1   **Phenotypic plasticity triggers rapid morphological convergence**

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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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38 **Introduction**

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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.

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84

85   **Results**

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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   corymbous 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 alone 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 ± 0.090, mean ± 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 ± 0.033, mean ± 1 s.e.m., *Z*-score =

151   6.27, *P* < 0.0001) and between the species belonging to the same genus (0.069 ± 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 ± 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 ±

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

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 ± 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

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[39]. 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.

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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.

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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

9

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   Tetradynamous 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 1×10^{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 where 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 (Dmax) is calculated, and compared with the

499   phenotypic distance between the current putatively convergent taxa (Dtip). The greater the

500   difference between Dmax and Dtip, 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

15

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

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Figures

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Figure 1. Plasticity-mediated floral disparity. (**A**) Floral morphospace of the Brassicaceae, showed as the projection of 31 traits recorded in 3140 species onto two NMDS axes. The position of the spring and summer phenotypes of *Moricandia arvensis* is linked by a thick lilac dashed line. We have also indicated the movements across this morphospace of several species changing their phenotypes due to floral colour polymorphism (black lines), single mutations in floral colour (blue lines), changes in breeding systems (orange lines), changes in gender expression (green lines), homeotic mutations (brown lines), and plasticity (lilac lines). Numbers matching species are as follow: 1-*Lobularia maritima*; 2-*Raphanus raphanistrum*; 3-*Matthiola incana*; 4-*Mathiola fruticulosa*; 5-*Erysimum cheiri*; 6-*Cakile maritima*; 7-*Matthiola lunata*; 8- *Marcus-kochia littorea*; 9- *Hesperis matronalis*; 10- *Hesperis laciniata*; 11-*Parrya nudicalis*; 12-*Streptanthus glandulosus*; 13- *Eruca vesicaria*; 14- *Capsella bursa-pastoris*; 15-*Hormathophylla spinosa*; 16- *Brassica napus*; 17- *Cardamine hirsuta*; 18- *Lepidium sisymbrioides*; 19-*Lepidium solandri*; 20-*Arabidopsis thaliana*; 21-*Boechera stricta*; 22-*Leavenworthia stylosa*; 23-*Leavenworthia crassa*; 24-*Pachycladon stellatum*; 25- *Pachycladon wallii*; 26-*Cardamine kokairensis*; 27-*Brassica rapa*. (**B**) Shepard plot showing the goodness of fit of the NMDS ordination. (**C**) *Moricandia arvensis* in spring. (**D**) *Moricandia arvensis* in summer. (**E**) Magnitude of floral disparity between different taxonomic levels of Brassicaceae species. The number above each boxplot shows the number of 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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Figure 2. Phylogenetic-mediated floral divergence. (**A**) Floral phylomorphospace using the supertree that includes 1876 Brassicaceae species. (**B**) Phylomorphospace considering only the eight *Moricandia* species, using the Perfectti et al.'s phylogeny (phylogeny # 1 in Table S8). (**C**) Floral disparity to the nearest ancestor, according to the supertree and 18 time-calibrated phylogenies (phylogeny codes in Table S8). We show the disparity between the two *M. arvensis* phenotypes and their direct ancestor (spring: lilac dots; summer: white dots) in those phylogenies

