

1 **Phenotypic plasticity triggers rapid morphological convergence**

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18

19 **Abstract**

20 Phenotypic convergence, the independent evolution of similar traits, is ubiquitous in nature,  
21 happening at all levels of biological organizations and in most kinds of living beings. Uncovering  
22 its mechanisms remains a fundamental goal in biology. Evolutionary theory considers that  
23 convergence emerges through independent genetic changes selected over long periods of time.  
24 We show in this study that convergence can also arise through phenotypic plasticity. We illustrate  
25 this idea by investigating how plasticity drives *Moricandia arvensis*, a mustard species displaying  
26 within-individual polyphenism in flowers, across the morphological space of the entire  
27 Brassicaceae family. By compiling the multidimensional floral phenotype, the phylogenetic  
28 relationships, and the pollination niche of over 3000 Brassicaceae species, we demonstrated that  
29 *Moricandia arvensis* exhibits a plastic-mediated within-individual floral disparity greater than that  
30 found not only between species but also between higher taxonomical levels such as genera and  
31 tribes. As a consequence of this divergence, *M. arvensis* moves outside the morphospace region  
32 occupied by its ancestors and close relatives, crosses into a new region where it encounters a  
33 different pollination niche and converges phenotypically with distant Brassicaceae lineages. Our  
34 study suggests that, by inducing phenotypes that explore simultaneously different regions of the  
35 morphological space, plasticity triggers rapid phenotypic convergence.

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37

## 38 Introduction

39

40 Phenotypic convergence, the independent evolution of similar traits in different evolutionary  
41 lineages, is ubiquitous in nature, happening at all levels of biological organizations and in most  
42 kinds of living beings (1-3). Convergent evolution plays a fundamental role in how evolutionary  
43 lineages occupy the morphological space (2, 4). The expansion of lineages across the  
44 morphological space is a complex process resulting from the ecological opportunities emerging  
45 when species enter into different regions of the ecospace and face new ecological niches (5, 6).  
46 When this occurs, divergent selection on some phenotypes makes lineages to diversify  
47 phenotypically, boosting morphological disparity, triggering a morphological radiation and  
48 eventually filling the morphospace (7, 8). Because the ecological space saturate as lineages  
49 diversify (9), unoccupied regions become rare in highly diversified lineages (10). Under these  
50 circumstances, entering into a new region usually entails sharing it with other species exploiting  
51 the same ecological niche (2, 10, 11). In this situation, independent lineages tend to evolve  
52 similar phenotypes through convergent evolution (2, 4). In diversified lineages occupying a  
53 saturated morphospace, divergent and convergent evolution are ineludibly connected (10, 12),  
54 and both processes contribute significantly to shape the geometry of the morphospace  
55 occupation (4, 11).

56

57 Uncovering the mechanisms triggering convergence remains a fundamental goal in biology.  
58 Evolutionary theory shows that convergent phenotypes emerge from several genetic  
59 mechanisms, such as independent mutations or gene reuse in different populations or species,  
60 polymorphic alleles, parallel gene duplication, introgression or whole-genome duplications, that  
61 are selected over long periods of time (13–15). Under these circumstances, the origin of  
62 morphological convergence is mostly slow, occurring over evolutionary time and associated with  
63 multiple events of speciation and cladogenesis (11). It is increasingly acknowledged, however,  
64 that phenotypic plasticity might elicit the emergence of novel phenotypes with new adaptive  
65 possibilities, which may be beneficial in some contexts (16, 17). Under these circumstances,  
66 plasticity may behave as a facilitator for evolutionary novelty and diversity, shaping the patterns of  
67 morphospace occupation (16, 18-21). In this study, we provide compelling evidence showing that  
68 phenotypic plasticity also plays a prominent role in the emergence of convergent phenotypes. By  
69 inducing the production of several phenotypes, plasticity may cause the species to explore  
70 different regions of the morphospace almost simultaneously (18, 19). This opens the opportunity  
71 for plastic species to diverge from their lineages and converge with the species already located in  
72 other morphospace regions. We illustrate this idea by investigating how plasticity drives  
73 *Moricandia arvensis*, a species exhibiting extreme polyphenism in flowers (18), across the

74 morphological space of the entire Brassicaceae family. *Moricandia arvensis* displays within-  
75 individual floral plasticity, with flower morphs varying seasonally on the same individual (18). By  
76 studying the multidimensional floral phenotypes, the phylogenetic relationships, and the  
77 pollination niches of over 3000 Brassicaceae species, we demonstrate that phenotypic plasticity  
78 makes the flowers of this mustard species to diverge from its ancestors and close relatives, to  
79 cross into a new region of the ecospace, and to converge morphologically with distant  
80 Brassicaceae lineages. This finding has great implications, suggesting that plasticity might not  
81 only promote the evolution of novelties and morphological divergence (16, 17, 20, 21) but can  
82 also provide an alternative explanation to the pervasiveness of convergence in nature.

83

84

## 85 **Results**

86

### 87 ***Plasticity-mediated floral disparity and divergence***

88 Changes in temperature, radiation and water availability induce the production of different types  
89 of flowers by the same *M. arvensis* individuals; large, cross-shaped lilac flowers in spring but  
90 small, rounded, white flowers in summer (18). To quantify the magnitude of floral disparity  
91 between these two phenotypes of *M. arvensis*, we first assessed floral disparity for the entire  
92 mustard family. Brassicaceae is one of the largest angiosperm families, with almost 4000 species  
93 grouped in 351 genera and 51 tribes (7, 22–24). We determined the magnitude and extent of  
94 floral disparity among 3140 plant species (approx. 80% of the accepted species) belonging to 330  
95 genera (94% of the genera) from the 51 tribes. Because we were interested in floral characters  
96 mediating the interaction with pollinators, we recorded for each studied species a total of 31 traits  
97 associated with pollination in Brassicaceae (Supplementary Data 1, Methods). We used the  
98 resulting phenotypic matrix to generate a family-wide floral morphospace. We first run a principal  
99 coordinate analysis (PCoA) to obtain a low-dimensional Euclidean representation of the  
100 multidimensional phenotypic similarity existing among the Brassicaceae species (25). Because  
101 the raw matrix was composed of quantitative, semi-quantitative and discrete variables, PCoA was  
102 based on Gower dissimilarities (25). We optimized this initial Euclidean configuration by running a  
103 non-metric multidimensional scaling (NMDS) algorithm with 5000 random starts (25). The  
104 resulting morphospace (Figure 1a) was significantly correlated with the initial PCoA configuration  
105 ( $r = 0.40$ ,  $P < 0.0001$ , Mantel test) and was a good representation of the original relationship  
106 among the species ( $R^2 > 0.95$ ,  $Stress = 0.2$ , Figure 1b). The distribution of the species across the  
107 morphospace was significantly associated with different pollination traits (Figure S1; Table S1).  
108 Species in the central region were mostly medium-sized plants bearing a moderate to high  
109 number of small, polysymmetric white flowers with short corolla tubes, exposed nectaries and

110 visible sepals (Figure 1a, Figure S1). Species in the bottom right corner were small or prostrate,  
111 bearing minute flowers, many time apetalous and with just 2 or 4 stamens, whereas species  
112 located in the bottom left corner were medium-sized plants with asymmetric flowers arranged in  
113 corymbose inflorescences. Plants with yellow flowers were located in the right region of the  
114 morphospace. In contrast, large plants with strongly tetradynamous androceum and large,  
115 veined, dissymmetrical to asymmetrical, pink to blue flowers with concealed nectaries, long  
116 corolla tubes and bullseyes were located in the upper left region (Figure 1a, Figure S1).  
117 *Moricandia arvensis*, when blooming in spring (Figure 1c), occupies this later peripheral region of  
118 the morphospace, close to other *Moricandia* species (purple dots in Figure 1a). However, during  
119 summertime, the individuals of *M. arvensis* are shorter and produce fewer, much smaller flowers  
120 with white, unveined and rounded corollas with overlapped petals and green sepals that are  
121 mostly arranged along the floral stems (Figure 1d) (18). Due to this radical phenotypic change,  
122 the summer phenotype of *M. arvensis* was located in a different, more central position of the floral  
123 morphospace (Figure 1a), far away from the region occupied by the *Moricandia* species. As a  
124 consequence of this jump, the morphological disparity between the spring and summer  
125 phenotypes of *M. arvensis*, calculated as their distance in the morphospace (26), was very high  
126 (0.264). In fact, it was much higher than the average pairwise disparities among all studied  
127 Brassicaceae species ( $0.155 \pm 0.090$ , mean  $\pm$  s.e.m., 4,912,545 pairwise disparities) and almost  
128 50% of the largest observed disparity (0.55) (Table S4). This outcome suggests that phenotypic  
129 plasticity prompts *M. arvensis* to explore two distant regions of the Brassicaceae floral  
130 morphospace simultaneously.

131

132 To know how intense is the plasticity-mediated *M. arvensis* disparity, we compared its value with  
133 the disparity values observed at different taxonomic levels within Brassicaceae. At the lowest  
134 level, discrete changes in pollination traits have been reported between individuals of the same  
135 species. In some species, this intraspecific phenotypic change is stable, like the gender  
136 polymorphism (27, 28) or the adaptive floral colour polymorphism exhibited as a response to the  
137 selective pressures exerted by certain pollinators (29, 30). In other species, discrete phenotypic  
138 changes, although affecting pollination traits, seem to be just the consequence of some singular  
139 and often unstable mutations affecting floral colour (31), the production of cleistogamous flowers  
140 (32) or changes in the expression of homeotic genes that modify the formation of the floral organs  
141 (33, 34). We compiled information on the phenotypes of the different morphs in 34 polymorphic  
142 species and calculated their values of intraspecific disparities (Figure 1a, Supplementary Data 2).  
143 Although several polymorphic species showed considerable values of between-morph disparity,  
144 they were significantly smaller than the disparity between spring and summer floral phenotypes of  
145 *M. arvensis* ( $Z$ -score = 5.06,  $P < 0.0001$ , Figure 1e, Table S2). We subsequently tested at what

146 taxonomic level of Brassicaceae the disparity was equivalent to the plasticity-mediated disparity  
147 observed in *M. arvensis*. For this, we calculated the floral disparity between pair of species  
148 belonging to the genus *Moricandia*, the same genus, the same tribe, and different tribes  
149 (Methods). The plasticity-mediated disparity of *M. arvensis* was significantly higher than the  
150 disparity existing between the *Moricandia* species ( $0.057 \pm 0.033$ , mean  $\pm 1$  s.e.m.,  $Z$ -score =  
151  $6.27$ ,  $P < 0.0001$ ) and between the species belonging to the same genus ( $0.069 \pm 0.055$ ,  $Z$ -score  
152 =  $3.51$ ,  $P < 0.0002$ ). It was marginally different from the disparity existing between species of  
153 different genera but the same tribes ( $0.150 \pm 0.085$ ,  $Z$ -score =  $1.34$ ,  $P = 0.089$ ) and it was  
154 statistically similar to the disparity occurring between species belonging to different tribes ( $0.167 \pm$   
155  $0.087$ ,  $Z$ -score =  $1.11$ ,  $P = 0.133$ , Figure 1e). These findings suggest that phenotypic plasticity  
156 allows *M. arvensis* individuals to jump in the morphospace longer distances than those granted  
157 by some macroevolutionary processes.

158

159 We explored whether plasticity-mediated disparity may cause evolutionary divergence by  
160 calculating the disparity of *M. arvensis* spring and summer phenotypes to their phylogenetic  
161 ancestors. We retrieved 80 partial phylogenies from the literature and online repositories  
162 (Methods), and assembled them into a supertree comprising 1876 taxa with information on their  
163 floral phenotype. We then projected this supertree onto the morphospace to get a family-wide  
164 phylomorphospace. We did not find evidence of phylogenetic constraints on morphospace  
165 occupation since there was not significant phylogenetic signal for the position occupied by each  
166 species (Multivariate *Mantel* test=0.005,  $P = 0.34$ ). The family-wide phylomorphospace was very  
167 tangled (Figure 2a), with 492,751 intersections among lineages, suggesting the presence of many  
168 events of floral divergence and convergence in the evolution of Brassicaceae pollination traits  
169 (11). To calculate the disparity of the *M. arvensis* floral phenotypes to their ancestor, because  
170 these analyses are sensitive to the tree topology and the inferred branch lengths (26), we used  
171 four independent, time-calibrated phylogenies that included this species (Methods). The results  
172 were consistent across phylogenies (Figure 2b,c; Tables S3). The spring phenotype did not  
173 significantly diverge neither from the most recent common ancestor (MRCA) of *Moricandia* ( $Z$ -  
174 score =  $0.36$ ,  $P = 0.36$ ) nor from its direct ancestor ( $Z$ -score =  $-1.24$ ,  $P = 0.108$ ). In contrast, the  
175 summer phenotype of *M. arvensis* diverged significantly both from *Moricandia* MRCA ( $Z$ -score =  
176  $2.48$ ,  $P = 0.007$ ) and from its direct ancestor ( $Z$ -score =  $1.77$ ,  $P = 0.038$ ). Hence, the summer  
177 phenotype explores a region of the floral morphospace located out of its phylogenetic clade range  
178 (Figure 2b). The ancestral disparity of the summer phenotype was even significantly higher than  
179 the ancestral disparity of most other Brassicaceae species (Figure 2c). These findings suggest  
180 that phenotypic plasticity causes the appearance of a novel phenotype that diverges radically  
181 from its ancestors.

182

### 183 **Plastic shifts in pollination niches**

184 Evolutionary divergence is mostly associated with the occupation of new ecological niches (2, 5).  
185 Shifts between pollination niches are an important factor driving diversification in angiosperms  
186 (35), including Brassicaceae (36, 37). We investigated whether the plasticity-mediated jump of *M.*  
187 *arvensis* across the floral morphospace implicated the exploration of new pollination niches. We  
188 compiled a comprehensive database comprising 456,031 visits done by over 800 animal species  
189 from 19 taxonomical orders, 276 families and 43 functional groups to 554 Brassicaceae species  
190 of 39 tribes (Methods, Supplementary Data 3). Afterwards, we identified the pollination niches of  
191 these Brassicaceae plants and determined the niche of each *M. arvensis* floral phenotype by  
192 means of bipartite modularity, a complex network tool that identifies the set of plants interacting  
193 with similar groups of pollinators (18). This analysis showed that the network was significantly  
194 modular (*Modularity* = 0.385,  $P < 0.0001$ ) and identified eight different pollination niches  
195 associated with different groups of pollinators (Figure 3a) located in different regions of the  
196 morphospace (Figure 3b,  $F = 44.4$ ,  $P < 0.001$ ,  $R^2 = 0.39$ , Adonis test; Table S4).

