

# Trade-offs among plant reproductive traits determine interactions with floral visitors

Jose B. Lanuza<sup>1,2\*</sup>, Romina Rader<sup>1</sup>, Jamie Stavert<sup>3</sup>, Liam K. Kendall<sup>4</sup>,  
Manu E. Saunders<sup>1</sup> and Ignasi Bartomeus<sup>2</sup>

Plant life strategies are constrained by cost-benefit trade-offs that determine plant form and function. However, despite recent advances in the understanding of trade-offs for vegetative and physiological traits, little is known about plant reproductive economics and how they constrain plant life strategies and shape interactions with floral visitors. Here, we investigate plant reproductive trade-offs and how these reproductive compromises drive interactions with floral visitors using a dataset of 17 reproductive traits for 1,506 plant species from 28 plant-pollinator studies across 18 countries. We tested whether a plant's reproductive strategy predicts its interactions with floral visitors and if the different reproductive traits predict the plant's role within the pollination network. We found that over half of all plant reproductive trait variation was explained by two independent axes that encompassed plant form and function. Specifically, the first axis indicated the presence of a trade-off between flower number and flower size, while the second axis indicated a pollinator dependency trade-off. Plant reproductive trade-offs somewhat explained the presence or absence of interactions with floral visitors, but not differences in visitation rate. However, we did find important differences in the interaction level among floral visitor guilds on the different axes of trait variation. Finally, we found that plant size and floral rewards were the most important traits in the understanding of the species network role. Our results highlight the importance of plant reproductive trade-offs in determining plant life strategies and plant-pollinator interactions in a global context.

---

<sup>1</sup> School of Environmental and Rural Science, University of New England, Armidale, New South Wales 2350, Australia. <sup>2</sup> Estación Biológica de Doñana (EBD-CSIC), E-41092 Seville, Spain. <sup>3</sup> Department of Conservation | Te Papa Atawhai, Auckland, New Zealand. <sup>4</sup> Centre for Environmental and Climate Science, Lund University, Sölvegatan 37, S-223 62 Lund, Sweden. \* e-mail: [barragansljose@gmail.com](mailto:barragansljose@gmail.com)

Despite the astonishing diversity of floral structures among flowering plants<sup>1,2</sup> and their importance in shaping plant-pollinator interactions<sup>3,4</sup>, a unified framework that explores plant reproductive compromises is currently lacking<sup>5</sup>. In addition, macroecological studies that investigate plant reproductive traits are scarce<sup>6–9</sup> and consequently, there is poor understanding of how reproductive traits drive interactions with floral

visitors at large scales<sup>10–13</sup>. Linking the position in the trait-space with the different pollinator groups could help to improve our understanding of plant-pollinator associations<sup>14</sup>. Further, there is increasing interest in understanding drivers of plant-pollinator interactions using trait-based approaches<sup>3,15</sup> and trait-matching analyses<sup>16,17</sup>. However, reproductive traits have been overlooked beyond highly specialised pollination systems<sup>4</sup> despite the apparent generalist nature of plant-pollinator interactions<sup>18,19</sup>. In addition, it is unclear how specific plant reproductive biology traits influence plant-pollinator interactions<sup>20,21</sup>.

Species can optimise their fitness through various life-history traits, yet trade-offs among those traits constrain the range of potential strategies that a species can use. With the recent availability of large trait databases (e.g., TRY <sup>22</sup> and COMPADRE <sup>23</sup>), plant ecological strategies are being increasingly examined, and are facilitating the identification of global patterns and constraints in plant form and function<sup>12,24,25</sup>. However, most studies have focused on vegetative traits such as leaf<sup>26</sup>, wood<sup>27</sup>, or root<sup>28</sup> trade-offs with little or no attention given to reproductive traits<sup>5,29</sup> which are critical to plant life strategies that shape interactions with pollinators and ultimately determine plant reproductive success. For instance, short lived versus perennial species tend to have low versus high levels of outcrossing, respectively<sup>9,30</sup> and outcrossing levels are positively correlated with flower size<sup>31</sup>. In addition, the presence of costly rewards (e.g., pollen or nectar) and showy flowers or floral displays can only be understood through consideration of plant species' reliance upon animal pollination (pollinator dependence) and its role in attracting pollinators<sup>32,33</sup>. However, it is still unknown to what extent these different reproductive compromises determine plant-pollinator interactions.

