., Tissut, M., and Ravanel, P. (2008). How can the fipronil
600 insecticide access phloem? *J Agric Food Chem* 56, 3732-3737.
- 601 Albrecht, M., Schmid, B., Hautier, Y., and Müller, C. B. (2012). Diverse pollinator communities enhance
602 plant reproductive success. *Proceedings of the Royal Society B: Biological Sciences* 279, 4845-
603 4852.
- 604 Alsayeda, H., Pascal-Lorber, S., Nallanthigal, C., Debrauwer, L., and Laurent, F. (2007). Transfer of the
605 insecticide [14C] imidacloprid from soil to tomato plants. *Environ Chem Lett* 6, 229-234.
- 606 Atwood, D., and Paisley-Jones, C. (2017). "Pesticides industry sales and usage: 2008- 2012 market
607 estimates." U.S. Environmental Protection Agency, Washington, DC.
608 [https://www.epa.gov/pesticides/pesticides-industry-sales-and-usage-2008-2012-market-](https://www.epa.gov/pesticides/pesticides-industry-sales-and-usage-2008-2012-market-estimates)
609 [estimates](https://www.epa.gov/pesticides/pesticides-industry-sales-and-usage-2008-2012-market-estimates) retrieved 04.12.2017
- 610 Baker, E. A., and Hunt, G. M. (1981). Developmental changes in leaf epicuticular waxes in relation to
611 foliar penetration. *New Phytol* 88, 731-747.
- 612 Balfour, N. J., Carreck, N. L., Blanchard, H. E., and Ratnieks, F. L. (2016). Size matters: Significant
613 negative relationship between mature plant mass and residual neonicotinoid levels in seed-
614 treated oilseed rape and maize crops. *Agric, Ecosyst Environ* 215, 85-88.
- 615 Baur, P., Buchholz, A., and Schönherr, J. (1997). Diffusion in plant cuticles as affected by temperature
616 and size of organic solutes: similarity and diversity among species. *Plant, Cell Environ* 20, 982-
617 994.
- 618 Baur, P., and Schönherr, J. (1995). Temperature dependence of the diffusion of organic compounds
619 across plant cuticles. *Chemosphere* 30, 1331-1340.
- 620 Bloomfield, J. P., Williams, R. J., Gooddy, D. C., Cape, J. N., and Guha, P. (2006). Impacts of climate
621 change on the fate and behaviour of pesticides in surface and groundwater--A UK perspective.
622 *Sci Total Environ* 369, 163-177.
- 623 Bonmatin, J. M., Giorio, C., Girolami, V., Goulson, D., Kreuzweiser, D. P., Krupke, C., Liess, M., Long,
624 E., Marzaro, M., Mitchell, E. A., Noome, D. A., Simon-Delso, N., and Tapparo, A. (2015).
625 Environmental fate and exposure; neonicotinoids and fipronil. *Environmental Science and*
626 *Pollution Research (international)* 22, 35-67.
- 627 Bonmatin, J. M., Moineau, I., Charvet, R., Colin, M. E., Fleche, C., and Bengsch, E. (2005). Behaviour of
628 imidacloprid in fields. Toxicity for honey bees. *Environ Chem* 5, 483-494.
- 629 Bonmatin, J. M., Moineau, I., Charvet, R., Fleche, C., Colin, M. E., and Bengsch, E. R. (2003). A LC/APCI-
630 MS/MS Method for Analysis of Imidacloprid in Soils, in Plants, and in Pollens. *Anal Chem* 75,
631 2027-2033.
- 632 Botias, C., David, A., Hill, E. M., and Goulson, D. (2017). Quantifying exposure of wild bumblebees to
633 mixtures of agrochemicals in agricultural and urban landscapes. *Environ Pollut* 222, 73-82.
- 634 Botias, C., David, A., Horwood, J., Abdul-Sada, A., Nicholls, E., Hill, E., and Goulson, D. (2015).
635 Neonicotinoid Residues in Wildflowers, a Potential Route of Chronic Exposure for Bees.
636 *Environ Sci Technol* 49, 12731-12740.
- 637 Briggs, G. G., and Bromilow, R. H. (1994). Influence of Physicochemical Properties on Uptake and Loss
638 of Pesticides and Adjuvants from the Leaf Surface. Springer Berlin Heidelberg, Berlin,
639 Heidelberg, pp. 1-26.
- 640 Briggs, G. G., Rigitano, R. L. O., and Bromilow, R. H. (1987). Physico-chemical factors affecting uptake
641 by roots and translocation to shoots of weak acids in barley. *Pestic Sci* 19, 101-112.