197

198 Because different insects visited *M. arvensis* in spring and summer (Table S5), this plant species  
199 shifted between pollination niches seasonally (Figure 3b). During spring, *M. arvensis* belonged to  
200 a niche where most frequent pollinators were long-tongued bees, beeflies, and hawkmoths  
201 (pollination niche 5 in Figure 3a) (18). This pollination niche was also shared by the other  
202 *Moricandia* species (Figure 3c). In contrast, during summer *M. arvensis* belonged to a niche  
203 dominated by short-tongued bees (pollination niche 3 in Figure 3a). This niche shift was  
204 substantial. In fact, the overlap between the spring and summer pollinator niches of *M. arvensis*  
205 (*Czekanowski* overlap index = 0.35) was significantly lower than the overlap between congeneric  
206 species of Brassicaceae ( $0.57 \pm 0.42$ , *Z*-score = -0.51,  $P = 0.003$ ). This shift even entailed the  
207 divergence from the ancestral niche of the *Moricandia* lineage (pollination niche 5 according to a  
208 stochastic character mapping inference, Figure 3c). The within-individual floral plasticity allows *M.*  
209 *arvensis* to exploit a pollination niche that differs markedly from that exploited by its closest  
210 relatives and that have largely diverged from the ancestral niche.

211

### 212 **Plasticity-mediated floral convergence**

213 A common consequence of adaptation to the same niche is convergent evolution (1, 2, 4). We  
214 explored the possibility of convergent evolution of *M. arvensis* with other Brassicaceae sharing  
215 either the spring niche (pollination niche 5) or the summer niche (pollination niche 3). We first  
216 checked for the occurrence of convergence among species belonging to these pollination niches.  
217 Because these analyses are extremely sensitive to the inferred branch lengths, we explored

218 morphological convergence using three time-calibrated large (> 150 spp) phylogenies that  
219 included *M. arvensis* (Methods). We tested for the occurrence of floral convergence between the  
220 species belonging to each of those two pollination niches using three methods: the angle formed  
221 by the phenotypic vectors connecting the position in the floral morphospace of each pair of  
222 species with that of their most recent common ancestor (38), the difference in phenotypic  
223 distances between convergent species and the maximum distances between all other lineages  
224 (39), and the phenotypic similarity of the allegedly convergent species penalized by their  
225 phylogenetic distance (*Wheatsheaf* index) (40). The three methods gave similar results, indicating  
226 that floral convergence was frequent among the species belonging to any of the two studied  
227 niches, irrespective of the method and the time-calibrated tree used (Table S6). These results  
228 show that, despite the rampant generalization observed in the pollination system of Brassicaceae,  
229 species interacting with similar pollinators converge phenotypically.

230

231 Once we determined the occurrence of convergence in these two pollination niches, we assessed  
232 whether plasticity caused the evolution of morphological convergence in *M. arvensis*. To do so,  
233 we first assessed the convergence region of *Moricandia*, the region that includes the lineages  
234 converging morphologically to the *Moricandia* lineage. We found that this region included most  
235 species of *Moricandia*, the spring phenotype of *M. arvensis*, and several clades belonging to  
236 disparate tribes that interact with pollination niche 5, but excluded the summer phenotype of *M.*  
237 *arvensis* (Figure 4, Table S7). Afterwards, we checked whether any of the two *M. arvensis* floral  
238 phenotypes entered the region of the phylomorphospace defined by their pollination niches. We  
239 used the C5 index, defined as the number of lineages that cross into the morphospace region of  
240 interest from outside<sup>39</sup>. This index detected between two and six convergent events towards  
241 pollination niche 5 depending on the phylogeny used (blue arrows in Figure 4a-c), but none was  
242 associated with the spring phenotype of *M. arvensis*. In contrast, the C5 index consistently  
243 detected that the summer phenotype of *M. arvensis* has converged with the species belonging to  
244 the pollination niche 3 (red arrow in Figure 4d-f). Altogether, these analyses suggest that,  
245 whereas the spring phenotype did not show any evidence of convergence, the summer  
246 phenotype of *M. arvensis* has converged with other distant Brassicaceae exploiting the same  
247 pollination niche.

248

249

## 250 **Conclusions**

251

252 Convergent selection exerted by efficient pollinators causes the evolution of similar suites of floral  
253 traits in different plant species (41–44). Our study shows that plasticity can promote the rapid



254 convergent evolution of floral traits, providing an additional explanation about how pollination  
255 syndromes may evolve. Under this idea, changes in floral traits precede shifts in pollinators, as  
256 frequently observed in generalist systems (37, 45). This may explain why many pollination  
257 systems are evolutionarily labile, undergoing frequent shifts and evolve multiple times within the  
258 same lineages by diverse evolutionary pathways (35, 46).

259

260 Morphological convergence is universally acknowledged to be the result of several genetic  
261 mechanisms, such as independent mutations in different populations or species, polymorphic  
262 genes or introgression (13). We provide in this study compelling evidence suggesting that  
263 morphological convergence may also arise as a consequence of phenotypic plasticity. The role of  
264 plasticity as a mechanism favouring quick responses of organisms to novel and rapidly changing  
265 environments is already beyond doubt (17, 21, 47, 48). Its evolutionary consequences are more  
266 debated though (20, 21, 49, 50). The 'plasticity-led evolution' hypothesis states that selection  
267 acting on a plastic lineage may either boost its environmental sensitivity and trigger the origin of  
268 polyphenisms or alternatively may promote the loss of plasticity and the canalization of the new  
269 phenotype through genetic assimilation (21, 49). The related 'flexible stem' hypothesis of adaptive  
270 radiation suggests that when a plastic lineage repeatedly colonizes similar niches, the multiple  
271 phenotypes fixed by genetic assimilation could converge among them giving rise to a collection of  
272 phylogenetically related convergent morphs (16, 50, 51). Our comprehensive study complements  
273 these hypotheses by suggesting that plasticity-mediated convergence may even evolve without  
274 the existence of basal flexible lineages. Rather, it can occur when plasticity evolving in otherwise  
275 non-plastic lineages promotes the colonization of a niche previously occupied by unrelated  
276 species. Under these circumstances, contrary to what it is predicted by the previous hypotheses,  
277 plasticity-mediated convergence is not circumscribed to phylogenetic-related species arising from  
278 a common stem lineage. This overlooked role of phenotypic plasticity may contribute to explain  
279 the ubiquity of morphological convergence in nature.

280

281

## 282 **Materials and Methods**

283

284 **Floral traits.** We recorded from the literature 31 floral traits in 3140 Brassicaceae plant species  
285 belonging to 330 genera and 51 tribes (Supplementary Data 1). All these traits have been proven  
286 to be important for the interaction with pollinators (Table S8). These traits were: (1) Plant height;  
287 (2) Flower display size; (3) Inflorescence architecture; (4) Presence of apetalous flowers; (5)  
288 Number of symmetry axes of the corolla; (6) Orientation of dominant symmetry axis of the corolla;  
289 (7) Corolla with overlapped petals; (8) Corolla with multilobed petals; (9) Corolla with visible

290 sepals; (10) Petal length; (11) Sepal length; (12) Asymmetric petals; (13) Petal limb length; (14)  
291 Length of long stamens; (15) Length of short stamens; (16) Stamen dimorphism; (17)  
292 Tetrodynamous condition; (18) Visible anthers; (19) Exserted stamens; (20) Number of stamens;  
293 (21) Concealed nectaries; (22) Petal carotenoids; (23) Petal anthocyanins; (24) Presence of  
294 bullseyes; (25) Presence of veins in the petals; (26) Coloured sepals; (27) Relative attractiveness  
295 of petals versus sepals; (28) Petal hue; (29) Petal colour as b CIELAB; (30) Sepal hue; (31) Sepal  
296 colour as b CIELAB. A detailed definition and description of these traits and their states is  
297 provided in Key Resource Table 1, whereas the original references used to determine the states  
298 of each trait per plant species is provided in Supplementary Data 1.

299

300 **Family-wide floral morphospace.** Using the original multidimensional trait-species matrix, we  
301 built a floral morphospace. For this, we reduced the high-dimensional matrix of floral traits to a  
302 two-dimensional space using an ordination technique (25). Because the set of floral traits  
303 included in this study were quantitative, semi-quantitative and qualitative, we used ordination  
304 techniques based on dissimilarity values. For this, we first constructed a pairwise square distance  
305 matrix of length equal to the number of Brassicaceae species included in the analysis ( $n = 3140$ ).  
306 We used the Gower distance, the number of mismatched traits over the number of shared traits.  
307 This dissimilarity index is preferable to the raw Euclidean distance when there are discrete and  
308 continuous traits co-occurring in the same dataset (52).

309 We reduced the dimensionality of this phenotypic matrix by projecting it in a two-dimensional  
310 space. For this, to ensure an accurate description of the distribution of the species in the  
311 morphospace, we first run a principal coordinate analysis (PCoA), a technique providing a  
312 Euclidean representation of a set of objects whose relationship is measured by any dissimilarity  
313 index. We corrected for negative eigenvalues using the Cailliez procedure (25). Afterwards, we  
314 used this metric configuration as the initial configuration to run a non-metric multidimensional  
315 scaling (NMDS) algorithm (25), a method that will further optimise the sample distribution so as  
316 more variation in species composition is represented by fewer ordination axes. Unlike methods  
317 that attempt to maximise the variance or correspondence between objects in an ordination,  
318 NMDS attempts to represent, as closely as possible, the pairwise dissimilarity between objects in  
319 a low-dimensional space. NMDS is a rank-based approach, where the original distance data is  
320 substituted with ranks, preserving the ordering relationships among species (25). Objects that are  
321 ordinated closer to one another are likely to be more similar than those further apart (53). This  
322 method is more robust than distance-based methods when the original matrix includes variables  
323 of contrasting nature. However, NMDS is an iterative algorithm that can fail to find the optimal  
324 solution. We decreased the potential effect of falling in local optima by running the analysis with  
325 5000 random starts and iterating each run  $1 \times 10^6$  times (54). The NMDS was run using a

326 monotone regression minimizing the Kruskal's stress-1 (55, 56), and compared each solution  
327 using Procrustes analysis, retaining that with the lowest residual. Because many species did not  
328 share trait states, a condition complicating ordination, we used *stepacross* dissimilarities, a  
329 function that replaces dissimilarities with shortest paths stepping across intermediate sites while  
330 regarding dissimilarities above a threshold as missing data (57). Furthermore, we used weak tie  
331 treatment, allowing equal observed dissimilarities to have different fitted values. The scores of the  
332 species in the final ordination configuration were obtained using weighted averaging. We checked  
333 if the reduction in dimensionality maintained the between-species relationship by checking the  
334 stress of the resulting ordination and finding goodness of fit measure for points in nonmetric  
335 multidimensional scaling (54). Both PCoA and NMDS ordinations were done using the R package  
336 *vegan* (58) and *ecodist* (59). It is important to note that, although the transfer function from  
337 observed dissimilarities to ordination distances is non-metric, the resulting NMDS configuration is  
338 Euclidean and rotation-invariant (60).

339

340 **Morphological Disparity.** Because we were interested in describing the position of the species  
341 in the floral morphospace, we calculated the morphological disparity using indices related to the  
342 distance between elements (26, 61). We first determined the absolute position of each of the  
343 Brassicaceae species in the morphospace by calculated their Euclidean distance with the overall  
344 centroid of the morphospace (61). The disparity between the spring and summer phenotype of *M.*  
345 *arvensis* was also calculated as their Euclidean distance in the floral morphospace. We then  
346 calculated the pairwise disparities between all species included in our analysis, between the  
347 different morphs of the polymorphic species considered here (Supplementary Data 2), between  
348 the species of the genus *Moricandia*, between species of the same genus, between species of  
349 different genera but same tribe and between species of different tribes. These disparity values  
350 were calculated using the function *dispRity* of the R package *dispRity* using the command  
351 *centroid* (62). We checked whether the disparity between spring and summer *M. arvensis*  
352 phenotypes was significantly different from the disparities of each of these sets of species using  
353 Z-score tests.

354

355 **Family-wide phylogeny.** We retrieved 80 phylogenetic trees from the literature and from the  
356 online repositories TreeBase (Table S9). All trees were downloaded in nexus format. The  
357 taxonomy of the species included in each tree was checked and updated using the species  
358 checklist with accepted names provided by Brassibase (<https://brassibase.cos.uni-heidelberg.de/>)  
359 (7, 23, 63). All trees were converted to TreeMan format (64) and concatenated into a single  
360 TreeMen file that was then converted into a multiPhylo class. Afterward, we estimated a  
361 supertree from this set of trees. Because trees did not share the same taxa, we used the Matrix

362 representation parsimony method (65). To make this supertree more accurate, it was re-  
363 constructed using as backbone phylogeny the tree provided by Walden et al. (7). We removed  
364 from the supertree those species without information on floral phenotype, resulting in a tree with  
365 1876 taxa. Because the original trees used to assemble this supertree were very  
366 heterogeneous, this supertree was not dated. We finally rooted the supertree using several  
367 species belonging to the sister families Capparaceae and Cleomaceae (66). All phylogenetic  
368 manipulations were performed using the R libraries *treebase* (67), *ape* (68), *treeman* (64),  
369 *phangorn* (69) and *phytools* (70).

370 We tested whether the position of the Brassicaceae species in the morphospace was  
371 associated with the phylogenetic relationship by assessing the phylogenetic signal of the  
372 morphospace position. This analysis was performed by means of a multivariate Mantel test, using  
373 the pairwise disparity (the Euclidean distance between species in the family-wide morphospace)  
374 as a morphological distance and the patristic distances between pairs of tips of the supertree as  
375 the phylogenetic distance (71). The correlation method used was Pearson and the statistical  
376 significance was found after bootstrapping 999 times the analysis (25). The test was done using  
377 the R libraries *vegan* (58) and *ecodist* (59).

378

379 **Family-wide phylomorphospace.** We reconstructed a family-wide phylomorphospace by  
380 projecting the phylogenetic relationships provided by the supertree into the floral morphospace.  
381 The ancestral character estimation of morphospace coordinate values for each internal tree node  
382 was done using maximum likelihood. For this, we used the function *fastAnc* in *phytools*. This  
383 function performs fast estimations of the ML ancestral states for continuous traits by re-rooting  
384 the tree at all internal nodes and computing the contrasts state at the root each time (70).

385 We counted the number of intersections between lineages as a measurement of the  
386 disorder of the phylomorphospace and evidence of the mode of evolution of the phenotypes (11).  
387 For this, we used R codes provided in Ref 11. We compared the observed number of crossings  
388 with those expected under several modes of evolution. For this, we counted the number of  
389 intersections in 10 simulated sets of species with floral phenotypes following Brownian Motion,  
390 Ornstein Uhlenbeck and Early Burst modes of evolution. All simulations were done using as  
391 backbone tree the family-wide supertree and considering 1875 species, and by means of the  
392 command *mvSIM* in *mvMORPH* (72).