Several studies have identified links between plant traits and plant-pollinator network properties<sup>34–36</sup>. Moreover, plant traits can define species' network roles (e.g., specialists vs generalists)<sup>20,37</sup>. For example, plant species that occupy reproductive trait space extremes are more likely to exhibit higher levels of specialisation and be more reliant

on the trait-matching with pollinators<sup>38,39</sup>. Morphological matching between plant and floral visitors often determines plant-pollinator interactions, and can thus strongly influence interaction network structure<sup>16,40</sup>. Remarkably, the combination of traits have shown to increase the predictive power of the network interactions<sup>41</sup>. Therefore, considering the different plant reproductive trade-offs which represent the species strategy within the network<sup>14</sup> could progress our understanding of plant-pollinator interactions. Further, we know little if the different network patterns generally studied at the community level are maintained when we scale up at macroecological scale.

Here, we aim to explore the potential trade-offs among reproductive traits and how these influence plant-pollinator interactions. First, we identify the major axes of reproductive trait variation and trade-offs that determine plant form and function. Second, we investigate how plant species' position in trait-space interactions with floral visitors. Finally, we investigate how both the main axes of trait variation, and individual traits, influence plant species' roles within networks using a set of complementary interaction network metrics (i.e., interaction strength, normalized degree and specialization).

## RESULTS

**Plant strategies.** The phylogenetically informed principal component analysis (pPCA) captured by the first two and three axes 51.8% and 70.97% of trait variation, respectively (Fig. 1 and Supplementary Fig. S5) and had a phylogenetic correlation ( $\lambda$ ) of 0.76. The first principal component (PC1) represented 26.72% of the trait variation and indicated a trade-off between flower number and flower size. We refer to this axis as the 'flower number - flower size trade-off', as already described in previous studies<sup>42,43</sup>. Hence, one end of the spectrum comprised species with high investment in flower number and plant height but small flower size, short style length and low ovule number. The other end of this spectrum comprised species that were short in height and invested in large flowers, long styles, many ovules, but few flowers. The main contributing traits to PC1