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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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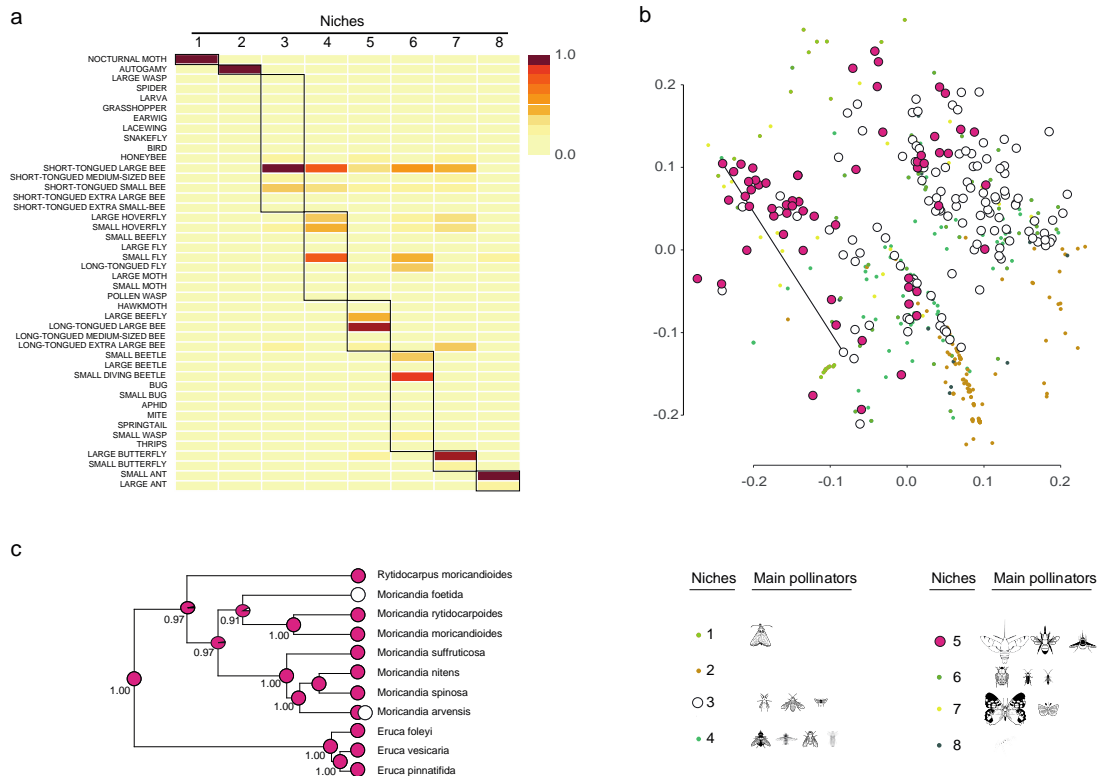
Figure 3. Plasticity-mediated changes in pollination niches. (**A**) Outcome of the modularity analysis showing the number of pollination niches inferred, the among-niche differences in relative frequency of each pollinator functional group, and the pollinator functional groups defining the niches (n = 511 Brassicaceae species). (**B**) Morphospatial distribution of the eight pollination niches detected in Brassicaceae. Insect silhouettes were drawn by Divulgare (www.divulgare.net) under a Creative Commons license (http://creativecommons.org/licenses/by-nc-sa/3.0). (**C**) Estimate of the ancestral pollination niche of the *Moricandia* lineage using a stochastic character mapping inference analysis. The numbers underneath each ancestral node indicate the posterior Bayesian probability of belonging to pollination niche 5.