393

394 **Morphological divergence of the plastic phenotypes.** Divergence in floral phenotype was  
395 estimated by calculating the disparity of *Moricandia arvensis* and the rest of Brassicaceae  
396 species from their ancestors. We first determined the floral phenotype of the Most Recent  
397 Common Ancestor (MRCA) using the projection of a recent time-calibrated phylogeny made for

398 the genus *Moricandia* (73) into the above-described phylomorphospace. We used this phylogeny  
399 because it is the only one including all the species of the genus. Once we inferred the coordinates  
400 of the MRCA in the morphospace, we calculated the disparity of all the *Moricandia* species and  
401 the two plastic phenotypes of *M. arvensis* to it. Afterwards, we calculated the divergence of the  
402 two plastic phenotypes from the direct ancestor of *M. arvensis*. This analysis was done for the  
403 family-wide supertree and for any of the four time-calibrated phylogenies included in our dataset  
404 that had *Moricandia* species (73-76). In addition, we calculated the divergence from the direct  
405 ancestors of the rest of Brassicaceae species included in these four phylogenies and in the rest  
406 of the time-calibrated trees included in our dataset (Table S9). All floral divergences were  
407 calculated using the command *ancestral.dist* of the function *dispRity* in the R package *dispRity*  
408 (62).

409

410 **Pollinator Database.** We have compiled a massive database including 21,212 records  
411 comprising 455,014 visits done by over 800 animal species from 19 taxonomical orders, 276  
412 families and 43 functional groups to 554 Brassicaceae species belonging to 39 tribes  
413 (Supplementary Data 3). Information is coming from literature, personal observation, online  
414 repositories and personal communication of several colleagues. The source of information is  
415 indicated in the database (Supplementary Data 3, Table S10). In those species studied by us  
416 (coded as UNIGEN data origin in the Supplementary Data 3), we conducted flower visitor counts  
417 in 1-16 populations per plant species. We visited the populations during the blooming peak,  
418 always at the same phenological stage and between 11:00 am and 5:00 pm. In these visits, we  
419 recorded the insects visiting the flowers for two hours without differentiating between individual  
420 plants. Insects were identified in the field, and some specimens were captured for further  
421 identification in the laboratory. We only recorded those insects contacting anthers or stigma and  
422 doing legitimate visits at least during part of their foraging at flowers. We did not record those  
423 insects only eating petals or thieving nectar without doing any legitimate visit. The information  
424 obtained from the literature and online repositories (coded as LITERATURE data origin in the  
425 Supplementary Data 3) includes records done during ecological studies, taxonomical studies and  
426 naturalistic studies. The reference of every record is included in the dataset. The plant species  
427 included in our network do not coexist, implying that this is a clade-oriented network rather than  
428 an ecological network (77).

429

430 **Spatial distribution of pollinator groups.** We tested the autocorrelation across the  
431 morphospace in the abundance of the functional groups using a multivariate Mantel test. The  
432 correlation method used was Pearson, and the statistical significance was found after  
433 bootstrapping 999 times the analysis (25). The test was done using the R libraries *vegan* (58).

434

435 **Pollination niches.** In plant species interacting with a diverse assemblage of pollinators, like  
436 those included in this study, many pollinator species interact with the flowers in a similar manner,  
437 have similar effectiveness and exert similar selective pressures and are thus indistinguishable for  
438 the plant (46, 78). These pollinators are thus grouped into functional groups, which are the  
439 relevant interaction units in generalised systems (46, 78, 79). We thereby grouped all pollinators  
440 visiting the Brassicaceae species using criteria of similarity in body length, proboscis length,  
441 morphological match with the flower, foraging behaviour, and feeding habits (46, 78, 79). Table  
442 S11 describes the 43 functional groups used in this study. Supplementary Data 4 shows the  
443 species with an autogamous pollination system.

444

445 We determined the occurrence of different pollination niches in our studied populations and  
446 seasons using bipartite modularity, a complex-network metric. Modularity has proven to be a  
447 good proxy of interaction niches both in ecological networks, those included coexisting species or  
448 population, as well as in clade-oriented network, those including species with information coming  
449 from disparate and contrasting sources (77). We constructed a weighted bipartite network,  
450 including pollinator data of four populations during the spring and summer flowering. In this  
451 network, we pooled the data from the different individuals in a population and did not consider the  
452 time difference involved in sampling across different species. We removed all plant species with  
453 less than 20 visits. We subsequently determined the modularity level in this weighted bipartite  
454 network by using the QuanBiMo algorithm (80). This method uses a Simulated Annealing Monte-  
455 Carlo approach to find the best division of populations into modules. A maximum of  $10^{10}$  MCMC  
456 steps with a tolerance level =  $10^{-10}$  was used in 100 iterations, retaining the iterations with the  
457 highest likelihood value as the optimal modular configuration. We tested whether our network was  
458 significantly more modular than random networks by running the same algorithm in 100 random  
459 networks, with the same linkage density as the empirical one (81). Modularity significance was  
460 tested for each iteration by comparing the empirical versus the random modularity indices using a  
461 Z-score test (80). After testing the modularity of our network, we determined the number of  
462 modules (82). We subsequently identified the pollinator functional groups defining each module  
463 and the plant species ascribed to each module. Modularity analysis was performed using the R  
464 package *bipartite* 2.0 (83). We quantified the niche overlap between all pair of Brassicaceae  
465 species using the Czekanowski index of resource utilization, an index that measures the area of  
466 intersection of the resource utilization histograms of each species pair (84). This index was  
467 calculated using the function *niche.overlap* in the R package *spaa* (85).

468

469 **Estimation of ancestral values of pollination niches.** The ancestral states of the pollination  
470 niche was inferred for the *Moricandia* lineage by simulate stochastic character mapping of  
471 discrete traits with Bayesian posterior probability distribution (86, 87). Three models of character  
472 evolution ("ER" - Equal Rates; "SYM" – symmetric; and "ARD" - All Rates Different) were first  
473 evaluated using the *fitDiscrete* function of the R package *Geiger* (88). The best model was  
474 selected using the Akaike Information Criterion (AIC) and used for stochastic character mapping.  
475 The posterior distribution of the transition rate matrix was determined using a Markov chain  
476 Monte Carlo (MCMC) simulation, and the stochastic mapping was simulated 100 times.  
477 Stochastic character mapping was performed using the *make.simmap* function and a plot of  
478 posterior probabilities were mapped using the *describe.simmap* function in R package '*phytools*  
479 (70).

480

481 **Morphological convergence.** To explore morphological convergence, we reconstructed the  
482 ancestral states of the species belonging to these two pollination niches and tested for each niche  
483 whether the species were morphologically more similar to each other than expected by their  
484 phylogenetic relationship (39, 40). We used three different approaches to detect morphological  
485 convergence, one based on comparing phenotypic and phylogenetic distances (39) and the other  
486 based on comparing the angles formed by two tested clades from their most recent common  
487 ancestor with the expected angle according to null evolutionary models (38). Because all these  
488 analyses are sensitive to the number of tips in the phylogeny and the inferred branch lengths, we  
489 tested for the occurrence of morphological convergence using three independent, time-calibrated  
490 phylogenies including more than 45 species (74-76).

491 Under the first approach, we calculated both distance- and frequency-based measures of  
492 convergence (39). Distance-based measures (C1–C4) are calculated between two lineages  
493 relative to their distance at the point in evolutionary history where the two lineages were  
494 maximally dissimilar. C1 specifically measures the proportion of phenotypic distance closed by  
495 evolution, ranging from 0 to 1 (where 1 indicates complete convergence). To calculate C1,  
496 ancestral states are reconstructed (via a Brownian motion model of evolution) for two or more  
497 putatively convergent lineages, back to their most recent common ancestor. The maximum  
498 phenotypic distance between any pair of ancestors ( $D_{max}$ ) is calculated, and compared with the  
499 phenotypic distance between the current putatively convergent taxa ( $D_{tip}$ ). The greater the  
500 difference between  $D_{max}$  and  $D_{tip}$ , the higher the index. C2 is the raw value of the difference  
501 between the maximum and extant distance between the two lineages. C3 is C2 scaled by the  
502 total evolution (sum of squared ancestor-to-descendant changes) between the two lineages. C4  
503 is C2 scaled by the total evolution in the whole clade. These four measures quantify incomplete  
504 convergence in multidimensional space. Finally, C5, the frequency-based measure, quantifies

505 and reports the number of convergent events where lineages evolve into a specific region of  
506 morphospace (crossing it from outside). C5 sums the number of times through the evolution of a  
507 clade that lineages evolve into a given region of phenotypic space. C5 is the number of focal taxa  
508 that reside within a limited but convergent region of a phylomorphospace (the phylogenetic  
509 connections between taxa represented graphically in a plot of morphological space). The  
510 significance of C1–C5 was found by running 1000 simulations for each comparison using  
511 Brownian-Motion on a variance–covariance matrix based on data-derived parameters, with  
512 convergence measures for each simulation calculated to determine if the observed C value is  
513 greater than expected by chance. A priori focal groups forming the basis of convergence tests  
514 were the same niche categorizations used in OUwie analyses. These analyses were performed  
515 using the R package *convevol* (89).

516 The second approach to measure convergence was based on comparing the angles  
517 formed by two tested clades from their most recent common ancestor with the expected angle  
518 according to null evolutionary models (38). Under the “state case”, *search.conv* computes the  
519 mean angle over all possible combinations of species pairs using one species per state. Each  
520 individual angle is divided by the patristic distance between the species. Significance is assessed  
521 by contrasting this value with a family of 1,000 random angles obtained by shuffling the state  
522 across the species (38). These analyses were performed using the R package *RRphylo* (90).

523 The third approach to measure convergence used the Wheatleaf metric (40). This index  
524 generates phenotypic (Euclidean) distances from any number of traits across species and  
525 penalizes them by phylogenetic distance before investigating similarity (in order to weight close  
526 phenotypic similarity higher for distantly related species). It uses an a priori designation of  
527 convergent species, which are defined as species belonging to a niche for which the traits are  
528 hypothesized to converge. The method then calculates a ratio of the mean (penalized) distances  
529 between all species to the mean (penalized) distances between allegedly convergent species.  
530 The index detects if convergent species diverge more in phenotypic space from the non-  
531 convergent species and show a tighter clustering to each other (40). The significance of this index  
532 was found by comparing the empirical values of the index with a distribution of simulated indices  
533 obtained running 5000 bootstrap simulations. These analyses were performed using the R  
534 package *windex* (91).

535

536

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548

#### 549 **Competing interests**

550 The authors declare no competing interests.

551

552

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782 **Figures**



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784 **Figure 1. Plasticity-mediated floral disparity.** (A) Floral morphospace of the Brassicaceae,  
 785 showed as the projection of 31 traits recorded in 3140 species onto two NMDS axes. The position  
 786 of the spring and summer phenotypes of *Moricandia arvensis* is linked by a thick lilac dashed line.  
 787 We have also indicated the movements across this morphospace of several species changing  
 788 their phenotypes due to floral colour polymorphism (black lines), single mutations in floral colour  
 789 (blue lines), changes in breeding systems (orange lines), changes in gender expression (green  
 790 lines), homeotic mutations (brown lines), and plasticity (lilac lines). Numbers matching species  
 791 are as follow: 1-*Lobularia maritima*; 2-*Raphanus raphanistrum*; 3-*Matthiola incana*; 4-*Matthiola*  
 792 *fruticulosa*; 5-*Erysimum cheiri*; 6-*Cakile maritima*; 7-*Matthiola lunata*; 8- *Marcus-kochia littorea*; 9-  
 793 *Hesperis matronalis*; 10- *Hesperis laciniata*; 11-*Parrya nudicalis*; 12-*Streptanthus glandulosus*;  
 794 13- *Eruca vesicaria*; 14- *Capsella bursa-pastoris*; 15-*Hormathophylla spinosa*; 16- *Brassica*  
 795 *napus*; 17- *Cardamine hirsuta*; 18- *Lepidium sisymbrioides*; 19-*Lepidium solandri*; 20-*Arabidopsis*  
 796 *thaliana*; 21-*Boechera stricta*; 22-*Leavenworthia stylosa*; 23-*Leavenworthia crassa*; 24-  
 797 *Pachycladon stellatum*; 25- *Pachycladon wallii*; 26-*Cardamine kokairensis*; 27-*Brassica rapa*. (B)  
 798 Shepard plot showing the goodness of fit of the NMDS ordination. (C) *Moricandia arvensis* in  
 799 spring. (D) *Moricandia arvensis* in summer. (E) Magnitude of floral disparity between different  
 800 taxonomic levels of Brassicaceae species. The number above each boxplot shows the number of  
 801 disparities per level. We have compared this value with the disparity between spring and summer

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802 phenotypes of *M. arvensis* (this comparison with boxplots in red is statistically significant at  $P <$   
803 0.05, in orange is marginally significant at  $P < 0.1$ , and in grey is non-significant).  
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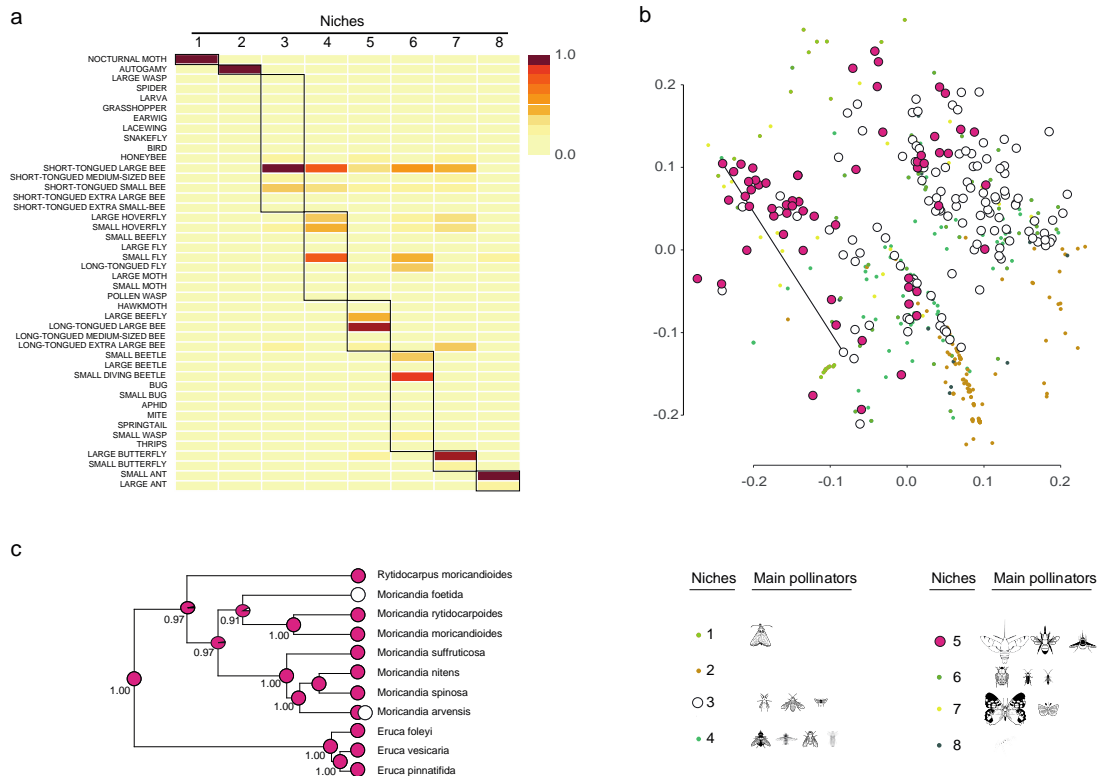
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808 **Figure 2. Phylogenetic-mediated floral divergence.** (A) Floral phylomorphospace using the  
 809 supertree that includes 1876 Brassicaceae species. (B) Phylomorphospace considering only the  
 810 eight *Moricandia* species, using the Perfectti et al.'s phylogeny (phylogeny # 1 in Table S8). (C)  
 811 Floral disparity to the nearest ancestor, according to the supertree and 18 time-calibrated  
 812 phylogenies (phylogeny codes in Table S8). We show the disparity between the two *M. arvensis*  
 813 phenotypes and their direct ancestor (spring: lilac dots; summer: white dots) in those phylogenies