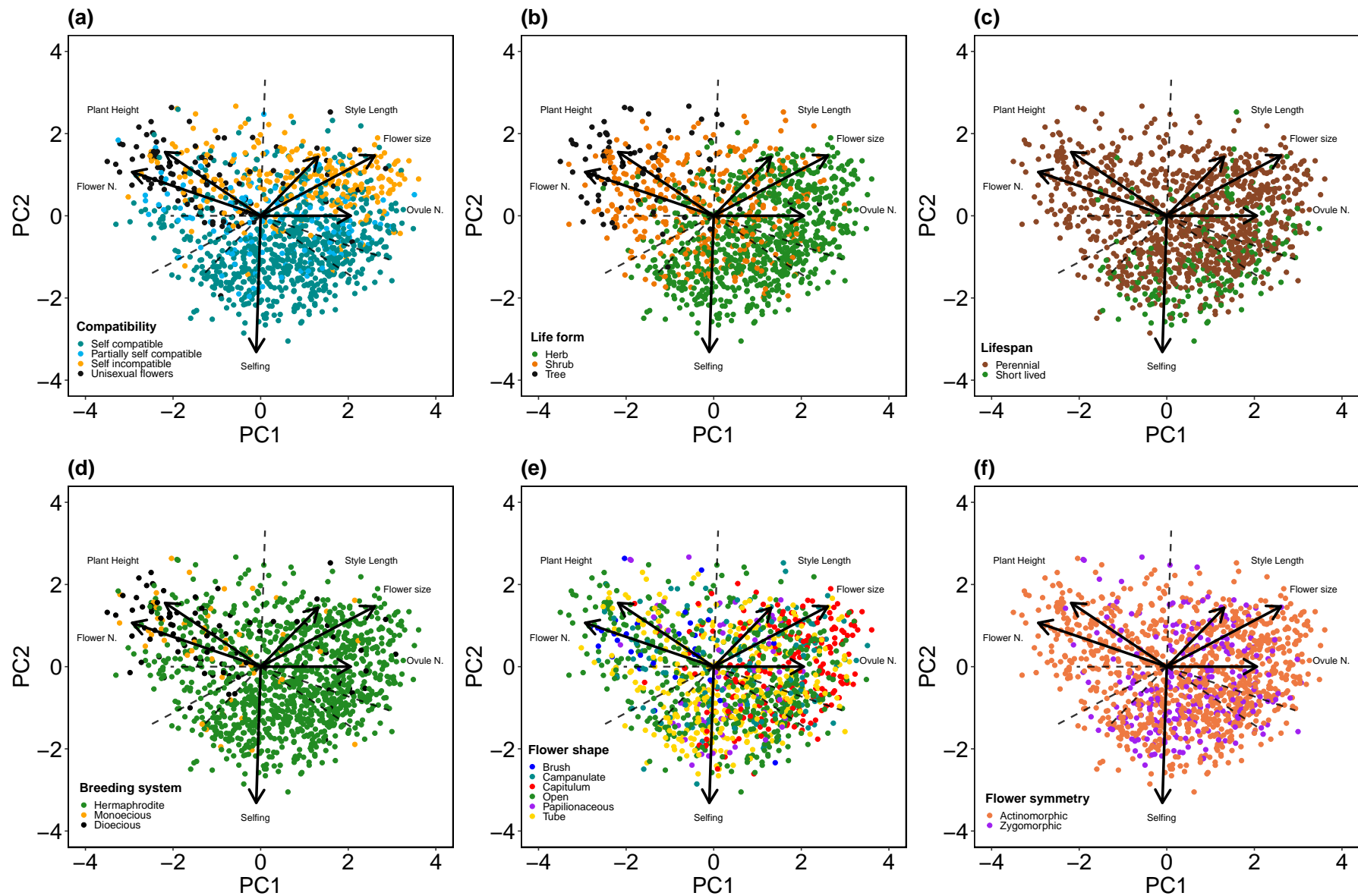
102 were plant height, flower number, ovule number and flower size (loadings  $> |0.5|$ ;  
103 Supplementary Table S3) but style length also contributed moderately on PC1 (loading  
104  $= -0.33$ ). The second principal component (PC2) represented 25.05% of the trait variation  
105 and indicated a trade-off between low and high pollinator dependence. We refer to  
106 this axis as the 'pollinator dependence trade-off'. The main driver of trait variation on  
107 PC2 was autonomous selfing (loading  $= 0.85$ ) but the other traits (except ovule number)  
108 also made moderate contributions (loadings from 0.27 to 0.4; Supplementary Table S3).  
109 We found that high pollinator dependence was associated with larger and a higher  
110 number of flowers, greater plant height and longer styles. In contrast, species with high  
111 levels of autonomous selfing tended to have fewer and smaller flowers, had shorter  
112 styles and were shorter in height. Further, PC3 explained a considerable amount of trait  
113 variability (19.17%) and the main contributors to this axis were style length (loading  
114  $= -0.66$ ) and the degree of autonomous selfing (loading  $= -0.51$ ). The remaining traits,  
115 apart from ovule number, were moderately correlated to changes on PC3 (loadings  
from -0.23 to -0.46; Supplementary Table S3). Thus, because style length was correlated  
with all traits on PC3 and was the main driver of trait variation, we refer to this axis  
as the 'style length trade-off'. Further, the pPCA with the subset of species that had  
nectar and pollen quantity data showed that nectar quantity (microlitres of nectar per  
flower) was positively associated with flower size, style length and ovule number (PC1,  
23.40%); and pollen quantity (pollen grains per flower) was positively correlated with  
flower number and plant height and negatively associated with autonomous selfing  
(PC2, 21.67%; Supplementary Fig. S6). This pPCA explained similar variance with the  
first two principal components (45.07%) and similar associations of traits despite some  
variability in the loadings (Supplementary Table S4).



**Fig. 1 | Plant life-history strategies.** Phylogenetically informed principal component analysis (pPCA) of 1,236 plant species from 28 plant-pollinator network studies. The solid arrows indicate the direction of the different quantitative traits (flower number, plant height, style length, flower size, ovule number and level of autonomous selfing) across the two main axes of trait variation. The length of the arrows indicate the weight of the variables on each principal component and the dashed lines show the opposed direction of trait variation. The icons at both ends of arrows and dashed lines illustrate the extreme form of the trait continuum.