642 Bromilow, R. H., and Chamberlain, K. (1989). Designing molecules for systemicity. *BR PLANT GR*, 113-
643 128.

644 Bromilow, R. H., and Chamberlain, K. (1995). Principles governing uptake and transport of chemicals.
645 *Plant contamination: Modeling and simulation of organic chemical processes*, 37-68.

646 Bromilow, R. H., Rigitano, R. L., Briggs, G. G., and Chamberlain, K. (1987). Phloem translocation of non-
647 ionised chemicals in *Ricinus communis*. *Pestic Sci* 19, 85-99.

648 Buchholz, A., and Nauen, R. (2002). Translocation and translaminar bioavailability of two
649 neonicotinoid insecticides after foliar application to cabbage and cotton. *Pest Manage Sci* 58,
650 10-16.

651 Byrne, F. J., Visscher, P. K., Leimkuehler, B., Fischer, D., Grafton-Cardwell, E. E., and Morse, J. G. (2014).
652 Determination of exposure levels of honey bees foraging on flowers of mature citrus trees
653 previously treated with imidacloprid. *Pest Manage Sci* 70, 470-482.

654 Carvalho, F. P. (2006). Agriculture, pesticides, food security and food safety. *Environ Sci Policy* 9, 685-
655 692.

656 Cessna, A. J., Knight, J. D., Ngombe, D., and Wolf, T. M. (2017). Effect of temperature on the dissipation
657 of seven herbicides in a biobed matrix. *Can J Soil Sci* 97, 717-731.

658 Cham, K. d. O., Rebelo, R. M., Oliveira, R. d. P., Ferro, A. A., Vianasilva, F. E. d. C., Borges, L. d. O.,
659 Saretto, C. O. S. D., Tonelli, C. A. M., and Macedo, T. C. (2017). "Manual de avaliação de risco
660 ambiental de agrotóxicos para abelhas." Instituto Brasileiro do Meio Ambiente e dos Recursos
661 Naturais Renováveis (Ibama), Brasília.

662 Chamberlain, K., Patel, S., and Bromilow, R. H. (1998). Uptake by roots and translocation to shoots of
663 two morpholine fungicides in barley. *Pestic Sci* 54, 1-7.

664 Chamberlain, K., Tench, A. J., Williams, R. H., and Bromilow, R. H. (1995). Phloem translocation of
665 pyridinecarboxylic acids and related imidazolinone herbicides in *Ricinus communis*. *Pest*
666 *Manage Sci* 45, 69-75.

667 Chauzat, M.-P., Martel, A.-C., Blanchard, P., Clément, M.-C., Schurr, F., Lair, C., Ribière, M., Wallner,
668 K., Rosenkranz, P., and Faucon, J.-P. (2010). A case report of a honey bee colony poisoning
669 incident in France. *J Apic Res* 49, 113-115.

670 Choudhary, A., and Sharma, D. C. (2008). Dynamics of pesticide residues in nectar and pollen of
671 mustard (*Brassica juncea* (L.) Czern.) grown in Himachal Pradesh (India). *Environ Monit Assess*
672 144, 143-150.

673 Cooper, J., and Dobson, H. (2007). The benefits of pesticides to mankind and the environment. *Crop*
674 *Protect* 26, 1337-1348.

675 Cowles, R. S., and Eitzer, B. D. (2017). Residues of neonicotinoid insecticides in pollen and nectar from
676 model plants. *Journal of Environmental Horticulture* 35, 24-34.

677 Di, H. J., Aylmore, L. A. G., and Kookana, R. S. (1998). Degradation rates of eight pesticides in surface
678 and subsurface soils under laboratory and field conditions. *Soil Science* 163, 404-411.

679 DiTomaso, J. M. (1999). Barriers to foliar penetration and uptake of herbicides. In "Proceedings of the
680 California Weed Science Society", Vol. 51, pp. 150-155.

