# Phenotypic plasticity triggers rapid morphological convergence

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**Abstract**

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

## Introduction

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

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

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

## Results

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

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

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

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

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

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

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

184 Evolutionary divergence is mostly associated with the occupation of new ecological niches (*2, 5*).
185 Shifts between pollination niches are an important factor driving diversification in angiosperms
186 (*35*), including Brassicaceae (*36, 37)*. We investigated whether the plasticity-mediated jump of *M.*
187 *arvensis* across the floral morphospace implicated the exploration of new pollination niches. We
188 compiled a comprehensive database comprising 456,031 visits done by over 800 animal species
189 from 19 taxonomical orders, 276 families and 43 functional groups to 554 Brassicaceae species
190 of 39 tribes (Methods, Supplementary Data 3). Afterwards, we identified the pollination niches of
191 these Brassicaceae plants and determined the niche of each *M. arvensis* floral phenotype by
192 means of bipartite modularity, a complex network tool that identifies the set of plants interacting
193 with similar groups of pollinators (*18*). This analysis showed that the network was significantly
194 modular (*Modularity* = 0.385, $P < 0.0001$) and identified eight different pollination niches
195 associated with different groups of pollinators (Figure 3a) located in different regions of the
196 morphospace (Figure 3b, $F = 44.4$, $P < 0.001$, $R^2 = 0.39$, Adonis test; Table S4).
197
198 Because different insects visited *M. arvensis* in spring and summer (Table S5), this plant species
199 shifted between pollination niches seasonally (Figure 3b). During spring, *M. arvensis* belonged to
200 a niche where most frequent pollinators were long-tongued bees, beeflies, and hawkmoths
201 (pollination niche 5 in Figure 3a) (*18*). This pollination niche was also shared by the other
202 *Moricandia* species (Figure 3c). In contrast, during summer *M. arvensis* belonged to a niche
203 dominated by short-tongued bees (pollination niche 3 in Figure 3a). This niche shift was
204 substantial. In fact, the overlap between the spring and summer pollinator niches of *M. arvensis*
205 (*Czekanowski* overlap index = 0.35) was significantly lower than the overlap between congeneric
206 species of Brassicaceae (0.57 ± 0.42, *Z*-score = -0.51, $P = 0.003$). This shift even entailed the
207 divergence from the ancestral niche of the *Moricandia* lineage (pollination niche 5 according to a
208 stochastic character mapping inference, Figure 3c). The within-individual floral plasticity allows *M.*
209 *arvensis* to exploit a pollination niche that differs markedly from that exploited by its closest
210 relatives and that have largely diverged from the ancestral niche.
211
212 ***Plasticity-mediated floral convergence***

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

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

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

## Conclusions

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

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

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

## Materials and Methods

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Under the first approach, we calculated both distance- and frequency-based measures of convergence (*39*). Distance-based measures (C1–C4) are calculated between two lineages relative to their distance at the point in evolutionary history where the two lineages were maximally dissimilar. C1 specifically measures the proportion of phenotypic distance closed by evolution, ranging from 0 to 1 (where 1 indicates complete convergence). To calculate C1, ancestral states are reconstructed (via a Brownian motion model of evolution) for two or more putatively convergent lineages, back to their most recent common ancestor. The maximum phenotypic distance between any pair of ancestors (Dmax) is calculated, and compared with the phenotypic distance between the current putatively convergent taxa (Dtip). The greater the difference between Dmax and Dtip, the higher the index. C2 is the raw value of the difference between the maximum and extant distance between the two 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. These four measures quantify incomplete convergence in multidimensional space. Finally, C5, the frequency-based measure, quantifies

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

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

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

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**Competing interests**

The authors declare no competing interests.