116 We found that most categorical traits were statistically associated with the first two axes  
 117 of trait variation (Fig. 2 and Supplementary Table S2). Flower symmetry, which was  
 118 only associated with PC2 (Sum of squares = 8.51, F-value = 14.72,  $P < 0.01$ ), and nectar  
 119 provision, which was independent of PC1 and PC2 (PC1: Sum of squares = 0.37, F-value

120 = 0.29 ,  $P = 0.59$ ; PC2: Sum of squares = 0.83, F-value = 1.43,  $P = 0.23$ ) showed lack of  
121 statistical association. In addition, we found (with a Tukey test) statistical differences  
122 between the different levels of categorical traits in the trait space (Supplementary Fig.  
123 S7). Regarding self compatibility, we found larger differences on PC2 (i.e., species  
124 with unisexual flowers that were self incompatible were statistically differentiated from  
125 species with partial or full self compatibility; Supplementary Fig. S7a and Fig. S7b). Life  
126 forms differed statistically across both axes of trait variation and followed a gradient  
127 of larger life forms (trees and shrubs) with higher pollinator dependence to smaller  
128 ones (herbs) with lower pollinator dependence (Supplementary Fig. S7c and Fig. S7d).  
129 Consequently, lifespan also followed this gradient but perennial and short lived species  
130 only differed statistically on PC2 (Supplementary Fig. S7e and Fig. S7f). Species with  
131 unisexual flowers (monoecious and dioecious) were clustered on both extremes of  
132 the first two principal components and had the highest pollinator dependence and  
133 highest number of flowers (Supplementary Fig. S7g and Fig. S7h). Moreover, we  
134 found that the campanulate and capitulum flower shapes were differentiated from tube,  
135 papilionaceous, open and brush shapes in the trait space. The former morphologies  
136 had larger flowers and greater pollinator dependence, while the latter had higher  
137 flower number and greater autonomous selfing (Supplementary Fig. S7i and Fig. S7j).  
138 Regarding flower symmetry, zygomorphic flowers were associated with lower levels of  
139 pollinator dependence, whereas actinomorphic flowers had higher levels of pollinator  
140 dependence (Supplementary Fig. S7k and Fig. S7l).