681 Dively, G. P., and Kamel, A. (2012). Insecticide residues in pollen and nectar of a cucurbit crop and
682 their potential exposure to pollinators. *J Agric Food Chem* 60, 4449-4456.

683 ECPA (2017). "Proposal for a protective and workable regulatory European bee risk assessment
684 scheme based on the EFSA bee guidance and other new data and available approaches."
685 European Crop Protection Authority. <http://www.ecpa.eu> retrieved 08.04.2018

686 EFSA (2012). Scientific Opinion on the science behind the development of a risk assessment of Plant
687 Protection Products on bees (*Apis mellifera*, *Bombus* spp. and solitary bees). *EFSA Journal* 10,
688 2668.

689 EFSA (2013). Guidance on the risk assessment of plant protection products on bees (*Apis mellifera*,
690 *Bombus* spp. and solitary bees). *EFSA Journal* 11, 3295.

691 FaoStat (2017). "FAOSTAT Database- Statistical databases." FAO- Food and Agriculture Organization
692 of the United Nations Rome, Italy. www.faostat.org retrieved 23.11.2017

693 Farha, W., Abd El-Aty, A. M., Rahman, M. M., Shin, H. C., and Shim, J. H. (2016). An overview on
694 common aspects influencing the dissipation pattern of pesticides: a review. *Environ Monit*
695 *Assess* 188, 693.

696 Fujisawa, T., Ichise, K., Fukushima, M., Katagi, T., and Takimoto, Y. (2002). Improved Uptake Models
697 of Nonionized Pesticides to Foliage and Seed of Crops. *J Agric Food Chem* 50, 532-537.

698 Gallai, N., Salles, J.-M., Settele, J., and Vaissière, B. E. (2009). Economic valuation of the vulnerability
699 of world agriculture confronted with pollinator decline. *Ecol Econ* 68, 810-821.

700 Gevao, B., Semple, K. T., and Jones, K. C. (2000). Bound pesticide residues in soils: a review. *Environ*
701 *Pollut* 108, 3-14.

702 Gilland, B. (2002). World population and food supply: can food production keep pace with population
703 growth in the next half-century? *Food Policy* 27, 47-63.

704 Gong, Y., and Diao, Q. (2017). Current knowledge of detoxification mechanisms of xenobiotic in honey
705 bees. *Ecotoxicology* 26, 1-12.

706 Goulson, D. (2013). REVIEW: An overview of the environmental risks posed by neonicotinoid
707 insecticides. *J Appl Ecol* 50, 977-987.

708 Goulson, D., Nicholls, E., Botias, C., and Rotheray, E. L. (2015). Bee declines driven by combined stress
709 from parasites, pesticides, and lack of flowers. *Science* 347, 1255957.

710 Heil, M. (2011). Nectar: generation, regulation and ecological functions. *Trends Plant Sci* 16, 191-200.

711 Hornsby, A. G., Wauchope, R. D., and Herner, A. (1995). "Pesticide Properties in the Environment,"
712 Springer Science & Business Media.

713 Hsu, F. C., and Kleier, D. A. (1996). Phloem mobility of xenobiotics VIII. A short review. *J Exp Bot* 47,
714 1265-1271.

715 Hull, H. M. (1970). Leaf structure as related to absorption of pesticides and other compounds. In
716 "Residue Reviews/Rückstands-Berichte", 1-150. Springer Verlag, Berlin, Heidelberg.

717 Hulme, P. E. (2017). Climate change and biological invasions: evidence, expectations, and response
718 options. *Biol Rev Camb Philos Soc* 92, 1297-1313.

719 Hunsche, M., Damerow, L., Schmitz-Eiberger, M., and Noga, G. (2007). Mancozeb wash-off from apple
720 seedlings by simulated rainfall as affected by drying time of fungicide deposit and rain
721 characteristics. *Crop Protect* 26, 768-774.

722 IPBES (2016). Summary for policymakers of the assessment report of the Intergovernmental Science-
723 Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food
724 production. (S.G. Potts, V. L. Imperatriz-Fonseca, H. T. Ngo, J. C. Biesmeijer, T. D. Breeze, L. V.
725 Dicks, L. A. Garibaldi, R. Hill, J. Settele, A. J. Vanbergen, M. A. Aizen, S. A. Cunningham, C.
726 Eardley, B. M. Freitas, N. Gallai, P. G. Kevan, A. Kovács-Hostyánszki, P. K. Kwapong, X. L. J. Li,
727 D. J. Martins, G. Nates-Parra, J. S. Pettis, R. Rader and B. F. Viana, eds.). Secretariat of the
728 Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn,
729 Germany, pp. 36.