814 that include *Moricandia*. We also show the disparities to their direct ancestors of those  
815 Brassicaceae species included in time-calibrated phylogenies of more than 45 species.  
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820 **Figure 3. Plasticity-mediated changes in pollination niches.** (A) Outcome of the modularity  
821 analysis showing the number of pollination niches inferred, the among-niche differences in  
822 relative frequency of each pollinator functional group, and the pollinator functional groups defining  
823 the niches ( $n = 511$  Brassicaceae species). (B) Morphospatial distribution of the eight pollination  
824 niches detected in Brassicaceae. Insect silhouettes were drawn by Divulgare ([www.divulgare.net](http://www.divulgare.net))  
825 under a Creative Commons license (<http://creativecommons.org/licenses/by-nc-sa/3.0>). (C)  
826 Estimate of the ancestral pollination niche of the *Moricandia* lineage using a stochastic character  
827 mapping inference analysis. The numbers underneath each ancestral node indicate the posterior  
828 Bayesian probability of belonging to pollination niche 5.

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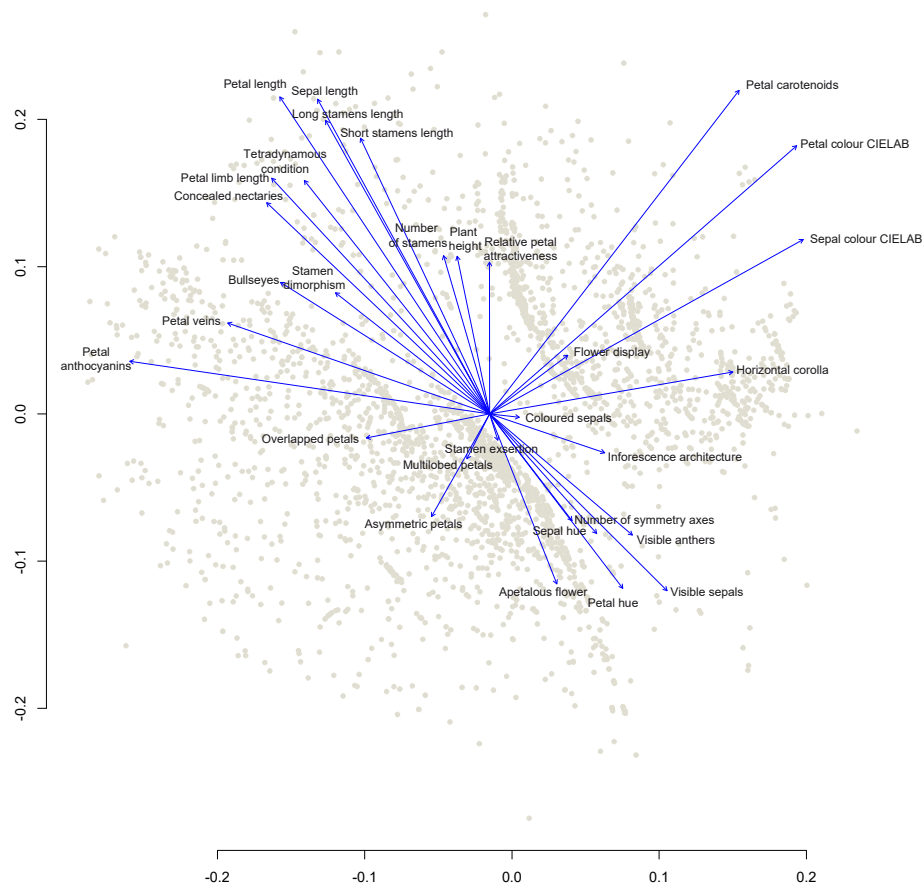
833 **Figure 4. Plasticity-mediated floral convergence.** Convergent lineages crossing into the region  
834 of the morphospace delimited by the pollination niche of the *M. arvensis* during spring (the shade  
835 convex hull) according to (A) Smith & Brown's phylogeny, (B) Gaynor et al.'s phylogeny, and (C)  
836 Huang et al.'s phylogeny (phylogenies 2-4, respectively, in Table S8). Convergent lineages  
837 crossing into the region of the morphospace delimited by the pollination niche of the *M. arvensis*  
838 during summer (the shade convex hull) according to (D) Smith & Brown's phylogeny, (E) Gaynor  
839 et al.'s phylogeny, and (F) Huang et al.'s phylogeny. Red arrows indicate the plasticity-mediated  
840 convergence, blue arrows the convergence events of the other lineages. The small purple area in  
841 all panels is the region of the floral morphospace that includes the lineages that have converged  
842 with the entire *Moricandia* clade according to each time-calibrated phylogeny.

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## SI FIGURES

**Figure S1.** Association among the 31 pollination traits of 3140 Brassicaceae species. Trait vectors represent the Spearman correlations, with the length and direction indicating the relationship with composite NMDS axes.



## SI TABLES

**Table S1.** Fitting of the floral traits onto the NMDS vectors.

|    | <b>Floral traits</b>                                 | <b>NMDS1</b> | <b>NMDS2</b> | <b>r<sup>2</sup></b> | <b>P value</b> |
|----|--|--------------|--------------|----------------------|----------------|
| 1  | Plant height   | -0.20147     | 0.97949      | 0.1126               | 0.001          |
| 2  | Flower display size                                  | 0.80044      | 0.59942      | 0.0415               | 0.001          |
| 3  | Inflorescence architecture                           | 0.94742      | -0.32001     | 0.0641               | 0.001          |
| 4  | Presence of apetalous flowers                        | 0.36770      | -0.92994     | 0.1452               | 0.001          |
| 5  | Number of symmetry axes of the corolla               | 0.66735      | -0.74474     | 0.1121               | 0.001          |
| 6  | Orientation of dominant symmetry axis of the corolla | 0.98547      | 0.16987      | 0.2650               | 0.001          |
| 7  | Corolla with overlapped petals                       | -0.98142     | -0.19188     | 0.0685               | 0.001          |
| 8  | Corolla with multilobed petals                       | -0.45075     | -0.89265     | 0.0110               | 0.001          |
| 9  | Corolla with visible sepals                          | 0.70871      | -0.7055      | 0.2729               | 0.001          |
| 10 | Petal length   | -0.55200     | 0.83385      | 0.6287               | 0.001          |
| 11 | Sepal length   | -0.47963     | 0.87747      | 0.5594               | 0.001          |
| 12 | Asymmetric petals                                    | -0.49289     | -0.87009     | 0.0604               | 0.001          |
| 13 | Petal limb length                                    | -0.67904     | 0.73410      | 0.4482               | 0.001          |
| 14 | Length of long stamen                                | -0.48773     | 0.87300      | 0.4915               | 0.001          |
| 15 | Length of short stamen                               | -0.42415     | 0.90559      | 0.4029               | 0.001          |
| 16 | Herkogamy  | -0.78612     | 0.61808      | 0.1671               | 0.001          |
| 17 | Herkogamy category                                   | -0.62172     | 0.78324      | 0.3864               | 0.001          |
| 18 | Visible anthers                                      | 0.76256      | -0.64691     | 0.1526               | 0.001          |
| 19 | Exserted stamens                                     | 0.29511      | -0.95546     | 0.0033               | 0.009          |
| 20 | Number of stamens                                    | -0.28006     | 0.95998      | 0.1182               | 0.001          |
| 21 | Concealed nectaries                                  | -0.72601     | 0.68768      | 0.4101               | 0.001          |
| 22 | Petal carotenoids                                    | 0.61077      | 0.7918       | 0.7264               | 0.001          |
| 23 | Petal anthocyanins                                   | -0.98947     | 0.14476      | 0.5757               | 0.001          |
| 24 | Presence of bullseyes                                | -0.84653     | 0.53235      | 0.2654               | 0.001          |
| 25 | Presence of veins in the petals                      | -0.94487     | 0.32746      | 0.3343               | 0.001          |
| 26 | Coloured sepal                                       | 0.99357      | -0.11318     | 0.0039               | 0.002          |
| 27 | Relative attractiveness of petals versus sepals      | -0.00049     | 0.99990      | 0.1001               | 0.001          |
| 28 | Petal hue  | 0.60720      | -0.79455     | 0.2096               | 0.001          |
| 29 | Petal colour as b CIELAB                             | 0.75326      | 0.65772      | 0.7232               | 0.001          |
| 30 | Sepal Hue  | 0.61109      | -0.79156     | 0.0791               | 0.001          |
| 31 | Sepal colour as b CIELAB                             | 0.87412      | 0.48571      | 0.5605               | 0.001          |

**Table S2.** Disparity, calculated as the Euclidean distance in the family-wide floral morphospace, between each of the 38 morphs included in our dataset (see Supplementary Data 2 for details and references) and their respective wild types.

| Type of polymorphism       | Species                         | Morph                            | NMDS        |
|----------------------------|---------------------------------|----------------------------------|-------------|
| Breeding system            | <i>Brassica napus</i>           | cleistogamous mutant             | 0.035856865 |
| Breeding system            | <i>Brassica rapa</i>            | female sterility mutant          | 0.133332180 |
| Breeding system            | <i>Cardamine kokairensis</i>    | cleistogamous mutant             | 0.111696867 |
| Breeding system            | <i>Leavenworthia crassa</i>     | Outcrosser morph                 | 0.015771684 |
| Colour mutant              | <i>Brassica napus</i>           | white mutant                     | 0.173001555 |
| Colour mutant              | <i>Moricandia arvensis</i>      | white mutant                     | 0.149565069 |
| Flower colour polymorphism | <i>Boechea stricta</i>          | pink morph                       | 0.060580070 |
| Flower colour polymorphism | <i>Boechea stricta</i>          | purple morph                     | 0.054429426 |
| Flower colour polymorphism | <i>Cakile maritima</i>          | white morph                      | 0.016547552 |
| Flower colour polymorphism | <i>Eruca vesicaria</i>          | white morph                      | 0.082257145 |
| Flower colour polymorphism | <i>Erysimum cheiri</i>          | purple cultivar                  | 0.073997237 |
| Flower colour polymorphism | <i>Erysimum cheiri</i>          | white cultivar                   | 0.026460490 |
| Flower colour polymorphism | <i>Hesperis laciniata</i>       | white morph                      | 0.069557518 |
| Flower colour polymorphism | <i>Hesperis matronalis</i>      | white morph                      | 0.094873544 |
| Flower colour polymorphism | <i>Hormathophylla spinosa</i>   | white morph                      | 0.101607789 |
| Flower colour polymorphism | <i>Leavenworthia stylosa</i>    | white morph                      | 0.066269050 |
| Flower colour polymorphism | <i>Lobularia maritima</i>       | deep purple cultivar             | 0.090407642 |
| Flower colour polymorphism | <i>Marcus-kochia littorea</i>   | light pink morph                 | 0.019542946 |
| Flower colour polymorphism | <i>Matthiola fruticulosa</i>    | greenish morph                   | 0.008349920 |
| Flower colour polymorphism | <i>Matthiola incana</i>         | white cultivar                   | 0.138357728 |
| Flower colour polymorphism | <i>Matthiola lunata</i>         | white morph                      | 0.079964493 |
| Flower colour polymorphism | <i>Parrya nudicaulis</i>        | white morph                      | 0.115226060 |
| Flower colour polymorphism | <i>Raphanus raphanistrum</i>    | white morph                      | 0.082072459 |
| Flower colour polymorphism | <i>Raphanus raphanistrum</i>    | yellow morph                     | 0.032685632 |
| Flower colour polymorphism | <i>Raphanus raphanistrum</i>    | pink morph                       | 0.082778860 |
| Flower colour polymorphism | <i>Streptanthus glandulosus</i> | white morph                      | 0.014907493 |
| Gender dimorphism          | <i>Hormathophylla spinosa</i>   | female morph                     | 0.035783402 |
| Gender dimorphism          | <i>Hormathophylla spinosa</i>   | male morph                       | 0.025226337 |
| Gender dimorphism          | <i>Lepidium sisymbrioides</i>   | female morph                     | 0.067913758 |
| Gender dimorphism          | <i>Lepidium solandri</i>        | female morph                     | 0.065685257 |
| Gender dimorphism          | <i>Pachycladon stellatum</i>    | female morph                     | 0.014244744 |
| Gender dimorphism          | <i>Pachycladon wallii</i>       | male morph                       | 0.059320935 |
| Homeotic mutant            | <i>Arabidopsis thaliana</i>     | AGAMOUS mutant                   | 0.001052532 |
| Homeotic mutant            | <i>Arabidopsis thaliana</i>     | APETALA1 mutant                  | 0.119617731 |
| Homeotic mutant            | <i>Arabidopsis thaliana</i>     | APETALA3 mutant                  | 0.102445400 |
| Homeotic mutant            | <i>Capsella bursapastoris</i>   | Spe mutant                       | 0.051187659 |
| Phenotypic plasticity      | <i>Cardamine hirsuta</i>        | plastic change in stamens number | 0.010624208 |
| Phenotypic plasticity      | <i>Cardamine hirsuta</i>        | plastic change in petal number   | 0.060755859 |



**Table S3.** Floral disparity of each species of *Moricandia* from the most recent common ancestor (MRCA) of the genus and from the direct ancestor of each species.