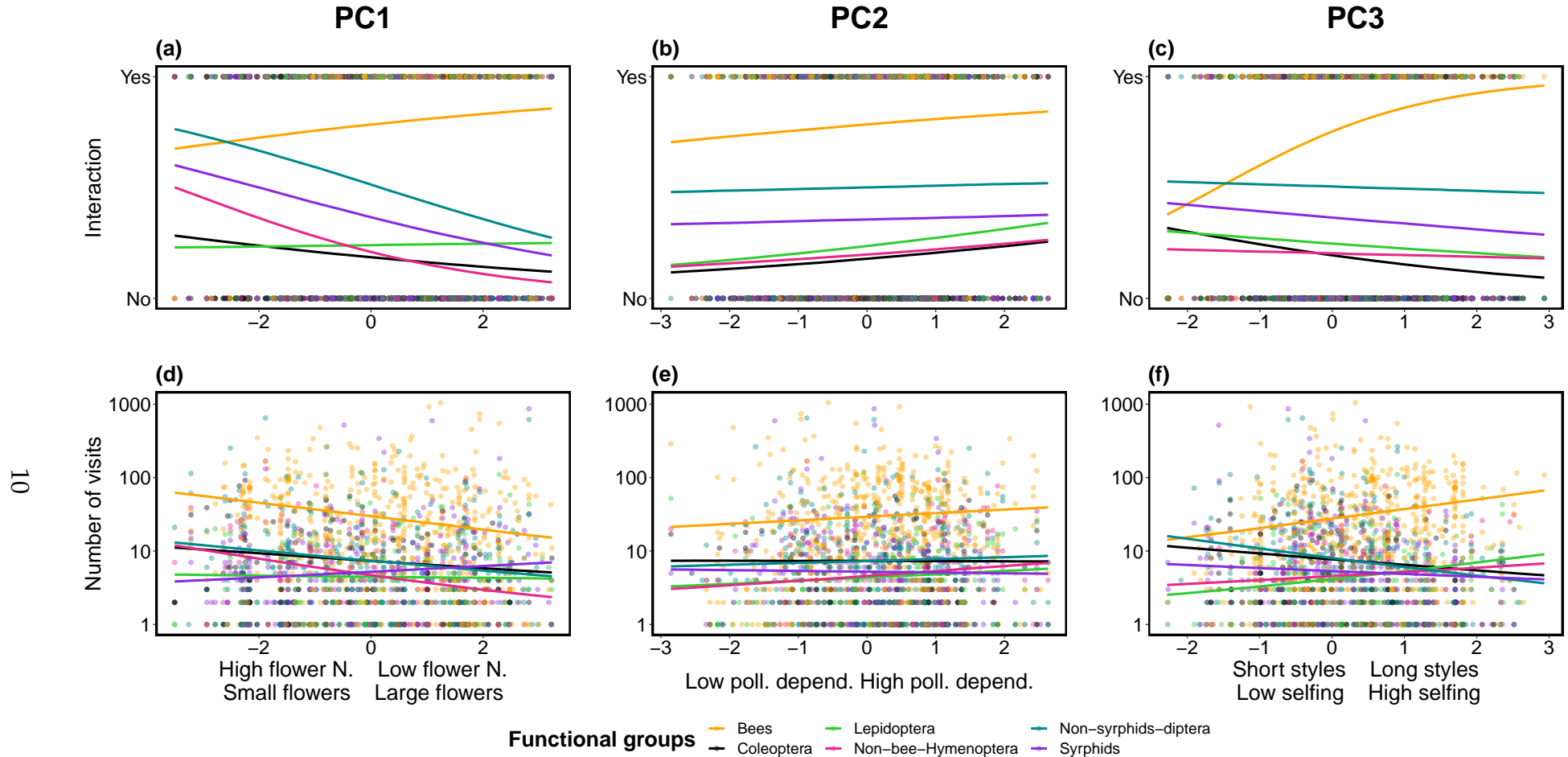
**Fig. 2 | Location of the different qualitative traits on the trait space.** The panel is composed by the traits that showed statistical association with the first two axes of trait variation: compatibility system (a), life form (b), lifespan (c), breeding system (d), flower shape (e) and flower symmetry (f).

**Phylogenetic signal of traits.** We found a strong phylogenetic signal ( $P < 0.01$ ) in all quantitative traits (Supplementary Table S5). The traits that showed the highest phylogenetic signal were ovule number ( $\lambda = 1$ ), pollen grains per flower ( $\lambda = 1$ ) and plant height ( $\lambda = 0.96$ ), followed by flower length ( $\lambda = 0.75$ ), flower width ( $\lambda = 0.73$ ), number of flowers per plant ( $\lambda = 0.69$ ) and nectar concentration ( $\lambda = 0.65$ ). The traits that showed a moderate phylogenetic signal were inflorescence width ( $\lambda = 0.57$ ), style length ( $\lambda = 0.49$ ) and autonomous selfing ( $\lambda = 0.34$ ). Finally, microliters of nectar per flower showed the lowest phylogenetic signal of all traits ( $\lambda = 0.14$ ).

**Visitation patterns.** The main axes of trait variation explained partly presence-absence interactions between plant and floral visitors (*conditional* $R^2 = 0.26$ ; *marginal* $R^2 = 0.20$ ) but little of the overall visitation rates (*conditional* $R^2 = 0.31$ ; *marginal* $R^2 = 0.06$ ). However, we found relevant trends across the different floral visitor guilds on both presence-absence and visitation interactions (Fig. 3). On the pollinator dependence trade-off, all floral visitor guilds interacted more frequently with plant species with higher pollinator dependence (PC2; Fig. 3b and Fig. 3e). For presence-absence interactions we found that all Diptera, Coleoptera and non-bee Hymenoptera guilds interacted more frequently with plants with high flower number and small flowers (flower number - flower size trade-off, PC1; Fig. 3a) but bees and Lepidoptera interacted slightly more frequently with plant species with low flower number but large flowers. For presence-absence interactions on PC3 (style length trade-off; Fig. 3c), we found that bees interacted clearly more with plant species with long styles and high selfing and the rest of the guilds interacted slightly more with plant species with short styles and low selfing. In addition, all guilds other than Syrphids and Lepidoptera (i.e., all Hymenoptera, non-Syrphidae-Diptera and Coleoptera) showed greater visitation rates on species with small numerous flowers (PC1; Fig. 3d). On the style length trade-off, bees, Lepidoptera and Non-Anthophila-Hymenoptera showed greater visitation rates on plant species with larger styles and higher levels of selfing; while Syrphidae, Non-Syrphidae-Diptera and Coleoptera showed higher visitation rates on species with shorter styles and lower selfing (Fig. 3f).