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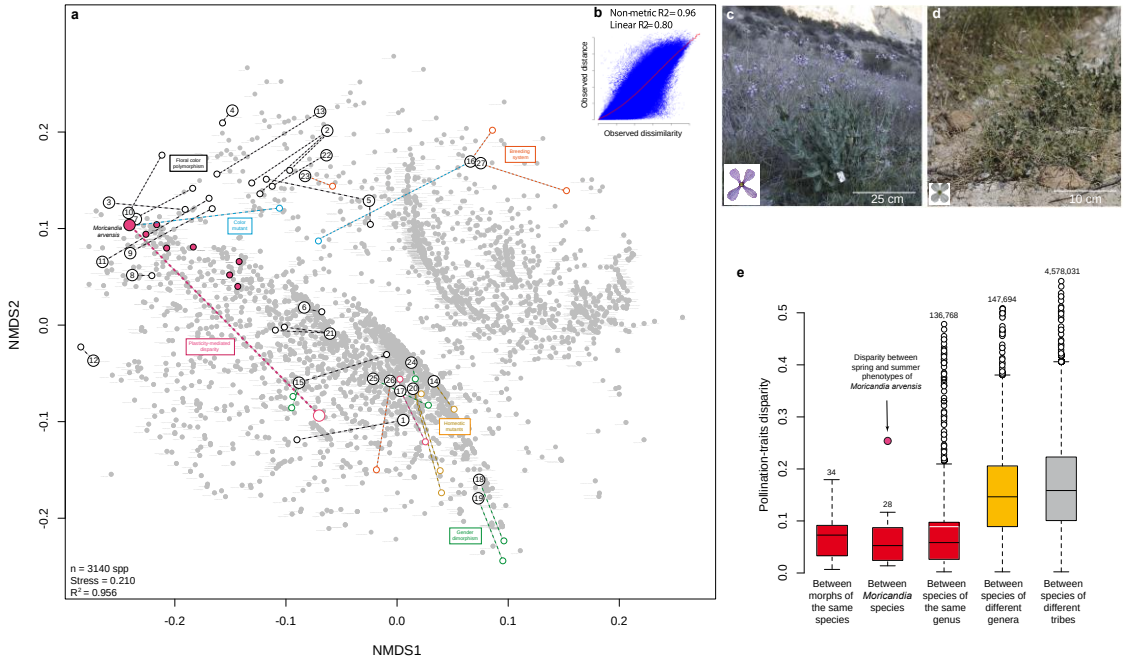
782 **Figures**

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

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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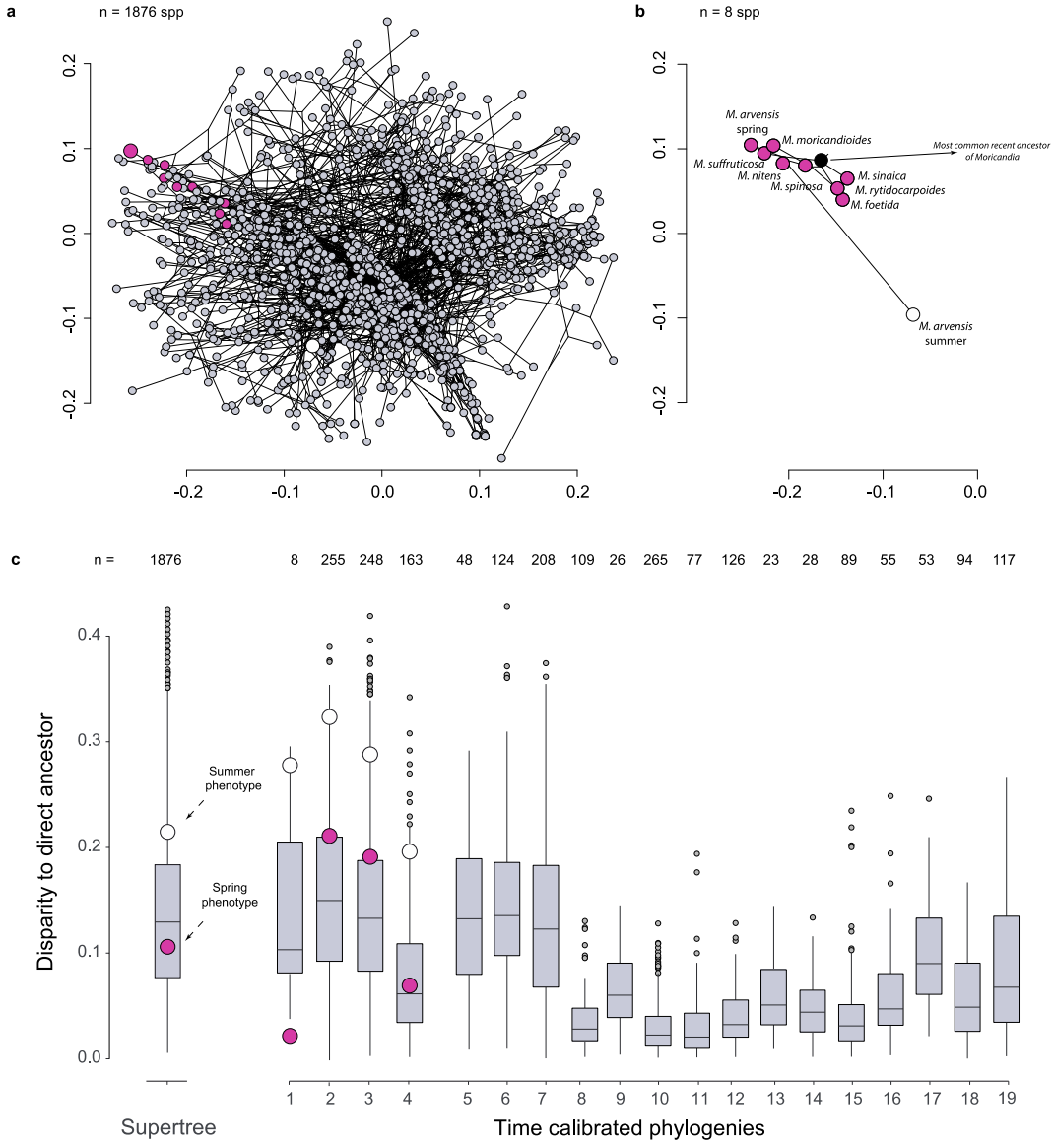