| Species                                     | Disparity to MRCA | Disparity to direct ancestor |
|---|-------------------|------------------------------|
| <i>Moricandia foetida</i>                   | 0.039566021       | 0.13987379                   |
| <i>Moricandia moricandioides</i>            | 0.059142993       | 0.03730920                   |
| <i>Moricandia nitens</i>                    | 0.041727403       | 0.07347209                   |
| <i>Moricandia rytidocarpoides</i>           | 0.025809374       | 0.10503623                   |
| <i>Moricandia sinaica</i>                   | 0.027589330       | 0.10550411                   |
| <i>Moricandia spinosa</i>                   | 0.019579372       | 0.20959717                   |
| <i>Moricandia suffruticosa</i>              | 0.063884437       | 0.20700167                   |
| <i>Moricandia arvensis</i> spring phenotype | 0.080840848       | 0.02385532                   |
| <i>Moricandia arvensis</i> summer phenotype | 0.195061288       | 0.28741584                   |

**Table S4.** Significance of the Mantel tests checking for spatial autocorrelation across the morphospace of the pollinator functional groups. Due to the small abundance of some pollinators, the original 43 functional groups have been pooled in 26 main functional groups.

| <b>Functional Groups</b>       | <b>Mantel R</b> | <b>p value</b> |
|--------------------------------|-----------------|----------------|
| Ant                            | 0.047           | 0.055          |
| Autogamy                       | 0.257           | 0.001          |
| Bug                            | 0.032           | 0.192          |
| Butterfly                      | 0.089           | 0.001          |
| Hawkmoth                       | 0.054           | 0.035          |
| Hoverfly                       | 0.072           | 0.003          |
| Large beefly                   | 0.043           | 0.079          |
| Large beetle                   | 0.046           | 0.063          |
| Large fly                      | 0.052           | 0.044          |
| Large wasp                     | 0.053           | 0.048          |
| Long tongued fly               | 0.092           | 0.001          |
| Long tongued large bee         | 0.242           | 0.001          |
| Long tongued medium-sized bee  | 0.051           | 0.041          |
| Moth                           | 0.039           | 0.113          |
| Nocturnal moth                 | 0.222           | 0.001          |
| Other                          | 0.018           | 0.497          |
| Pollen wasp                    | 0.026           | 0.313          |
| Small beetle                   | 0.012           | 0.613          |
| Small diving beetle            | 0.003           | 0.899          |
| Small fly                      | 0.112           | 0.001          |
| Small wasp                     | 0.041           | 0.112          |
| Short tongued large bee        | 0.065           | 0.004          |
| Short tongued medium-sized bee | 0.012           | 0.590          |
| Short tongued small bee        | 0.073           | 0.001          |
| Short tongued extra small bee  | 0.020           | 0.454          |
| Thrips                         | -0.014          | 0.758          |

**Table S5.** Differences between the two *Moricandia arvensis* phenotypes in the visitation frequency (both in absolute number of insects and in proportion of visits) of every pollinator functional group. Fifteen censuses of 1 hr and two researchers per phenotype.

| <b>Pollinator functional group</b> | <b>spring phenotype</b> | <b>summer phenotype</b> | <b>spring phenotype (proportion)</b> | <b>summer phenotype (proportion)</b> |
|------------------------------------|-------------------------|-------------------------|--------------------------------------|--------------------------------------|
| Hawkmoth                           | 91                      | 0                       | 0.036                                | 0.000                                |
| Honeybee                           | 40                      | 0                       | 0.016                                | 0.000                                |
| Large beefly                       | 309                     | 72                      | 0.124                                | 0.148                                |
| Large beetle                       | 30                      | 40                      | 0.012                                | 0.082                                |
| Large butterfly                    | 280                     | 66                      | 0.112                                | 0.135                                |
| Large fly                          | 38                      | 0                       | 0.015                                | 0.000                                |
| Large hoverfly                     | 8                       | 7                       | 0.003                                | 0.014                                |
| Long tongued large bee             | 1131                    | 5                       | 0.453                                | 0.010                                |
| Long tongued medium-sized bee      | 226                     | 0                       | 0.090                                | 0.000                                |
| Small beefly                       | 6                       | 0                       | 0.002                                | 0.000                                |
| Small beetle                       | 21                      | 8                       | 0.008                                | 0.016                                |
| Small butterfly                    | 11                      | 0                       | 0.004                                | 0.000                                |
| Small diving beetle                | 25                      | 12                      | 0.010                                | 0.025                                |
| Small fly                          | 12                      | 0                       | 0.005                                | 0.000                                |
| Small hoverfly                     | 49                      | 37                      | 0.020                                | 0.076                                |
| Small moth                         | 2                       | 7                       | 0.001                                | 0.014                                |
| Short tongued large bee            | 89                      | 3                       | 0.036                                | 0.006                                |
| Short tongued medium-sized bee     | 36                      | 0                       | 0.014                                | 0.000                                |
| Short tongued small bee            | 78                      | 207                     | 0.031                                | 0.424                                |
| Short tongued extra small bee      | 1                       | 0                       | 0.000                                | 0.000                                |
| Thrips                             | 15                      | 24                      | 0.006                                | 0.049                                |

**Table S6.** Outcome of the analyses to test the occurrence of floral convergence among plants from niches 3 and 5. **Angle** is the mean theta angle between all species belonging to the same niche. **Angle/time** is the angle divided by time distance. The significance of these angles has been found by comparing with a null model consisting in shuffling each niche 1,000 times across the tree tips and calculating a distribution of random angle. **C1** measures the proportion of phenotypic distance closed by evolution, ranging from 0 to 1 (where 1 indicates complete convergence). **C2** is the raw value of the difference between the maximum and extant distance between the lineages. **C3** is C2 scaled by the total evolution (sum of squared ancestor-to-descendant changes) between the two lineages. **C4** is C2 scaled by the total evolution in the whole clade. The significance of C1-C2, was evaluated by running 1000 simulations for each comparison using Brownian-Motion models. **Wheatleaf** is the ratio of the mean (penalized) distances between all species to the mean (penalized) distances between allegedly convergent species. Significance found by running 2000 bootstrapping simulations. In bold, significant values.

| Phylogenies    | Smith & Brown 2018 |       | Gaynor et al. 2018 |       | Huang et al. 2019 |       |
|----------------|--------------------|-------|--------------------|-------|-------------------|-------|
|                | Value              | p     | Value              | p     | Value             | p     |
| <b>Niche 3</b> |                    |       |                    |       |                   |       |
| Angle          | <b>80.587</b>      | 0.008 | <b>79.431</b>      | 0.002 | <b>64.930</b>     | 0.055 |
| Angle/time     | 2.350              | 0.719 | 1.645              | 0.397 | 4.023             | 0.815 |
| C1             | <b>0.373</b>       | 0.000 | <b>0.472</b>       | 0.000 | <b>0.415</b>      | 0.000 |
| C2             | <b>0.104</b>       | 0.000 | <b>0.142</b>       | 0.000 | <b>0.104</b>      | 0.000 |
| C3             | <b>0.141</b>       | 0.000 | <b>0.166</b>       | 0.000 | <b>0.219</b>      | 0.000 |
| C4             | 0.003              | 0.720 | 0.002              | 0.700 | 0.008             | 0.600 |
| Wheatleaf      | 0.830              | 0.986 | 0.940              | 0.715 | <b>1.060</b>      | 0.028 |
| <b>Niche 5</b> |                    |       |                    |       |                   |       |
| Angle          | <b>70.093</b>      | 0.002 | <b>73.491</b>      | 0.002 | <b>58.313</b>     | 0.049 |
| Angle/time     | <b>1.393</b>       | 0.021 | 1.783              | 0.745 | <b>2.474</b>      | 0.011 |
| C1             | <b>0.356</b>       | 0.000 | <b>0.472</b>       | 0.000 | <b>0.240</b>      | 0.000 |
| C2             | <b>0.110</b>       | 0.000 | <b>0.142</b>       | 0.000 | <b>0.075</b>      | 0.000 |
| C3             | <b>0.128</b>       | 0.000 | <b>0.166</b>       | 0.000 | <b>0.118</b>      | 0.000 |
| C4             | 0.003              | 0.727 | 0.002              | 0.700 | 0.006             | 0.545 |
| Wheatleaf      | 1.120              | 0.673 | <b>1.170</b>       | 0.094 | 0.920             | 0.978 |

**Table S7.** Outcome of the analyses testing for morphological convergence between the *Moricandia* clade and the rest of clades included in each time-calibrated phylogeny. **Clade size** is the number of species within the *Moricandia* clade.  $\theta_{real}$  is the mean angle over all possible combinations of pairs of species taking one species per clade.  $\theta_{ace}$  is the mean angle between ancestral states between each pairs of clades.  $dist_{mrca}$  is the patristic distance (sum of branch length) between the most recent common ancestors of each pair of clade. We indicate the convergent clades and the pollination niches of each species included in the convergent clades. In red *Moricandia* clades including *Moricandia arvensis* spring phenotype. Tribes (E= Erysimeae, A= Anchioleae, C=Cardamineae, M=Malcolmieae, An=Anastaticae).

| Moricandia clade                     | Clade 2 | Clade size | $\theta_{real}$ | $\theta_{ace}$ | $dist_{mrca}$ | $\theta_{real}/dist_{mrca}$ | $\theta_{real}/dist_{mrca}$ p-value | $\theta_{ace}+\theta_{real}/dist_{mrca}$ | $\theta_{ace}+\theta_{real}/dist_{mrca}$ p-value | Convergent clades  | Tribe | Niche     |
|--------------------------------------|---------|------------|-----------------|----------------|---------------|-----------------------------|-------------------------------------|--|--|--|-------|-----------|
| <b>Smith &amp; Brown's phylogeny</b> |         |            |                 |                |               |                             |                                     |  |  |  |       |           |
| 253                                  | 347     | 7          | 15.200          | 4.420          | 124.236       | 0.122                       | 0.058                               | 0.158                                    | 0.012  | <i>Erysimum bicolor/ scoparium</i>   | E     | 5,5       |
| 254                                  | 347     | 5          | 19.035          | 5.389          | 129.718       | 0.147                       | 0.058                               | 0.188                                    | 0.016  | <i>Erysimum bicolor/ scoparium</i>   | E     | 5,5       |
| 255                                  | 347     | 4          | 22.601          | 6.331          | 133.342       | 0.169                       | 0.052                               | 0.217                                    | 0.019  | <i>Erysimum bicolor/ scoparium</i>   | E     | 5,5       |
| 256                                  | 347     | 2          | 6.180           | 7.281          | 133.538       | 0.046                       | 0.026                               | 0.101                                    | 0.005  | <i>Erysimum bicolor/ scoparium</i>   | E     | 5,5       |
| 256                                  | 316     | 2          | 12.950          | 2.109          | 59.810        | 0.217                       | 0.061                               | 0.252                                    | 0.018  | <i>Matthiola</i> clade   | A     | 6,1       |
| 256                                  | 375     | 2          | 8.543           | 13.786         | 49.285        | 0.173                       | 0.066                               | 0.453                                    | 0.045  | <i>Cardamine pentaphyllo/ pratensis</i>                                      | C     | 3,7       |
| 256                                  | 405     | 2          | 8.616           | 1.048          | 44.577        | 0.193                       | 0.068                               | 0.217                                    | 0.022  | <i>Malcolmia maritima— Marcus-kochia ramosissima</i>                         | M/An  | 5,7       |
| 256                                  | 335     | 2          | 28.715          | 33.529         | 128.518       | 0.223                       | 0.077                               | 0.484                                    | 0.049  | <i>Erysimum popovii/ bastetanum/ semperflorens</i>                           | E     | 5,5,6     |
| 257                                  | 347     | 2          | 39.021          | 6.003          | 133.462       | 0.292                       | 0.103                               | 0.337                                    | 0.015  | <i>Erysimum bicolor/ scoparium</i>   | E     | 5,5       |
| 258                                  | 347     | 2          | 5.613           | 4.410          | 124.383       | 0.045                       | 0.012                               | 0.081                                    | 0.002  | <i>Erysimum bicolor/ scoparium</i>   | E     | 5,5       |
| <b>Gaynor et al.'s phylogeny</b>     |         |            |                 |                |               |                             |                                     |  |  |  |       |           |
| 481                                  | 334     | 2          | 10.943          | 17.832         | 78.194        | 0.140                       | 0.052                               | 0.368                                    | 0.037  | <i>Erysimum bicolor/ scoparium</i>   | E     | 5,5       |
| 479                                  | 334     | 2          | 9.357           | 12.654         | 81.141        | 0.115                       | 0.052                               | 0.271                                    | 0.033  | <i>Erysimum bicolor/ scoparium</i>   | E     | 5,5       |
| 479                                  | 333     | 2          | 12.809          | 14.978         | 81.151        | 0.158                       | 0.070                               | 0.342                                    | 0.049  | <i>Erysimum lagascae/ rondae</i>   | E     | 5,3       |
| <b>Huang et al.'s phylogeny</b>      |         |            |                 |                |               |                             |                                     |  |  |  |       |           |
| 143                                  | 83      | 2          | 4.960           | 0.985          | 23.966        | 0.207                       | 0.023                               | 0.248                                    | 0.001  | <i>Erucaria</i> clade  | B     | 3,5       |
| 143                                  | 82      | 2          | 7.094           | 0.554          | 22.049        | 0.322                       | 0.041                               | 0.347                                    | 0.002  | <i>Erucaria</i> clade + <i>Cakile</i> clade                                  | B     | 3,3,3,5   |
| 143                                  | 81      | 2          | 6.651           | 40.317         | 18.008        | 0.369                       | 0.046                               | 2.608                                    | 0.170  | <i>Erucaria</i> clade + <i>Cakile</i> clade + <i>Eremophyton chevallieri</i> | B     | 3,3,3,5,5 |
| 143                                  | 84      | 2          | 9.229           | 1.876          | 23.466        | 0.393                       | 0.066                               | 0.473                                    | 0.003  | <i>Cakile</i> clade  | B     | 3,3       |
| 143                                  | 86      | 2          | 11.634          | 12.691         | 24.281        | 0.479                       | 0.074                               | 1.002                                    | 0.026  | <i>Zilla</i> clade   | B     | 5,5       |
| 143                                  | 85      | 2          | 9.383           | 12.437         | 24.007        | 0.391                       | 0.076                               | 0.909                                    | 0.029  | <i>Zilla</i> clade + <i>Foleyola billotii</i>                                | B     | 3,5,5     |

**Table S8. Description of floral traits related to pollinator attraction used to generate the floral morphospace in Brassicaceae.** Pollinators respond to the variability of numerous phenotypic traits of plants, and the magnitude of their response shapes the reproductive success of the plants. We estimated for each plant included in our data set the values of several important floral traits.

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1) **Plant height.** Plant height has strong direct and indirect effects on plant fitness in many Brassicaceae. The assessment of plant height for a large number of plant species is not possible without accurate ecological studies. In addition, the information on plant size in general (and plant height in particular) appearing in the floristic catalogues is limited and most time very vague. For this reason, we decided to consider this variable as semi-quantitative, with three levels:

0 = This group includes plants with a prostrate life habit. Plants belonging to this group are those with a cushion shape, displaying flowers located very close to the ground and that thereby can be accessed both by flying and crawling insects (ants, springtails, mites, etc.).