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Figure 4. Plasticity-mediated floral convergence. Convergent lineages crossing into the region of the morphospace delimited by the pollination niche of the *M. arvensis* during spring (the shade convex hull) according to (**A**) Smith & Brown's phylogeny, (**B**) Gaynor et al.'s phylogeny, and (**C**) Huang et al.'s phylogeny (phylogenies 2-4, respectively, in Table S8). Convergent lineages crossing into the region of the morphospace delimited by the pollination niche of the *M. arvensis* during summer (the shade convex hull) according to (**D**) Smith & Brown's phylogeny, (**E**) Gaynor et al.'s phylogeny, and (**F**) Huang et al.'s phylogeny. Red arrows indicate the plasticity-mediated convergence, blue arrows the convergence events of the other lineages. The small purple area in all panels is the region of the floral morphospace that includes the lineages that have converged 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.
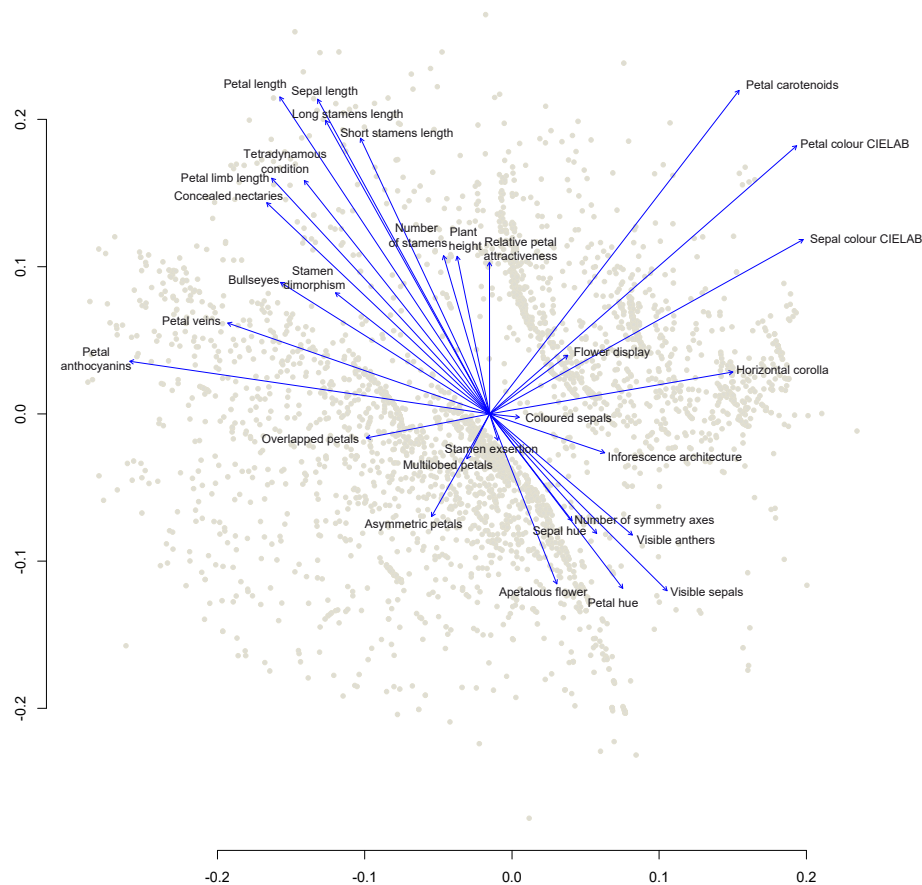
SI TABLES