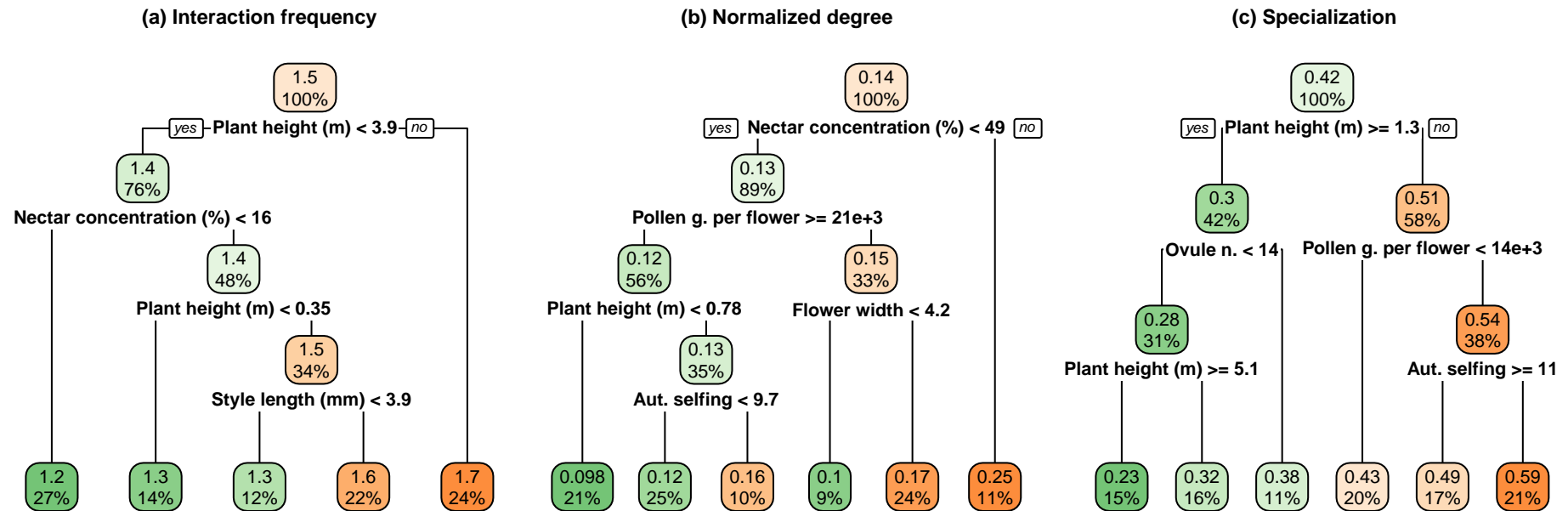
170 The additional model for both presence-absence of interactions (*marginalR2* = 0.29;  
171 *conditionalR2* = 0.19) and visitation rate (*marginalR2* = 0.30; *conditionalR2* = 0.03)  
172 for the most represented families of bees showed that the family Apidae was the main  
173 driver of the observed patterns and that the contrasting differences between presence-  
174 absence and visitation rate for bees on PC1 (Fig. 3a and Fig. 3d) were driven by the  
175 family Andrenidae which interacted more frequently on presence-absence interactions  
176 with plant species with low number of flower but large (Supplementary Fig. S8).



**Fig. 3 | Interaction (yes/no) and visitation rates across the three main axes of trait variation per floral visitor guild.** Fitted posterior estimates of the presence/absence of interaction (a, b and c) and number of visits (d, e and f) made by the different floral visitors guilds in relation to PC1, PC2 and PC3. PC1 represents the flower number - flower size trade-off, PC2 represents the pollinator dependence trade-off and PC3, the style length trade-off. For visualization purposes, due to large differences between the visitation rates of bees and the rest of guilds, the number of visits was log-transformed (Y-axis of lower panel).