1 = This group includes plants of intermediate size. We included in this group those plants shorter than 50 cm. This threshold is appropriate because it teases apart medium-sized species from those species with a large size. Many pollinators have a specific flight pattern with changes in flight zones occurring around this threshold. Within this group, there are also subshrub species with stunted growth habit.

2 = This group includes plants of large size. We included in this group those plants taller than 50 cm. These are plants particularly big, usually log-lived and sometimes woody species.

(2) **Flower display size.** The number of flowers produced per individual plant has strong direct and indirect effects on plant fitness in most Brassicaceae species. As occurring with plant height, the assessment of floral display size for a large number of plant species is not possible without accurate ecological studies. In addition, the information on flower number per individual appearing in the floristic catalogues is limited and most time very vague. For this reason, we decided to consider this variable as semi-quantitative, with three levels:

0 = This group includes species with few flowers per individual (pauciflorous), usually less than 50 flowers per individual.

1 = This group includes species with medium number to many flowers per individuals, usually between 50 and 1000 flowers per individual.

2 = This group includes species mass-flowering species, usually with more than 1000 flowers per individual.

(3) **Inflorescence architecture.** The configuration of flowers along the flowering stems and the inflorescence architecture have been shown to affect the attractiveness and foraging behaviour of pollinators in many angiosperm groups since long time. In Brassicaceae three main types of inflorescences can be distinguished:

0 = Inflorescences where flowers are arranged in solitary. In this species, flowers do not form a dense inflorescence but are solitary usually at the end of the flowering stems.

1 = Inflorescences where flowers are arranged in racemes. A simple inflorescence in which the main axis is indeterminate. This is the most frequent type of inflorescence in Brassicaceae.

2 = Inflorescences where flowers are arranged in corymbs. This is a special case of a panicle where flowers lie in a single plane. Panicles are determinate compound inflorescences in which branching does not occur from the axils of prophylls.

(4) **Presence of apetalous flowers.** Several species from some Brassicaceae genera, especially *Lepidium* and *Rorippa*, and to a lesser extent *Romanschulzia*, *Clypeola*, *Cardamine* and other minor genera, produce flowers without petals. We classified this floral trait as presence (1) or absence (0) of apetalous flowers.

(5) **Number of symmetry axes of the corolla.** Flower symmetry is an important trait in flowering plants. The Brassicaceae flower is defined as a cruciform, actinomorphic or radial flowers with many symmetry axes. However, it is widely acknowledged that some genera such as *Iberis* or *Teesdalia* produce monomorphic or actinomorphic flowers. The number of symmetry axes is even greater in some species. We have distinguished four groups based on number of symmetry axes:

0 = This group includes plants with flowers having no symmetry axis, like many species of *Matthiola*, some *Hesperis*,

1 = This group includes plants bearing flowers with one symmetry axis or actinomorphic flowers. In this group we included *Iberis*, *Teesdalia*, and several species of *Noccaea*, *Thlaspi*, etc.

2 = This group includes plants bearing flowers with two symmetry axes or dissymmetric flowers. This is probably the most abundant group, including most common species of Brassicaceae, like *Erysimum*, *Brassica*, *Diplotaxis*, etc.

4 = This group includes plants bearing flowers with four or more symmetry axes or polysymmetric flowers. This group, including common species of Brassicaceae, like *Lepidium*, some *Erysimum*, many *Heliophila*, many *Sisymbrium*, etc.

(6) **Orientation of dominant symmetry axis of the corolla.** In Brassicaceae, most flowers orientate vertically. Thereby, we classified this floral trait as horizontally- (1) or vertically- (0) orientated flowers.

(7) **Corolla with overlapped petals.** Much like flower symmetry, the presence of overlapped petals and rounded corollas affect fitness in several plant groups, including some Brassicaceae species by mediating the attractiveness of the flowers and the behaviour of pollinators. We classified this floral trait as corolla with overlapped petals (1) or with non-overlapped petals (0).

(8) **Corolla with multilobed petals.** In Brassicaceae petal lobes is not widespread, although it is frequent in some clades such as *Schizopetalon*, *Berteroa*, *Dryopetalon*. We classified this floral trait as corolla with multilobed petals (1) or without them (0).

(9) **Corolla with visible sepals.** Sepals play an important role in the pollination of many plant species. Some plant species, including Brassicaceae, have extended sepals that are visible from the top of the corolla. These visible petals may have important consequences on the behaviour of some pollinators, indirectly influencing the pollination success of the

flower. We scored this floral trait as corolla with visible sepals from the top of the corolla (1) or not (0).

(10) **Petal length.** Different studies have found a significant association between the length of flower petals and the behaviour of pollinators, by increasing corolla size and attractiveness or the floral attraction surface. As a consequence, it has been frequently proven the occurrence of a significant effect of petal length and flower size on the efficiency of pollination. We included in the data set the length of the petal in mm of each plant species. For this, we retrieved from the literature the description of the petal length, and calculated the mean of the values appearing in that description.

(11) **Sepal length.** In Brassicaceae the length of the sepals is positively correlated with the length of the corolla tube and the amount of nectar produced by the flowers. We included in the data set the length of the sepals in mm of each plant species. As in traits 10, we retrieved from the literature the description of the sepal length, and calculated the mean of the values appearing in that description.

(12) **Asymmetric petals.** Brassicaceae is characterized for bearing four symmetric petals. However, some species exhibit corollas with asymmetric petals, a character considered a morphological novelty. Presence of asymmetric petals causes corollas to show zygomorphy. This character, by affecting in an extreme way the number of symmetry axes, have large effects on pollinator preference, pollination efficiency and reproduction success. We scored this floral trait as corolla with asymmetric petals (1) or not (0).

(13) **Petal limb length.** The limb of the petal is the showy part that directly attracts pollinators. We included in the data set the length of the petal limb in mm of each plant species. For this, we retrieved from the literature the description of the petal length, and calculated the mean of the values appearing in that description.

(14) **Length of long stamens.** Brassicaceae has a tetradynamous androceum, with an outer whorl of two short stamens and an inner whorl of four long stamens. The length of the long stamens has been proven to affect pollinator visitation rate and effectiveness, having a strong effect on pollen removal and male fitness. We included in the data set the length of the long stamen in mm of each plant species as appearing in the literature.

(15) **Length of short stamens.** Short stamens may function in outcrossing Brassicaceae to reduce pollen depletion with high rates of pollinator visitation. In self-compatible, short stamens may favour delayed autogamy. In addition, short stamens may also affect pollinator visitation rate and effectiveness, having potential effect on pollen removal and male. We included in the data set the length of the short stamen in mm of each plant species as appearing in the literature.

(16) **Stamen dimorphism.** The difference in length between long and short stamens, hereinafter herkogamy, is related in Brassicaceae with pollinator attraction and evolution of selfing syndrome. We included this trait by estimating the length difference between long and short stamens from the data obtained in the literature.

(17) **Tetradynamous conditions.** In addition, we classified all Brassicaceae included in our dataset as having an androecium with all stamens equally long (0), slightly tetradynamous (1), normal tetradynamous condition (2) and strong tetradynamous condition (3). We used the classification appearing in the floral and formal description of the species.



(18) **Visible anthers.** Most species of Brassicaceae have anthers visible from outside the corolla during anthesis, which ease the magnitude of pollen removal by flower visitors. However, species of some genera (*Matthiola*, *Hesperis*, *Farsetia*, etc.) have stamens well hidden within the corolla tube and imperceptible from outside, a trait that difficult short-tongued insects to collect pollen. We scored this floral trait as corolla with visible anthers (1) or not (0).

(19) **Exserted stamens.** In some Brassicaceae the filaments are very long, causing stamens to be highly exserted. Stamens exsertion influences the behaviour and abundance of certain pollinators, shaping pollinator-mediated selection through male fitness. We scored this floral trait as non-exserted stamens (0) slightly exserted stamens (1) and strongly exserted stamens (2).

(20) **Number of stamens.** The basic number of stamens per Brassicaceae flower is six. However, departure from this number is frequent in some lineages such as *Lepidium* or to a lesser extent *Cardamine* or *Alyssum*, where some species bear 2, 4 or 5 stamens. In addition, some species of the genus *Megacarpa* have flowers with 9 or more stamens. We included for each species in the dataset the number of stamens indicated in the literature.

(21) **Concealed nectaries.** Some Brassicaceae species produce nectar that is concealed in the bottom of long corolla tubes, whereas other species bearing bowl-shaped flowers produce nectar that is freely exposed and easily accessible. This trait may have important consequences for the interaction with pollinators. We scored this floral trait as corolla with concealed nectaries (1) or not (0).

(22) **Petal carotenoids.** Flower colour is a crucial visual cue used by pollinators to locate flowers. In the Brassicaceae, there are numerous studies highlighting the role of flower colour in pollinator attraction and plant reproduction. Petal colour is mainly determined by the presence of pigments; we thereby decided to include the presence or absence of floral pigments in our dataset. Yellow colour is produced in Brassicaceae by the accumulation of carotenoids. We scored this trait as the presence (1) or absence (0) of petal carotenoids.

(23) **Petal anthocyanins.** In the Brassicaceae, species with pink, lilac, blue, purple, orange and red petals are caused by the accumulation of anthocyanins. We scored this floral trait as the presence of petal anthocyanins (1) or absence (0).

(24) **Presence of bullseyes.** Some flowers have circular patterns in the centre of the corolla called bullseyes that is involved in the attraction of pollinators. Bullseyes may be visible to human vision or invisible due to its absorbance in the ultraviolet region of the light spectrum; we considered only the first ones as is the information provide in the consulted Floras. We scored this floral trait as corolla with (1) or without (0) bullseyes.

(25) **Presence of veins in the petals.** In the Brassicaceae, some species may show petals with prominent veins having a different colour from the rest of the petals. The presence of coloured veins in the petals may function as nectar guides, providing visual orientation directing the pollinator to the central landing platform and the entrance to the flower. We scored this floral trait as petals with (1) or without (0) veins.

(26) **Coloured sepals.** As commented in the trait 9, sepals may be involved in pollination attraction in many species. Colouring sepals by accumulating anthocyanins or carotenoids and may help flowers to differentiate from the green background. We scored this floral trait as coloured sepals (1) or green sepals (0).

(27) **Relative attractiveness of petals versus sepals.** In some species of the Brassicaceae, the sepals are bigger and more attractive than the petals. This occurs frequently in some genera such as *Streptanthus*, *Roripa*, *Lepidium* and *Heliophila*. We scored this floral trait as (1) when petals are more attractive than sepals or (0) in the opposite case.

(28) **Petal hue.** Although measuring flower colour with spectrophotometric methods are recommended over methodologies based on human vision, obtaining reflectance data of more than 3000 species widely distributed around the world is virtually unfeasible. We designed a method that allows incorporating colour description in the Floras to generate categorical variables. We used a modification of colour identification with reference standards which are commonly used in comparative studies of flower colour and generates relatively good estimates of flower colour variation. First, we used a subset of 200 species that we have digital photos taken with the same camera and similar light conditions to prevent artificial colour modifications. The colour of petals was assigned to the closest matching Munsell colour chip; the same person performed these measures in order to avoid erroneous assignation due to inter-observer differences in colours perception. A total of 24 colour types were identified covering shades of blue (2.5P7/6, 10PB7/6), lilac-purple (7.5P8/4, 7.5P6/8, 7.5P6/10, 7.5P4/10, 5P6/8, 5P8/4, 5P5/10), pink (7.5RP8/4, 5RP6/10, 2.5RP5/10), yellow (5Y9/6; 5Y9/4, 5Y8.5/12), orange (5Y8/8, 2.5Y8/12, 2.5YR6/14), brown-bronze (10YR6/10, 5YR6/12, 10R5/8), green (2.5G5/5, 10GY6/8) and white (N9). We used spectral characteristics of Munsell colours to transform the categorical colour data to semi-quantitative measures of colour. Hue is one of the best colour descriptors for plant colourimetry; thus, we calculated hue values as the wavelength at peak reflectance. In order to accommodate the Brassicaceae petal colour information provided in the Floras to our 24 Munsell colour types, we generated ten colour categories. The hue of each new colour category was calculated as the mean of the hue values containing each category (i.e., among colour shades). In species with petal colour variation, including petal colour polymorphism, we scored the more common petal colour; if this information is not available, we assigned the colour derived of the presence of floral pigments (anthocyanins, carotenoids or both). The values of the ten hue categories are: 454.31 nm (blue), 503.55 nm (pink), 558.08 nm (lilac-purple), 572.46 nm (yellow), 575.43 nm (pale yellow), 579.38 nm (yellow-orange), 592.74 nm (orange), 589.44 nm (brown-bronze), 546.10 nm (green) and 611.37 nm (white).

(29) **Petal colour as b CIELAB.** We also used a second parameter related to petal colour, the “b\*” parameter of the CIE 1976 L\*a\*b\*. In this colour space, b\* dimension represent values from -100 (blue colours) to 100 (yellow colours). This metrics is recommendable for the analysis of flower colour, particularly in groups of plant species containing petals with shades of yellow, as occurs in the Brassicaceae. b\* values were obtained with the same methodology explained in the previous trait (28). The values of the ten b\* categories are: -18.46 (blue), -4.77 (pink), -19.71 (lilac-purple), 45.03 (pale yellow), 80.1 (yellow), 80.45 (yellow-orange), 65.3 (orange), 52.02 (brown-bronze), 29.79 (green) and 0.00 (white).

(30) **Sepal hue.** Sepals of Brassicaceae species are sometimes coloured, differing from the common green. As already mentioned above for traits 9, sepals play an important role in the pollination of many plant species. We used the same method and hue values detailed in the trait 28 to score the sepal colour as hue category.

(31) **Sepal colour as b CIELAB.** For the same reasons mentioned above, we decided to include this trait because of the effect it can have on attracting pollinators. We used the same method and values detailed in the trait 29 to score the sepal colour as “b\*” parameter of the CIE 1976 L\*a\*b\*.