**Figure 2. Phylogenetic-mediated floral divergence.** (**A**) Floral phylomorphospace using the supertree that includes 1876 Brassicaceae species. (**B**) Phylomorphospace considering only the eight *Moricandia* species, using the Perfectti et al.'s phylogeny (phylogeny # 1 in Table S8). (**C**) Floral 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

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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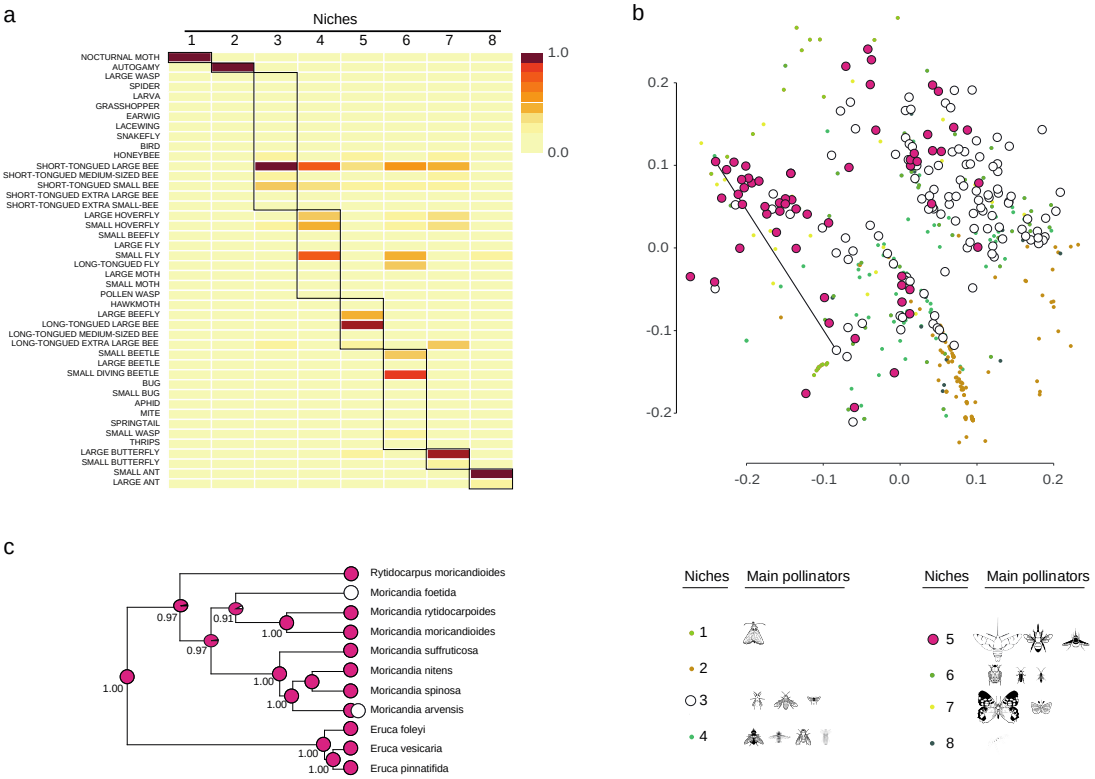