730 Jiang, D.-X., Lu, X.-L., Hu, S., Zhang, X.-B., and Xu, H.-H. (2009). A new derivative of fipronil: Effect of
731 adding a glyciny group to the 5-amine of pyrazole on phloem mobility and insecticidal activity.
732 *Pestic Biochem Physiol* 95, 126-130.

733 Jiang, J., Ma, D., Zou, N., Yu, X., Zhang, Z., Liu, F., and Mu, W. (2018). Concentrations of imidacloprid
734 and thiamethoxam in pollen, nectar and leaves from seed-dressed cotton crops and their
735 potential risk to honeybees (*Apis mellifera* L.). *Chemosphere* 201, 159-167.

736 Johnson, D. G. (2000). Population, food, and knowledge. *The American Economic Review* 90, 1-14.

737 Johnson, J. (2012). "The role of pesticides on honey bee health and hive maintenance with an
738 emphasis on the neonicotinoid, imidacloprid," University of Maryland, Baltimore.

739 Johnson, R. M., Ellis, M. D., Mullin, C. A., and Frazier, M. (2010). Pesticides and honey bee toxicity –
740 USA. *Apidologie* 41, 312-331.

741 Kasiotis, K. M., Anagnostopoulos, C., Anastasiadou, P., and Machera, K. (2014). Pesticide residues in
742 honeybees, honey and bee pollen by LC–MS/MS screening: Reported death incidents in
743 honeybees. *Sci Total Environ* 485, 633-642.

744 Kiljanek, T., Niewiadowska, A., Gawel, M., Semeniuk, S., Borzecka, M., Posyniak, A., and Pohorecka, K.
745 (2017). Multiple pesticide residues in live and poisoned honeybees - Preliminary exposure
746 assessment. *Chemosphere* 175, 36-44.

747 Kirkwood, R. C. (1999). Recent developments in our understanding of the plant cuticle as a barrier to
748 the foliar uptake of pesticides. *Pest Manage Sci* 55, 69-77.

749 Klein, A. M., Vaissiere, B. E., Cane, J. H., Steffan-Dewenter, I., Cunningham, S. A., Kremen, C., and
750 Tschardt, T. (2007). Importance of pollinators in changing landscapes for world crops.
751 *Proceedings of the Royal Society B* 274, 303-13.

752 Klittich, C., Jr., Green, F. R., 3rd, Ruiz, J. M., Weglarz, T., and Blakeslee, B. A. (2008). Assessment of
753 fungicide systemicity in wheat using LC-MS/MS. *Pest Manage Sci* 64, 1267-77.

754 Koch, K., Bhushan, B., and Barthlott, W. (2008). Diversity of structure, morphology and wetting of plant
755 surfaces. *Soft Matter* 4, 1943-1963.

756 Kubik, M., Nowacki, J., Pidek, A., Warakomska, Z., Michalczyk, L., and Goszczyński, W. (1999). Pesticide
757 residues in bee products collected from cherry trees protected during blooming period with
758 contact and systemic fungicides. *Apidologie* 30, 521-532.

759 Kunz, N., Frommberger, M., Dietzsch, A. C., Wirtz, I. P., Stähler, M., Frey, E., Illies, I., Dyrba, W.,
760 Alkassab, A., and Pistorius, J. (2015). Neonicotinoids and bees: A large scale field study
761 investigating residues and effects on honeybees, bumblebees and solitary bees in oilseed rape
762 grown from clothianidin-treated seed. *Julius-Kühn-Archiv* 450, 155.

763 Kyriakopoulou, K., Kandris, I., Pachiti, I., Kasiotis, K. M., Spyropoulou, A., Santourian, A., Kitromilidou,
764 S., Pappa, G., and Glossioti, M. (2017). Collection and analysis of pesticide residue data for
765 pollen and nectar – Final Report. EFSA Supporting Publications 14.