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**Table S9.** List of the phylogenies retrieved from the online repositories and from the literature to built up the Brassicaceae supertree. Within brackets appears the number of species included in the analysis of disparity

| Code   | Species    | Dated | Rooted | Focal taxa       | Reference  |
|--|------------|-------|--------|------------------|--|
| <b>Phylogenies including Moricandia</b>                  |            |       |        |                  |  |
| 1  | 15 [8]     | YES   | YES    | Moricandia       | Perfectti, F., Gómez, J. M., González-Megías, A., Abdelaziz, M., & Lorite, J. (2017). Molecular phylogeny and evolutionary history of Moricandia DC (Brassicaceae). <i>PeerJ</i> , 5, e3964.   |
| 2  | 273 [255]  | YES   | YES    |                  | Smith, S. A., & Brown, J. W. (2018). Constructing a broadly inclusive seed plant phylogeny. <i>American journal of botany</i> , 105(3), 302-314  |
| 3  | 1508 [248] | YES   | YES    |                  | Gaynor, M. L., Ng, J., & Laport, R. G. (2018). Phylogenetic structure of plant communities: are polyploids distantly related to co-occurring diploids?. <i>Frontiers in Ecology and Evolution</i> , 6, 52.   |
| 4  | 195 [163]  | YES   | YES    | Brassicaceae     | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| <b>Time-calibrated phylogenies with more than 45 spp</b> |            |       |        |                  |  |
| 5  | 84 [48]    | YES   | YES    | Euclidieae       | Chen, H., German, D. A., Al-Shehbaz, I. A., Yue, J., & Sun, H. (2020). Phylogeny of Euclidieae (Brassicaceae) based on plastome and nuclear ribosomal DNA data. <i>Molecular Phylogenetics and Evolution</i> , 153, 106940   |
| 6  | 130 [124]  | YES   | YES    |                  | Durka, W., & Michalski, S. G. (2012). Daphne: a dated phylogeny of a large European flora for phylogenetically informed ecological analyses: <i>Ecological Archives E093-214</i> . <i>Ecology</i> , 93(10), 2297-2297  |
| 7  | 316 [208]  | YES   | YES    |                  | Walden, N., German, D. A., Wolf, E. M., Kiefer, M., Rigault, P., Huang, X. C., Kiefer, C., Schmickl R., Franzke A., Neuffer B., Mummenhoff, K., & Koch, M.A. (2020). Nested whole-genome duplications coincide with diversification and high morphological disparity in Brassicaceae. <i>Nature communications</i> , 11(1), 1-12 |
| 8  | 165 [109]  | YES   | YES    | Alysseae         | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 9  | 46 [26]    | YES   | YES    | Anchonieae       | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 10   | 265 [265]  | YES   | YES    | Arabidae         | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 11   | 84 [77]    | YES   | YES    | Boechereae       | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 12   | 160 [126]  | YES   | YES    | Cardamineae      | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 13   | 57 [23]    | YES   | YES    | Chorisporaeae    | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 14   | 51 [28]    | YES   | YES    | Coluteocarpaceae | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 15   | 110 [89]   | YES   | YES    | Erysimeae        | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 16   | 75 [55]    | YES   | YES    | Euclidieae       | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 17   | 56 [53]    | YES   | YES    | Heliophileae     | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 18   | 139 [94]   | YES   | YES    | Lepidieae        | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 19   | 130 [117]  | YES   | YES    | Thelypodieae     | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| <b>Time-calibrated phylogenies with less than 45 spp</b> |            |       |        |                  |  |
| 20   | 10         | YES   | YES    | Aethionemeae     | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |

|    |    |     |     |                  |  |
|----|----|-----|-----|------------------|--|
| 21 | 9  | YES | YES | Alyssopsidaeae   | events. <i>Annals of Botany</i> , 125(1), pp.29-47.<br>Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47. |
| 22 | 30 | YES | YES | Anastaticaeae    | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 23 | 10 | YES | YES | Aphragmeae       | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 24 | 5  | YES | YES | Asteae           | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 25 | 19 | YES | YES | Biscutelleae     | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 26 | 6  | YES | YES | Buniadeae        | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 27 | 8  | YES | YES | Calepineae       | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 28 | 27 | YES | YES | Camelineae       | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 29 | 16 | YES | YES | Cochleariaeae    | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 30 | 8  | YES | YES | Conringieae      | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 31 | 29 | YES | YES | Cremolobeae      | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 32 | 13 | YES | YES | Crucihimalayaeae | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 33 | 41 | YES | YES | Descurainieae    | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 34 | 17 | YES | YES | Dontostemoneae   | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 35 | 24 | YES | YES | Eudemeae         | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 36 | 25 | YES | YES | Eutremeae        | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 37 | 23 | YES | YES | Halimolobeae     | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 38 | 11 | YES | YES | Hesperideae      | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 39 | 13 | YES | YES | Hillilleae       | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 40 | 6  | YES | YES | Iberideae        | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 41 | 34 | YES | YES | Isatideae        | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 42 | 5  | YES | YES | Kernereae        | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 43 | 5  | YES | YES | Malcolmieae      | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 44 | 8  | YES | YES | Megacarpaeae     | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in  |

|  |     |     |     |                 |  |
|--|-----|-----|-----|-----------------|--|
|  |     |     |     |                 | Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 45                                     | 26  | YES | YES | Microlepidieae  | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 46                                     | 4   | YES | YES | Notothlaspeidae | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 47                                     | 5   | YES | YES | Oreophytoneae   | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 48                                     | 40  | YES | YES | Physarieae      | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 49                                     | 20  | YES | YES | Schizopetaleae  | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 50                                     | 23  | YES | YES | Sisymbrieae     | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 51                                     | 23  | YES | YES | Smelowskieae    | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 52                                     | 19  | YES | YES | Thlaspeidae     | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 53                                     | 5   | YES | YES | Turritideae     | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| 54                                     | 8   | YES | YES | Yinshanieae     | Huang, X.C., German, D.A. and Koch, M.A., 2020. Temporal patterns of diversification in Brassicaceae demonstrate decoupling of rate shifts and mesopolyploidization events. <i>Annals of Botany</i> , 125(1), pp.29-47.  |
| <b>Non-time calibrated phylogenies</b> |     |     |     |                 |  |
| 55                                     | 115 | NO  | YES |                 | Gómez, J. M., Torices, R., Lorite, J., Klingenberg, C. P., & Perfectti, F. (2016). The role of pollinators in the evolution of corolla shape variation, disparity and integration in a highly diversified plant family with a conserved floral bauplan. <i>Annals of Botany</i> , 117(5), 889-904.                                     |
| 56                                     | 44  | NO  | NO  | Erysimum        | Gómez, J. M., Perfectti, F., Abdelaziz, M., Lorite, J., Muñoz-Pajares, A. J., & Valverde, J. (2015). Evolution of pollination niches in a generalist plant clade. <i>New Phytologist</i> , 205(1), 440-453.  |
| 57                                     | 569 | NO  | YES |                 | Couvreur, T. L., Franzke, A., Al-Shehbaz, I. A., Bakker, F. T., Koch, M. A., & Mummenhoff, K. (2010). Molecular phylogenetics, temporal diversification, and principles of evolution in the mustard family (Brassicaceae). <i>Molecular Biology and Evolution</i> , 27(1), 55-71.  |
| 58                                     | 115 | NO  | NO  |                 | Salariato, D. L., Manchego, M. A. C., Cano, A., & Al-Shehbaz, I. A. (2019). Phylogenetic placement of the Peruvian-endemic genus <i>Machaerophorus</i> (Brassicaceae) based on molecular data and implication for its systematics. <i>Plant Systematics and Evolution</i> , 305(1), 77-87.   |
| 59                                     | 53  | NO  | YES |                 | Guo, X., Liu, J., Hao, G., Zhang, L., Mao, K., Wang, X., ... & Koch, M. A. (2017). Plastome phylogeny and early diversification of Brassicaceae. <i>BMC genomics</i> , 18(1), 176.   |
| 60                                     | 60  | NO  | YES | Thysanocarpus   | Alexander, P. J., Windham, M. D., Govindarajulu, R., Al-Shehbaz, I. A., & Bailey, C. D. (2010). Molecular phylogenetics and taxonomy of the genus <i>Thysanocarpus</i> (Brassicaceae). <i>Systematic Botany</i> , 35(3), 559-577.  |
| 61                                     | 56  | NO  | YES |                 | Huang, C.H., Sun, R., Hu, Y., Zeng, L., Zhang, N., Cai, L., Zhang, Q., Koch, M.A., Al-Shehbaz, I., Edger, P.P. and Pires, J.C., 2016. Resolution of Brassicaceae phylogeny using nuclear genes uncovers nested radiations and supports convergent morphological evolution. <i>Molecular biology and evolution</i> , 33(2), pp.394-412. |
| 62                                     | 186 | NO  | YES |                 | Warwick, S. I., Mummenhoff, K., Sauder, C. A., Koch, M. A., & Al-Shehbaz, I. A. (2010). Closing the gaps: phylogenetic relationships in the Brassicaceae based on DNA sequence data of nuclear ribosomal ITS region. <i>Plant Systematics and Evolution</i> , 285(3-4), 209-232.   |
| 63                                     | 101 | NO  | YES |                 | Arias, T., Beilstein, M. A., Tang, M., McKain, M. R., & Pires, J. C. (2014). Diversification times among Brassica (Brassicaceae) crops suggest hybrid formation after 20 million years of divergence. <i>American journal of botany</i> , 101(1), 86-91.   |
| 64                                     | 27  | NO  | NO  | Microthlaspi    | Ali, T., Schmuker, A., Runge, F., Solovyeva, I., Nigrelli, L., Paule, J., Buch, A.K., Xia, X., Ploch, S., Orren, O. and Kummer, V., 2016. Morphology, phylogeny, and taxonomy of <i>Microthlaspi</i> (Brassicaceae: Coluteocarpeae) and related genera. <i>Taxon</i> , 65(1), 79-98.   |
| 65                                     | 22  | NO  | YES | Alysseae        | Cecchi, L., Gabbriellini, R., Arnetoli, M., Gonnelli, C., Hasko, A., & Selvi, F. (2010). Evolutionary lineages of nickel hyperaccumulation and systematics in European <i>Alysseae</i> (Brassicaceae): evidence from nrDNA sequence data. <i>Annals of Botany</i> , 106(5), 751-767.   |
| 66                                     | 53  | NO  | YES |                 | Soza, V. L., & Di Stilio, V. S. (2014). Pattern and process in the evolution of the sole dioecious member of Brassicaceae. <i>EvoDevo</i> , 5(1), 42.  |
| 67                                     | 38  | NO  | YES | Descurainia     | Goodson, B. E., Rehman, S. K., & Jansen, R. K. (2011). Molecular systematics and   |

|    |     |    |     |              |   |
|----|-----|----|-----|--------------|---|
|    |     |    |     |              | biogeography of <i>Descourainia</i> (Brassicaceae) based on nuclear ITS and non-coding chloroplast DNA. <i>Systematic Botany</i> , 36(4), 957-980.  |
| 68 | 15  | NO | NO  | Thlaspi      | Koch, M., & Al-Shehbaz, I. A. (2004). Taxonomic and phylogenetic evaluation of the American. <i>Systematic Botany</i> , 29(2), 375-384.   |
| 69 | 101 | NO | NO  |              | From TreeBase - d13 [R-package APE, Fri May 31 09:08:01 2019]   |
| 70 | 130 | NO | NO  |              | Salariato, D. L., Manchego, M. A. C., Cano, A., & Al-Shehbaz, I. A. (2019). Phylogenetic placement of the Peruvian-endemic genus <i>Machaerophorus</i> (Brassicaceae) based on molecular data and implication for its systematics. <i>Plant Systematics and Evolution</i> , 305(1), 77-87.                                      |
| 71 | 103 | NO | YES |              | From TreeBase - T3061 [R-package APE, Thu Oct 15 18:34:08 2020]   |
| 72 | 56  | NO | YES |              | From TreeBase - Parrya [R-package APE, Thu Oct 15 19:34:09 2020] - Nikolov, L.A., Shushkov, P., Nevado, B., Gan, X., Al-Shehbaz, I.A., Filatov, D., Bailey, C.D. and Tsiantis, M., 2019. Resolving the backbone of the Brassicaceae phylogeny for investigating trait diversity. <i>New Phytologist</i> , 222(3), pp.1638-1651. |
| 73 | 223 | NO | YES |              | From TreeBase - varios [R-package APE, Fri Oct 16 07:38:56 2020]  |
| 74 | 97  | NO | NO  | Vella        | Simon-Porcar, V. I., Perez-Collazos, E., & Catalan, P. (2015). Phylogeny and systematics of the western Mediterranean <i>Vella pseudocytisus</i> - <i>V. aspera</i> complex (Brassicaceae). <i>Turkish Journal of Botany</i> , 39(3), 472-486.  |
| 75 | 109 | NO | NO  | Vella        | Crespo, M.B., Lledó, M.D., Fay, M.F. and Chase, M.W., 2000. Subtribe Vellinae (Brassicaceae, Brassicaceae): a combined analysis of ITS nrDNA sequences and morphological data. <i>Annals of Botany</i> , 86(1), pp.53-62.   |
| 76 | 49  | NO | YES | Pachycladon  | Joly, S., Heenan, P.B. and Lockhart, P.J., 2009. A Pleistocene inter-tribal allopolyploidization event precedes the species radiation of <i>Pachycladon</i> (Brassicaceae) in New Zealand. <i>Molecular phylogenetics and evolution</i> , 51(2), pp.365-372.  |
| 77 | 189 | NO | YES |              | German, D.A., Friesen, N., Neuffer, B., Al-Shehbaz, I.A. and Hurka, H., 2009. Contribution to ITS phylogeny of the Brassicaceae, with special reference to some Asian taxa. <i>Plant Systematics and Evolution</i> , 283(1-2), pp.33-56.  |
| 78 | 195 | NO | NO  | Brassicaceae | BrassiBase ITS tree- <a href="https://brassibase.cos.uni-heidelberg.de/?action=phlv&amp;subaction=Brassicaceae">https://brassibase.cos.uni-heidelberg.de/?action=phlv&amp;subaction=Brassicaceae</a>  |
| 79 | 598 | NO | YES |              | Bailey, C.D., Koch, M.A., Mayer, M., Mummenhoff, K., O'Kane Jr, S.L., Warwick, S.I., Windham, M.D. and Al-Shehbaz, I.A., 2006. Toward a global phylogeny of the Brassicaceae. <i>Molecular biology and evolution</i> , 23(11), pp.2142-2160.  |
| 80 | 370 | NO | YES |              | Friesen, N., Čalasan, A.Ž., Neuffer, B., German, D.A., Markov, M. and Hurka, H., 2020. Evolutionary history of the Eurasian steppe plant <i>Schivereckia podolica</i> (Brassicaceae) and its close relatives. <i>Flora</i> , p.151602.  |

**Table S10.** List of ecologists kindly sharing unpublished information on Brassicaceae pollinators. The host institutions are those at the time of the contact with our team.