**Figure 3. Plasticity-mediated changes in pollination niches**. (**A**) Outcome of the modularity analysis showing the number of pollination niches inferred, the among-niche differences in relative frequency of each pollinator functional group, and the pollinator functional groups defining the niches (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.

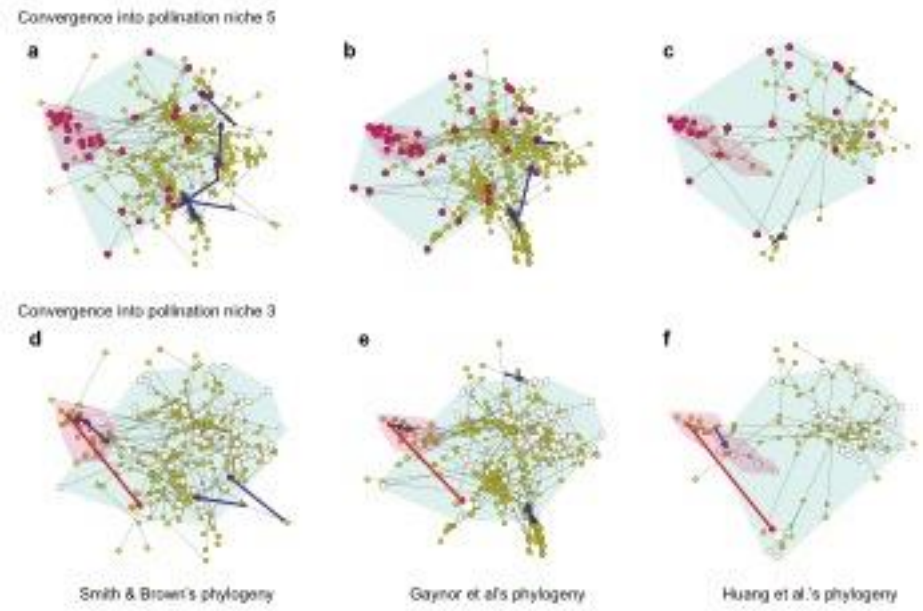
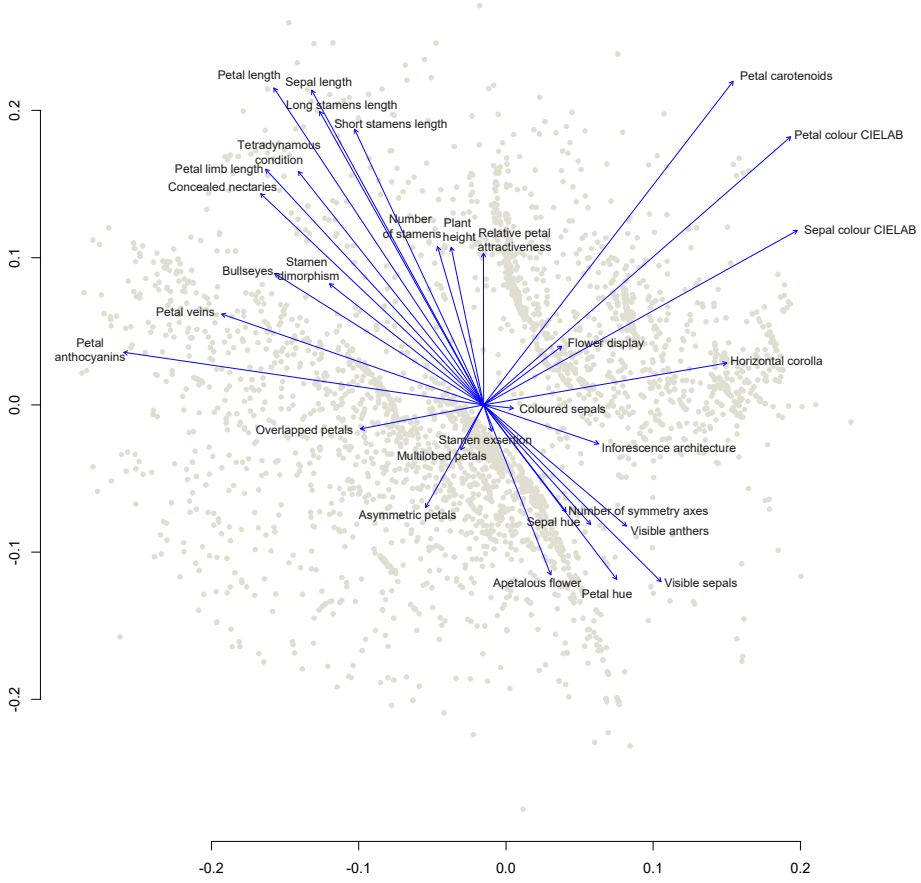