766 Laurent, F. M., and Rathahao, E. (2003). Distribution of [14C] imidacloprid in sunflowers (*Helianthus*
767 *annuus* L.) following seed treatment. *J Agric Food Chem* 51, 8005-8010.

768 Lee, K. V., Steinhauer, N., Rennich, K., Wilson, M. E., Tarpy, D. R., Caron, D. M., Rose, R., Delaplane, K.
769 S., Baylis, K., Lengerich, E. J., Pettis, J., Skinner, J. A., Wilkes, J. T., Sagili, R., and vanEngelsdorp,
770 D. (2015). A national survey of managed honey bee 2013–2014 annual colony losses in the
771 USA. *Apidologie* 46, 292-305.

772 Lewis, K. A., Tzilivakis, J., Warner, D. J., and Green, A. (2016). An international database for pesticide
773 risk assessments and management. *Human and Ecological Risk Assessment: An International*
774 *Journal* 22, 1050-1064.

775 Lundin, O., Rundlof, M., Smith, H. G., Fries, I., and Bommarco, R. (2015). Neonicotinoid Insecticides
776 and Their Impacts on Bees: A Systematic Review of Research Approaches and Identification of
777 Knowledge Gaps. *PLoS One* 10, e0136928.

778 Mitton, F. M., Gonzalez, M., Monserrat, J. M., and Miglioranza, K. S. (2016). Potential use of edible
779 crops in the phytoremediation of endosulfan residues in soil. *Chemosphere* 148, 300-306.

780 Mostafalou, S., and Abdollahi, M. (2017). Pesticides: an update of human exposure and toxicity. *Arch*
781 *Toxicol* 91, 549-599.

782 Nauen, R., Reckmann, U., Armbrorst, S., Stupp, H. P., and Elbert, A. (1999). Whitefly-active metabolites
783 of imidacloprid: Biological efficacy and translocation in cotton plants. *Pest Manage Sci* 55, 265-
784 271.

785 Oerke, E. C., and Dehne, H. W. (2004). Safeguarding production—losses in major crops and the role of
786 crop protection. *Crop Protect* 23, 275-285.

787 Oliveira, C. M., Auad, A. M., Mendes, S. M., and Frizzas, M. R. (2014). Crop losses and the economic
788 impact of insect pests on Brazilian agriculture. *Crop Protect* 56, 50-54.

789 Oliver, R., and Hewitt, H. G. (2014). "Fungicides in Crop Protection," 2/Ed. CABI Publishing.

790 Ollerton, J. (2017). Pollinator diversity: distribution, ecological function, and conservation. *Annual*
791 *Review of Ecology, Evolution, and Systematics* 48.

792 Otani, T., and Seike, N. (2007). Rootstock control of fruit dieldrin concentration in grafted cucumber
793 (*Cucumis sativus*). *J Pestic Sci* 32, 235-242.

794 Otani, T., Seike, N., and Sakata, Y. (2007). Differential uptake of dieldrin and endrin from soil by several
795 plant families and Cucurbitaceae genera. *Soil Sci Plant Nutr* 53, 86-94.

796 Pacini, E., Guarnieri, M., and Nepi, M. (2006). Pollen carbohydrates and water content during
797 development, presentation, and dispersal: a short review. *Protoplasma* 228, 73-77.

798 Pacini, E., Nepi, M., and Vesprini, J. L. (2016). Nectar biodiversity: a short review. *Plant Syst Evol* 238,
799 7-21.

800 Pessaraki, M. (2014). "Handbook of plant and crop physiology," CRC Press.

801 Peterson, C. A., and Edgington, L. V. (1976). Entry of pesticides into the plant symplast as measured
802 by their loss from an ambient solution. *Pestic Sci* 7, 483-491.

803 Pettis, J. S., vanEngelsdorp, D., Johnson, J., and Dively, G. (2012). Pesticide exposure in honey bees
804 results in increased levels of the gut pathogen *Nosema*. *Naturwissenschaften* 99, 153-158.

805 Pimentel, D. (1997). Pest management in agriculture In "Techniques for Reducing Pesticide Use:
806 Environmental and Economic Benefits. " (D. Pimentel, ed.), 456. John Wiley & Sons,
807 Chichester, UK.

808 Pimentel, D. (2005). Environmental and economic costs of the application of pesticides primarily in
809 the United States. *Environ Dev Sustainability* 7, 229-252.