| <b>Last Name</b> | <b>First Name</b> | <b>Host institution</b>                              |
|------------------|-------------------|--|
| Abdelaziz        | Mohamed           | University of Granada (Spain)                        |
| Aizen            | Marcelo           | Universidad Nacional del Comahue-CONICET (Argentina) |
| Aguado           | Luis Oscar        | Castilla y Leon Regional Government (Spain)          |
| Alarcon          | Ruben             | University Arizona (USA)                             |
| Amat             | Elena             | Real Jardín Botánico de Madrid (Spain)               |
| Arista           | Montserrat        | University of Seville (Spain)                        |
| Banza            | Paula             | University of Hull (UK)                              |
| Barbir           | Jelena            | ICA-CSIC (Spain)                                     |
| Bartomeus        | Ignasi            | EBD-CSIC (Spain)                                     |
| Bergerot         | Benjamin          | University of Rennes (France)                        |
| Bommarco         | Riccardo          | Swedish University of Agricultural Sciences (Sweden) |
| Bosch            | Jordi             | CREAF-UAB (Spain)                                    |
| Bruinsma         | Maaïke            | Leiden University (The Netherlands)                  |
| Burkle           | Laura             | Montana State University (USA)                       |
| CaraDonna        | Paul              | Northwestern University (USA)                        |
| Cartar           | Ralph             | University of Calgary (Canada)                       |
| Castro           | Silvia            | University of Coimbra (Portugal)                     |
| Castro-Urgal     | Rocio             | IMEDEA-CSIC (Spain)                                  |
| Chacoff          | Natacha           | Universidad Nacional del Comahue-CONICET (Argentina) |
| Conner           | Jeffrey           | Michigan State University (USA)                      |
| Cuerda           | David             | Junta de Andalucía (Spain)                           |
| Dennis           | Roger L. H.       | Staffordshire University (UK)                        |
| Ebeling          | Anne              | University of Jena (Germany)                         |
| Escudero         | Adrián            | Universidad Rey Juan Carlos (Spain)                  |
| Evans            | Darren            | University of Hull (UK)                              |
| Fernández        | Juande            | Greenpeace (Spain)                                   |
| Ferrero          | Victoria          | University of León (Spain)                           |
| Fründ            | Jochen            | Georg-August-Universität (Germany)                   |
| Fultz            | Jessica           | Idaho State University (USA)                         |
| Garbuzov         | Mihail            | University Sussex (UK)                               |
| García           | Begoña            | IPE-CSIC (Spain)                                     |
| García-Camacho   | Raúl              | Universidad Rey Juan Carlos (Spain)                  |
| García           | Yedra             | CIDE (University of New Brunswick)                   |
| García de Lucas  | Sandra            | Junta de Andalucía (Spain)                           |
| Giménez          | Luis              | Universidad Rey Juan Carlos (Spain)                  |
| Iriondo          | José María        | Universidad Rey Juan Carlos (Spain)                  |
| Junker           | Robert R.         | University of Salzburg (Austria)                     |
| Kuppler          | Jonas             | ULM University (Germany)                             |
| Lance            | Richard           | Northern Arizona University (USA)                    |
| Lara             | Carlos            | Universidad Rey Juan Carlos (Spain)                  |
| Lázaro           | Amparo            | IMEDEA-CSIC (Spain)                                  |
| Lorite           | Juan              | University of Granada (Spain)                        |
| Louadi           | Kamel             | University Frères Mentouri Konstantine (Algeria)     |
| Loureiro         | João              | University of Coimbra (Portugal)                     |
| Lucas-Barbosa    | Dani              | Wageningen University (The Netherlands)              |
| Majetic          | Cassey J.         | Saint Mary's College Indiana (USA)                   |
| Marcos           | Maria Ángeles     | Universidad de Alicante (Spain)                      |
| Medel            | Rodrigo           | University of Santiago de Chile (Chile)              |
| Meindl           | George            | Binghamton University (USA)                          |
| Melen            | Miranda           | University of California-Santa Cruz (USA)            |
| Méndez           | Marcos            | Universidad Rey Juan Carlos (Spain)                  |
| Menéndez         | Rosa              | University of Lancaster (UK)                         |

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|               |            |  |
|---------------|------------|--|
| Milla         | Rubén      | Universidad Rey Juan Carlos (Spain)                  |
| Morales       | Carolina   | Universidad Nacional del Comahue-CONICET (Argentina) |
| Morente       | Javier     | Universidad Rey Juan Carlos (Spain)                  |
| Muñoz-Pajares | A. Jesus   | University of Coimbra (Portugal)                     |
| Norfolk       | Olivia     | University of Nottingham (UK)                        |
| Norton        | Nicholas   | Washington State University (USA)                    |
| O'Malley      | Rachel     | San Jose State University (USA)                      |
| Ojeda         | Fernando   | University of Cádiz (Spain)                          |
| Pelayo        | Roxibel    | Universidad de las Andes (Venezuela)                 |
| Petanidou     | Theodora   | University of the Aegean (Greece)                    |
| Razanajatovo  | Mialy      | University Konstanz (Germany)                        |
| Roberts       | S.P.M.     | University of Reading (UK)                           |
| Santamaría    | Silvia     | Universidad Rey Juan Carlos (Spain)                  |
| Schlinkert    | Hella      | University Goettingen (Germany)                      |
| Schrader      | Julian     | University Goettingen (Germany)                      |
| Schupp        | Eugene W.  | Utah State University (USA)                          |
| Simaika       | John P.    | Stellenbosch University (South Africa)               |
| Simanonok     | Michael P. | MSU- Northern Prairie Wildlife Research Center (USA) |
| Stang         | Martina    | University of Leiden (The Netherlands)               |
| Stanley       | Dara A.    | Trinity College Dublin (Ireland)                     |
| Stout         | Jane       | Trinity College Dublin (Ireland)                     |
| Strauss       | Sharon     | University of California at Davis (USA)              |
| Torices       | Rubén      | University Lausanne (Switzerland)                    |
| Traveset      | Anna       | IMEDEA-CSIC (Spain)                                  |
| Tscharntke    | Teja       | University of Göttingen (Germany)                    |
| Tur           | Cristina   | IMEDEA-CSIC (Spain)                                  |
| Valido        | Alfredo    | IPNA-CSIC (Spain)                                    |
| Valverde      | Javier     | EBD-CSIC (Spain)                                     |
| Vargas        | Pablo      | Real Jardín Botánico de Madrid (Spain)               |
| Warzecha      | Daniela    | Goethe University (Germany)                          |
| Whittall      | Justen     | Santa Clara University (USA)                         |
| Winfree       | Rachael    | Rutgers University (USA)                             |
| Wonneck       | Mark       | University of Calgary (Canada)                       |
| Zink          | Lindsay    | University of Calgary (Canada)                       |

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**Table S11.** Brief description of the functional groups of the insects visiting the flowers of the studied species.

|    | Functional Group                | Body length   | Resource        | Behavioural notes   | Type of visits            | Order       | Examples  |
|----|---------------------------------|---------------|-----------------|---|---------------------------|-------------|---|
| 1  | Long-tongued extra-large bees   | ≥ 15 mm       | Nectar + Pollen | Partially introducing the head in the flower                        | Legitimate                | Hymenoptera | Anthophoridae, Apidae   |
| 2  | Long-tongued large bees         | 10-15 mm      | Nectar + Pollen | Partially introducing the head in the flower                        | Legitimate                | Hymenoptera | Anthophoridae   |
| 3  | Long-tongued medium-sized bees  | < 10 mm       | Nectar + Pollen | Partially introducing the head in the flower                        | Legitimate                | Hymenoptera | Anthophoridae   |
| 4  | Honeybees                       | 6-12 mm       | Nectar + Pollen | Introducing the whole head in the flower                            | Legitimate                | Hymenoptera | Apidae ( <i>Apis</i> spp.)  |
| 5  | Short-tongued extra-large bees  | ≥ 15 mm       | Nectar + Pollen | Introducing the head in the flower                                  | Legitimate                | Hymenoptera | Apidae  |
| 6  | Short-tongued large bees        | > 10 mm       | Pollen + Nectar | Introducing the whole head in the flower                            | Legitimate                | Hymenoptera | Halictidae, Megachilidae, Colletidae Andrenidae                           |
| 7  | Short-tongued medium-sized bees | 5 – 10 mm     | Pollen + Nectar | Introducing the whole head in the flower                            | Legitimate                | Hymenoptera | Halictidae, Colletidae, Andrenidae , Apidae Xylocopinae, Apidae Nomidinae |
| 8  | Short-tongued small bees        | 2 – 5 mm      | Pollen + Nectar | They access the nectar legitimately or from between the sepals      | Illegitimate + Legitimate | Hymenoptera | Halictidae, Colletidae, Andrenidae , Apidae Xylocopinae, Apidae Nomidinae |
| 9  | Short-tongued extra-small bees  | < 2 mm        | Nectar + Pollen | They access the nectar legitimately or from between the sepals      | Legitimate + Illegitimate | Hymenoptera | Halictidae, Colletidae  |
| 10 | Large ants                      | > 2 mm        | Nectar          | They can introduce the whole body in the flower to reach the nectar | Legitimate + Illegitimate | Hymenoptera | Formicidae  |
| 11 | Small ants                      | < 2 mm        | Nectar          | Mostly sipping nectar from between sepals                           | Illegitimate + Legitimate | Hymenoptera | Formicidae  |
| 12 | Large pollen wasps              | Variable      | Pollen          | Partially introducing the head in the flower                        | Legitimate                | Hymenoptera | Massarinae  |
| 13 | Large nectar-collecting wasps   | > 7mm         | Nectar          | Partially introducing the head in the flower                        | Legitimate                | Hymenoptera | Vespidae  |
| 14 | Small nectar-collecting wasps   | Usually < 3mm | Nectar          | Mostly sipping nectar from between sepals                           | Illegitimate + Legitimate | Hymenoptera | Chalcidoidea, Ichneumonoidea  |
| 15 | Hovering long-tongued           | Variable      | Nectar +        | Hovering while nectaring and collecting some pollen                 | Legitimate                | Diptera     | Bombyliidae ( <i>Bombylius</i> )  |

|    | flies                           |          | Pollen          |   |                           |             |   |
|----|---------------------------------|----------|-----------------|---|---------------------------|-------------|---|
| 16 | Non-hovering long tongued flies | Variable | Nectar          | Nectaring without hovering; long buccal apparatus   | Legitimate                | Diptera     | Bombyliidae, Tachinidae, Nemestrinidae,   |
| 17 | Large hoverflies                | >5 mm    | Pollen          | Collect pollen without entering the flower  | Legitimate                | Diptera     | Syrphidae (Eristalini)  |
| 18 | Small hoverflies                | < 5 mm   | Pollen + Nectar | Collect pollen without entering the flower and sometimes sip nectar from between the sepals           | Legitimate + Illegitimate | Diptera     | Syrphidae   |
| 19 | Large flies                     | >5 mm    | Nectar + Pollen | Collect pollen without entering the flower and nectar   | Legitimate + Illegitimate | Diptera     | Muscidae, Calliphoridae, Tabanidae, Scatophagidae, Anthomyiidae   |
| 20 | Small flies                     | < 5 mm   | Nectar + Pollen | Mostly sipping nectar   | Illegitimate + Legitimate | Diptera     | Muscidae, Anthomyiidae, Micetophyllidae, Drosophilidae, Stratiomyidae                                       |
| 21 | Long tongued small flies        | < 5 mm   | Nectar          | Sipping nectar  | Illegitimate + Legitimate | Diptera     | Bibionidae, Empididae   |
| 22 | Large beetles                   | > 7 mm   | Mostly Pollen   | Consuming not only pollen, also anthers, petals, and other floral parts                               | Legitimate + Illegitimate | Coleoptera  | Cetonidae, Lagridae, Mylabridae, Allecuninae  |
| 23 | Small beetles                   | < 7 mm   | Pollen + Nectar | Consuming pollen during legitimate visits and also robbing nectar from the bottom part of the flowers | Legitimate + Illegitimate | Coleoptera  | Melyridae (Malachidae, Dasytidae), Cleridae, Oedemeridae, Elateridae, Bruchidae, Buprestidae, Chrysomelidae |
| 24 | Small diving beetles            | <3 mm    | Nectar + Pollen | Entering completely into the flower, crawling down the corolla for nectar                             | Legitimate                | Coleoptera  | Nitidulidae, Dermestidae, Phalacridae   |
| 25 | Large Butterflies               | ≥ 20 mm  | Nectar          | Feeding on nectar both from inside the flower and between the sepals                                  | Legitimate                | Lepidoptera | Nymphalidae, ,Papilionidae, Pieridae  |
| 26 | Small Butterflies               | < 20 mm  | Nectar          | Feeding on nectar both from inside the flower and between the sepals                                  | Legitimate                | Lepidoptera | Lycaenidae, Pieridae, Hesperidae  |
| 27 | Hawkmoths                       | > 7 mm   | Nectar          | Hovering to sip nectar  | Legitimate                | Lepidoptera | Sphingidae  |
| 28 | Large moths                     | > 3mm    | Nectar          | Sipping nectar while landed onto the corolla  | Legitimate                | Lepidoptera | Crambidae, Noctuidae  |
| 29 | Small moths                     | < 3mm    | Nectar          | Sipping nectar without entering the flower  | Illegitimate + Legitimate | Lepidoptera | Adelidae, Plutellidae   |
| 30 | Nocturnal moths                 | variable | Nectar          | Sipping nectar while landed onto the corolla or by hovering; Visiting the flowers at night            | Legitimate                | Lepidoptera | Noctuidae   |

|    |              |           |                       |   |                           |               |                         |
|----|--------------|-----------|-----------------------|---|---------------------------|---------------|-------------------------|
| 31 | Bugs         | variable  | Nectar                | Sipping nectar without entering the flower. Also acting as sapsuckers in vegetative tissues | Legitimate + Illegitimate | Hemiptera     | Lygaeidae, Pentatomidae |
| 32 | Thrips       | < 3 mm    | Pollen                | Feeding from inside the flowers   | Legitimate                | Thysanoptera  |                         |
| 33 | Grasshoppers | variable  | Pollen + Floral parts | Mostly nymphs   | Legitimate                | Orthoptera    |                         |
| 34 | Aphids       | < 2 mm    | Nectar                | Mostly winged individuals   | Legitimate                | Hemiptera     | Aphidoidea              |
| 35 | Earwig       | > 15 mm   | Pollen                |   | Legitimate + Illegitimate | Dermaptera    |                         |
| 36 | Lacewing     | > 15 mm   | Pollen + Nectar       |   | Legitimate + Illegitimate | Neuroptera    | Chrysopidae             |
| 37 | Snakeflies   | > 8 mm    | Pollen + Nectar       |   | Legitimate + Illegitimate | Raphidioptera |                         |
| 38 | Birds        | >>> 15 mm | Nectar                |   | Legitimate                | Passeriformes |                         |
| 39 | Springtails  | < 2 mm    | Nectar                |   | Legitimate + Illegitimate |               |                         |
| 40 | Mites        | < 2 mm    | Nectar                |   | Legitimate + Illegitimate |               |                         |
| 41 | Spiders      | < 2 mm    | Unknown               |   | Illegitimate              |               |                         |
| 42 | Larvae       | variable  | Unknown               |   | Illegitimate              |               |                         |
| 43 | Others       | variable  | Unknown               |   | Illegitimate              |               |                         |