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

	Floral traits	NMDS1	NMDS2	r^2	P value
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	Longeth 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	Excerted 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 bulleyes	-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	*Brassica napus*	cleistogamous mutant	0.035856865
Breeding system	*Brassica rapa*	female sterility mutant	0.133332180
Breeding system	*Cardamine kokairensis*	cleistogamous mutant	0.111696867
Breeding system	*Leavenworthia crassa*	Outcrosser morph	0.015771684
Colour mutant	*Brassica napus*	white mutant	0.173001555
Colour mutant	*Moricandia arvensis*	white mutant	0.149565069
Flower colour polymorphism	*Boechera stricta*	pink morph	0.060580070
Flower colour polymorphism	*Boechera stricta*	purple morph	0.054429426
Flower colour polymorphism	*Cakile maritima*	white morph	0.016547552
Flower colour polymorphism	*Eruca vesicaria*	white morph	0.082257145
Flower colour polymorphism	*Erysimum cheiri*	purple cultivar	0.073997237
Flower colour polymorphism	*Erysimum cheiri*	white cultivar	0.026460490
Flower colour polymorphism	*Hesperis laciniata*	white morph	0.069557518
Flower colour polymorphism	*Hesperis matronalis*	white morph	0.094873544
Flower colour polymorphism	*Hormathophylla spinosa*	white morph	0.101607789
Flower colour polymorphism	*Leavenworthia stylosa*	white morph	0.066269050
Flower colour polymorphism	*Lobularia maritima*	deep purple cultivar	0.090407642
Flower colour polymorphism	*Marcus-kochia littorea*	light pink morph	0.019542946
Flower colour polymorphism	*Matthiola fruticulosa*	greenish morph	0.008349920
Flower colour polymorphism	*Matthiola incana*	white cultivar	0.138357728
Flower colour polymorphism	*Matthiola lunata*	white morph	0.079964493
Flower colour polymorphism	*Parrya nudicaulis*	white morph	0.115226060
Flower colour polymorphism	*Raphanus raphanistrum*	white morph	0.082072459
Flower colour polymorphism	*Raphanus raphanistrum*	yellow morph	0.032685632
Flower colour polymorphism	*Raphanus raphanistrum*	pink morph	0.082778860
Flower colour polymorphism	*Streptanthus glandulosus*	white morph	0.014907493
Gender dimorphism	*Hormathophylla spinosa*	female morph	0.035783402
Gender dimorphism	*Hormathophylla spinosa*	male morph	0.025226337
Gender dimorphism	*Lepidium sisymbrioides*	female morph	0.067913758
Gender dimorphism	*Lepidium solandri*	female morph	0.065685257
Gender dimorphism	*Pachycladon stellatum*	female morph	0.014244744
Gender dimorphism	*Pachycladon wallii*	male morph	0.059320935
Homeotic mutant	*Arabidopsis thaliana*	AGAMOUS mutant	0.001052532
Homeotic mutant	*Arabidopsis thaliana*	APETALA1 mutant	0.119617731
Homeotic mutant	*Arabidopsis thaliana*	APETALA3 mutant	0.102445400
Homeotic mutant	*Capsella bursapastoris*	Spe mutant	0.051187659
Phenotypic plasticity	*Cardamine hirsuta*	plastic change in stamens number	0.010624208
Phenotypic plasticity	*Cardamine hirsuta*	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
Moricandia foetida	0.039566021	0.13987379
Moricandia moricandioides	0.059142993	0.03730920
Moricandia nitens	0.041727403	0.07347209
Moricandia rytidocarpoides	0.025809374	0.10503623
Moricandia sinaica	0.027589330	0.10550411
Moricandia spinosa	0.019579372	0.20959717
Moricandia suffruticosa	0.063884437	0.20700167
Moricandia arvensis spring phenotype	0.080840848	0.02385532
Moricandia arvensis 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.

Functional Groups	Mantel R	p value
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. Diferences 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.

Pollinator functional group	spring phenotype	summer phenotype	spring phenotype (proportion)	summer phenotype (proportion)
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
Niche 3						
Angle	**80.587**	0.008	**79.431**	0.002	**64.930**	0.055
Angle/time	2.350	0.719	1.645	0.397	4.023	0.815
C1	**0.373**	0.000	**0.472**	0.000	**0.415**	0.000
C2	**0.104**	0.000	**0.142**	0.000	**0.104**	0.000
C3	**0.141**	0.000	**0.166**	0.000	**0.219**	0.000
C4	0.003	0.720	0.002	0.700	0.008	0.600
Wheatleaf	0.830	0.986	0.940	0.715	**1.060**	0.028
Niche 5						
Angle	**70.093**	0.002	**73.491**	0.002	**58.313**	0.049
Angle/time	**1.393**	0.021	1.783	0.745	**2.474**	0.011
C1	**0.356**	0.000	**0.472**	0.000	**0.240**	0.000
C2	**0.110**	0.000	**0.142**	0.000	**0.075**	0.000
C3	**0.128**	0.000	**0.166**	0.000	**0.118**	0.000
C4	0.003	0.727	0.002	0.700	0.006	0.545
Wheatleaf	1.120	0.673	**1.170**	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. θ_{real} is the mean angle over all possible combinations of pairs of species taking one species per clade. θ_{ace} is the mean angle between ancestral states between each pairs of clades. **dist$_{mrca}$** is the patristic distance (sum of brach length) between the most recent common ancestors of each pair of clade. We indicate the congervent 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= Anchonieae, C=Cardamineae, M=Malcolmieae, An=Anastaticeae).

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

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 larges 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 *Megacarpea* 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 an 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*.