810 Pohorecka, K., Skubida, P., Miszczak, A., Semkiw, P., Sikorski, P., Zagibajto, K., Teper, D., Koltowski, Z.,
811 Skubida, M., Zdańska, D., and Bober, A. (2012). Residues of Neonicotinoid Insecticides in Bee
812 Collected Plant Materials from Oilseed Rape Crops and their Effect on Bee Colonies. *J Apic Sci*
813 56, 115- 134.

814 Population Reference Bureau (2017). "2017 World Population Data Sheet," Washington, DC.
815 <https://www.prb.org/international/indicator/population/snapshot/> retrieved 08.12.2017

816 Potts, S. G., Biesmeijer, J. C., Kremen, C., Neumann, P., Schweiger, O., and Kunin, W. E. (2010a). Global
817 pollinator declines: trends, impacts and drivers. *Trends Ecol Evol* 25, 345-53.

818 Potts, S. G., Roberts, S. P. M., Dean, R., Marris, G., Brown, M. A., Jones, R., Neumann, P., and Settele,
819 J. (2010b). Declines of managed honey bees and beekeepers in Europe. *J Apic Res* 49, 15-22.

820 Price, C. E., and Anderson, N. H. (1985). Uptake of chemicals from foliar deposits: effects of plant
821 species and molecular structure. *Pest Manage Sci* 16, 369-377.

822 Radolinski, J., Wu, J., Xia, K., and Stewart, R. (2018). Transport of a neonicotinoid pesticide,
823 thiamethoxam, from artificial seed coatings. *Sci Total Environ* 618, 561-568.

824 Ramsey, R. J. L., Stephenson, G. R., and Hall, J. C. (2002). Effect of relative humidity on the uptake,
825 translocation, and efficacy of glufosinate ammonium in wild oat (*Avena fatua*). *Pestic Biochem*
826 *Physiol* 73, 1-8.

827 Rolke, D., Persigehl, M., Peters, B., Sterk, G., and Blenau, W. (2016). Large-scale monitoring of effects
828 of clothianidin-dressed oilseed rape seeds on pollinating insects in northern Germany:
829 residues of clothianidin in pollen, nectar and honey. *Ecotoxicology* 25, 1691-1701.

830 Rortais, A., Arnold, G., Dorne, J. L., More, S. J., Sperandio, G., Streissl, F., Szentes, C., and Verdonck, F.
831 (2017). Risk assessment of pesticides and other stressors in bees: Principles, data gaps and
832 perspectives from the European Food Safety Authority. *Sci Total Environ* 587-588, 524-537.

833 Rosenzweig, C., Iglesias, A., Yang, X., Epstein, P. R., and Chivian, E. (2001). Climate change and extreme
834 weather events; implications for food production, plant diseases, and pests. *Global Change*
835 *Hum Health* 2, 90-104.

836 Sanchez-Bayo, F., Belzunces, L., and Bonmatin, J. M. (2017). Lethal and sublethal effects, and
837 incomplete clearance of ingested imidacloprid in honey bees (*Apis mellifera*). *Ecotoxicology*
838 26, 1199-1206.

839 Sanchez-Bayo, F., and Goka, K. (2014). Pesticide residues and bees--a risk assessment. *PLoS One* 9,
840 e94482.

841 Schmuck, R., Schöning, R., Stork, A., and Schramel, O. (2001). Risk posed to honeybees (*Apis mellifera*
842 L, Hymenoptera) by an imidacloprid seed dressing of sunflowers. *Pest Manage Sci* 57, 225-
843 238.

844 Seitz, N., Traynor, K. S., Steinhauer, N., Rennich, K., Wilson, M. E., Ellis, J. D., Rose, R., Tarpy, D. R.,
845 Sagili, R. R., Caron, D. M., Delaplane, K. S., Rangel, J., Lee, K., Baylis, K., Wilkes, J. T., Skinner, J.
846 A., Pettis, J. S., and vanEngelsdorp, D. (2016). A national survey of managed honey bee 2014–
847 2015 annual colony losses in the USA. *J Apic Res* 54, 292-304.

848 Sicbaldi, F., Sacchi, G. A., Trevisan, M., and Del Re, A. A. (1997). Root uptake and xylem translocation
849 of pesticides from different chemical classes. *Pest Manage Sci* 50, 111-119.