**Figure 4. Plasticity-mediated floral convergence**. Convergent lineages crossing into the region of the morphospace delimited by the pollination niche of the *M. arvensis* during spring (the shade convex hull) according to (**A**) Smith & Brown's phylogeny, (**B**) Gaynor et al.'s phylogeny, and (**C**) 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.

## 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. $\theta_{real}$ is the mean angle over all possible combinations of pairs of species taking one species per clade. $\theta_{ace}$ is the mean angle between ancestral states between each pairs of clades. $dist_{mrca}$ is the patristic distance (sum of 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 | $\theta_{real}$ | $\theta_{ace}$ | $dist_{mrca}$ | $\theta_{real}/dist_{mrca}$ | $\theta_{real}/dist_{mrca}$ p-value | $\theta_{ace}+\theta_{real}/dist_{mrca}$ | $\theta_{ace}+\theta_{real}/dist_{mrca}$ p-value | Convergent clades | Tribe | Niche |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **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.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

(12) **Asymmetric petals**. Brassicaceae is characterized for bearing four symmetric petals. However, some species exhibit corollas with asymmetric petals, a character considered a morphological novelty. Presence of asymmetric petals causes corollas to show zygomorphy. This character, by affecting in an extreme way the number of symmetry axes, have 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 |

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|---|---|---|---|---|---|
| | | | | | 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 |

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| | | | | | 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 |

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|---|---|---|---|---|---|
| | | | | | 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) |

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

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

| | Functional Group | Body length | Resource | Behavioural notes | Type of visits | Order | Examples |
|---|---|---|---|---|---|---|---|
| 1 | Long-tongued extra-large bees | ≥ 15 mm | Nectar + Pollen | Partially introducing the head in the flower | Legitimate | Hymenoptera | Anthophoridae, Apidae |
| 2 | Long-tongued large bees | 10-15 mm | Nectar + Pollen | Partially introducing the head in the flower | Legitimate | Hymenoptera | Anthophoridae |
| 3 | Long-tongued medium-sized bees | < 10 mm | Nectar + Pollen | Partially introducing the head in the flower | Legitimate | Hymenoptera | Anthophoridae |
| 4 | Honeybees | 6-12 mm | Nectar + Pollen | Introducing the whole head in the flower | Legitimate | Hymenoptera | Apidae (*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*) |

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|---|---|---|---|---|---|---|---|
| | 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 |

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|---|---|---|---|---|---|---|---|
| 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 | | |