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
Phylogenies including Moricandia					
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). PeerJ, 5, e3964.
2	273 [255]	YES	YES		Smith, S. A., & Brown, J. W. (2018). Constructing a broadly inclusive seed plant phylogeny. American journal of botany, 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?. Frontiers in Ecology and Evolution, 6, 52.
4	195 [163]	YES	YES	Brassiceae	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. Annals of Botany, 125(1), pp.29-47.
Time-calibrated phylogenies with more than 45 spp					
5	84 [48]	YES	YES	Euclideae	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. Molecular Phylogenetics and Evolution, 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: Ecological Archives E093-214. Ecology, 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. Nature communications, 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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 125(1), pp.29-47.
13	57 [23]	YES	YES	Chorisporeae	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. Annals of Botany, 125(1), pp.29-47.
14	51 [28]	YES	YES	Coluteocarpaeae	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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 125(1), pp.29-47.
Time-calibrated phylogenies with less than 45 spp					
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. Annals of Botany, 125(1), pp.29-47.
21	9	YES	YES	Alyssopsideae	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. Annals of Botany, 125(1), pp.29-47.
22	30	YES	YES	Anastaticeae	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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 125(1), pp.29-47.
29	16	YES	YES	Cochlearieae	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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 125(1), pp.29-47.
32	13	YES	YES	Crucihimalayeae	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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 125(1), pp.29-47.
39	13	YES	YES	Hillielleae	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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 125(1), pp.29-47.
46	4	YES	YES	Notothlaspideae	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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 125(1), pp.29-47.
52	19	YES	YES	Thlaspideae	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. Annals of Botany, 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. Annals of Botany, 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. Annals of Botany, 125(1), pp.29-47.

Non-time calibrated phylogenies

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. Annals of Botany, 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. New Phytologist, 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). Molecular Biology and Evolution, 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 Machaerophorus (Brassicaceae) based on molecular data and implication for its systematics. Plant Systematics and Evolution, 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. BMC genomics, 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 Thysanocarpus (Brassicaceae). Systematic Botany, 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. Molecular biology and evolution, 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. Plant Systematics and Evolution, 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. *American journal of botany*, 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 Microthlaspi (Brassicaceae: Coluteocarpeae) and related genera. Taxon, 65(1), 79-98.
65	22	NO	YES	Alysseae	Cecchi, L., Gabbrielli, R., Arnetoli, M., Gonnelli, C., Hasko, A., & Selvi, F. (2010). Evolutionary lineages of nickel hyperaccumulation and systematics in European Alysseae (Brassicaceae): evidence from nrDNA sequence data. Annals of Botany, 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. EvoDevo, 5(1), 42.
67	38	NO	YES	Descurainia	Goodson, B. E., Rehman, S. K., & Jansen, R. K. (2011). Molecular systematics and

					biogeography of Descurainia (Brassicaceae) based on nuclear ITS and non-coding chloroplast DNA. Systematic Botany, 36(4), 957-980.
68	15	NO	NO	Thlaspi	Koch, M., & Al-Shehbaz, I. A. (2004). Taxonomic and phylogenetic evaluation of the American. Systematic Botany, 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 Machaerophorus (Brassicaceae) based on molecular data and implication for its systematics. Plant Systematics and Evolution, 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. New Phytologist, 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 Vella pseudocytisus-V. aspera complex (Brassicaceae). Turkish Journal of Botany, 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 (Brassiceae, Brassicaceae): a combined analysis of ITS nrDNA sequences and morphological data. Annals of Botany, 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 Pachycladon (Brassicaceae) in New Zealand. Molecular phylogenetics and evolution, 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. Plant Systematics and Evolution, 283(1-2), pp.33-56.
78	195	NO	NO	Brassiceae	BrassiBase ITS tree- https://brassibase.cos.uni-heidelberg.de/?action=phlv&subaction=Brassiceae
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. Molecular biology and evolution, 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 Schivereckia podolica (Brassicaceae) and its close relatives. Flora, 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.

Last Name	First Name	Host institution
Abdelaziz	Mohamed	University of Granada (Spain)
Aizen	Marcelo	Universidad Nacional del Comahue-CONICET (Argentina)
Aguado	Luis Oscar	Castilla y Leon Regional Goverment (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	Maaike	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)

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)

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	Hymeneptera	Apidae (*Apis* 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 (*Bombylius*)

	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, Micetophyliidae, 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		