850 Stamm, M. D., Heng-Moss, T. M., Baxendale, F. P., Siegfried, B. D., Blankenship, E. E., and Nauen, R.
851 (2016). Uptake and translocation of imidacloprid, clothianidin and flupyradifurone in seed-
852 treated soybeans. *Pest Manage Sci* 72, 1099-1109.

853 Stoner, K. A., and Eitzer, B. D. (2012). Movement of soil-applied imidacloprid and thiamethoxam into
854 nectar and pollen of squash (*Cucurbita pepo*). *PLoS One* 7, e39114.

855 Sur, R., and Stork, A. (2003). Uptake, translocation and metabolism of imidacloprid in plants. *Bull*
856 *Insectol* 56, 35-40.

857 Thorbek, P., and Hyder, K. (2006). Relationship between physicochemical properties and maximum
858 residue levels and tolerances of crop-protection products for crops set by the USA, European
859 Union and Codex. *Food Addit Contam* 23, 764-776.

860 Tilman, D. (1999). Global environmental impacts of agricultural expansion: the need for sustainable
861 and efficient practices. *Proceedings of the National Academy of Sciences* 96, 5995-6000.

862 Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W.
863 H., Simberloff, D., and Swackhamer, D. (2001). Forecasting agriculturally driven global
864 environmental change. *Science* 292, 281-284.

865 Tosi, S., Costa, C., Vesco, U., Quaglia, G., and Guido, G. (2018). A 3-year survey of Italian honey bee-
866 collected pollen reveals widespread contamination by agricultural pesticides. *Sci Total Environ*
867 615, 208-218.

868 Trapp, S. (2004). Plant uptake and transport models for neutral and ionic chemicals. *Environ Sci Pollut*
869 *R* 11, 33-39.

870 Tsiipi, D., Botitsi, H., and Economou, A. (2015). Pesticide Chemistry and Risk Assessment. In "Mass
871 Spectrometry for the Analysis of Pesticide Residues and Their Metabolites", 1-34. John Wiley
872 & Sons, Inc.

873 Tyree, M. T., Peterson, C. A., and Edgington, L. V. (1979). A Simple Theory Regarding Ambimobility of
874 Xenobiotics with Special Reference to the Nematicide, Oxamyl. *Plant Physiol* 63, 367-374.

875 UN (2017). "World Population Prospects: The 2017 Revision, Key Findings and Advance Tables.."
876 United Nations, Department of Economic and Social Affairs, Population Division, New York.

877 USEPA (2014). "Guidance for Assessing Pesticide Risks to Bees ". United States Environmental
878 Protection Agency, Office of Chemical Safety and Pollution Prevention, Office of Pesticide
879 Programs, Washington, D.C.

880 Vanbergen, A. J., Heard, M. S., Breeze, T., Potts, S. G., and Hanley, N. (2014). Status and value of
881 pollinators and pollination services. Department for Environment, Food and Rural Affairs
882 53pp.

883 Veddel, D., Olschewski, R., Tschardtke, T., and Klein, A.-M. (2008). The contribution of non-managed
884 social bees to coffee production: new economic insights based on farm-scale yield data.
885 *Agroforest Syst* 73, 109-114.

886 Vidal, M. d. G., Jong, D. d., Wien, H. C., and Morse, R. A. (2006). Nectar and pollen production in
887 pumpkin (*Cucurbita pepo* L.). *Brazilian Journal of Botany* 29, 267-273.

888 Villa, S., Vighi, M., Finizio, A., and Serini, G. B. (2000). Risk assessment for honeybees from pesticide-
889 exposed pollen. *Ecotoxicology* 9, 287-297.

890 Vryzas, Z. (2016). The Plant as Metaorganism and Research on Next-Generation Systemic Pesticides –
891 Prospects and Challenges. *Frontiers in Microbiology* 7, 1968.

892 Wallner, K. (2009). Sprayed and seed dressed pesticides in pollen, nectar and honey of oilseed rape.
893 *Julius-Kühn-Archiv* 423, 152-153.

894 Wang, C. J., and Liu, Z. Q. (2007). Foliar uptake of pesticides—Present status and future challenge.
895 Pestic Biochem Physiol 87, 1-8.

896 Wilson, C., and Tisdell, C. (2001). Why farmers continue to use pesticides despite environmental,
897 health and sustainability costs. Ecol Econ 39, 449-462.

898 Wist, T. J., and Davis, A. R. (2006). Floral nectar production and nectary anatomy and ultrastructure of
899 *Echinacea purpurea* (Asteraceae). Ann Bot 97, 177-93.

900 Woodcock, B., Bullock, J., Shore, R., Heard, M., Pereira, M., Redhead, J., Ridding, L., Dean, H., Sleep,
901 D., and Henrys, P. (2017). Country-specific effects of neonicotinoid pesticides on honey bees
902 and wild bees. Science 356, 1393-1395.

903 Wu, H. X., Yang, W., Zhang, Z. X., Huang, T., Yao, G. K., and Xu, H. H. (2012). Uptake and phloem
904 transport of glucose-fipronil conjugate in *Ricinus communis* involve a carrier-mediated
905 mechanism. J Agric Food Chem 60, 6088-6094.

906 Wu, J. Y., Anelli, C. M., and Sheppard, W. S. (2011). Sub-lethal effects of pesticide residues in brood
907 comb on worker honey bee (*Apis mellifera*) development and longevity. PLoS One 6, e14720.

908 Wyss, P., and Bolsinger, M. (1997). Translocation of pymetrozine in plants. Pestic Sci 50, 195-202.

909 Yu, Y., Zhu, H., Frantz, J. M., Reding, M. E., Chan, K. C., and Ozkan, H. E. (2009). Evaporation and
910 coverage area of pesticide droplets on hairy and waxy leaves. Biosys Eng 104, 324-334.

911 Zhang, P., Ren, C., Sun, H., and Min, L. (2018). Sorption, desorption and degradation of neonicotinoids
912 in four agricultural soils and their effects on soil microorganisms. Sci Total Environ 615, 59-69.

913 Zhang, W., Jiang, F., and Ou, J. (2011). Global pesticide consumption and pollution: with China as a
914 focus. Proceedings of the International Academy of Ecology and Environmental Sciences 1,
915 125.

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934 **Tables**

935 **Table 1** Summary of selected PPP residues in pollen expressed as Residue Unit Dose (RUD) (mg a.i. kg⁻¹ pollen at an
 936 application rate of 1 kg a.i. ha⁻¹) derived from two different sources. The minimum, maximum and mean values demonstrate
 937 the high variability of residues found in pollen from spray applications. Some calculations were not derived from a single
 938 crop or active ingredient, but many different crops/active ingredients were summarised (“various”).

Crop	Active ingredient	Min (RUD mg kg ⁻¹)	Max (RUD mg kg ⁻¹)	Mean (RUD mg kg ⁻¹)	Source*
various	various	0.0002	149.8	6.1 ± 30.704 (SD)	a
various	various	0.004	366	65.06 ± 89.421 (SD)	b
various	alpha- Cypermethrin	11.370	366.3	167.3 ± 121.438 (SD)	b
<i>Brassica</i> sp.	various	2.083	366.3	87.06 ± 102.8 (SD)	b
	Teflubenzuron	21.7	149.8	**	a
	Acetamiprid	3.4	14.8	**	a

Examples for PPP residues of the same active ingredient in different crops

Active ingredient	Crop			Source*
Spirotetramat	Melon (<i>Cucurbitaceae</i>)	<i>Phacelia tanacetifolia</i> L.	<i>Brassica</i> sp.	a
	2.2	63.5	83.1	

939 *Sources: a) EFSA 2013, see Annex F; b) Kyriakopoulou et al. 2017

940 ** Only two residue values were provided for this active ingredient/ crop combination

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945 **Table 2:** Relationship between dose rate, residues in pollen (ppm) and Residue Unit Dose (RUD) for three active

946 ingredients. Data from Choudhary and Sharma (2007). Application of 750 L ha⁻¹ water in mustard (*Brassica juncea* Czern.)

947 in 2003/2004.

Active ingredient	Dose rate (g a.i. ha ⁻¹)	Residues pollen ppm	RUD
Endosulfan	525	2.126	4.05
Spiromesifen	225	2.052	9.12
Lambda- Cyhalothrin	75	1.607	21.43

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