**Plant species functional roles.** The variance of the different plant species-level network metrics was poorly explained by the three main axes of trait variation (Supplementary Fig. S9; interaction frequency ~ PCs, *conditionalR2* = 0.11, *marginalR2* = 0.02; normalized degree ~ PCs, *conditionalR2* = 0.24, *marginalR2* = 0.02; and, specialization ~ PCs, *conditionalR2* = 0.37, *marginalR2* = 0.03). Overall, the most notable trends were found on PC1 and PC3 for interaction frequency and specialization. On the flower number - flower size trade-off (PC1), interaction frequency was higher for plant species with more flowers but was lower for plant species with larger flowers. On PC1, specialization showed the opposite trend. On the style length trade-off (PC3), interaction frequency was lower for plants with shorter styles and lower autonomous selfing and higher for species with longer styles and higher autonomous selfing. Again, specialization showed the opposite trend to interaction frequency.

When we further investigate which combination of traits drive plant network roles, we show that the regression tree for visitation frequency was best explained by plant height, nectar concentration and style length (Fig. 4a). Specifically, species taller than 3.9 m had the highest interaction frequency, while species that were shorter than 3.9 m and had a nectar concentration lower than 16% had the lowest interaction frequency. Normalized degree was best explained by nectar concentration, pollen grains per flower, plant height, flower width and autonomous selfing (Fig. 4b). Species with a nectar concentration over 49% had the highest levels of normalized degree, whereas species with nectar concentration lower than 49%, more than 21,000 pollen grains per flower and height less than 0.78 m had the lowest normalized degree. Finally, specialization was best explained by plant height, ovule number, pollen grains per flower and autonomous selfing (Fig. 4c). Overall, plant species with the highest specialization were shorter than 1.3 m, had more than 14,000 pollen grains per flower and autonomously self-pollinated less than 11% of their fruits. In contrast, species taller or equal than 5.1 m and with lower than 14 ovules per flower had the lowest specialization values.



**Fig. 4 | Contribution of traits in plant's network roles.** Regression tree analysis of interaction frequency (log-transformed), normalized degree and specialization for the subset of species with quantitative data for pollen and nectar traits. The superior value inside the node indicates the mean value of the different species-level metric and the lower value, the percentage of species that are considered in each node. Thus, the top node has the mean value of the named trait for the 100% of species. Each node has a yes/no question and when the condition is fulfilled, the branch turns to the 'yes' direction and when not, to the 'no' direction. This rationale is followed in all the regression trees as indicated in the first branch division of the topmost node of each tree.

## DISCUSSION

Here, we show that plant species exhibit clear trade-offs among their vegetative and reproductive traits that determined different interaction levels with floral visitor guilds. These trade-offs are differentiated on three main axes of trait variation: (i) flower number - flower size, (ii) pollinator dependence and (iii) style length. These reproductive trade-offs somewhat explained the presence or absence of interactions with floral visitors, but not differences in visitation rate. However, on both qualitative and quantitative interactions we found marked associations of floral visitor guilds with the main axes of trait variation. Further, we found that plant height and floral reward related traits were best at characterising plant species functional roles within pollination networks.

Over half of all plant trait variation was captured by the flower number - flower size and pollinator dependence trade-offs. Trait variation on these two axes was associated with the 'fast-slow continuum' in plant<sup>12</sup> and animal<sup>44</sup> life-history strategies, as indicated by the different floral and reproductive biology traits associated with plant height, life form and lifespan. The 'slow' part of this continuum (i.e., tall trees and shrubs) included plant species with many flowers, few ovules, higher pollinator dependence, frequent occurrence of self-incompatibility and more complex breeding systems (e.g., monoecious and dioecious species). In contrast, plant species that employed the 'fast' strategy (i.e., short herbs), had fewer flowers, more ovules, frequent occurrence of self-compatibility and lower pollinator dependence. Further, on the first two axes of trait variation, we found additional support for the previously described positive association between higher outcrossing rate and larger floral display<sup>31</sup>. The positive correlation between larger floral display and higher pollinator dependence in our dataset further confirmed this trend (see Supplementary Fig. S10).

Despite the low predictive power of the main trait variation axes for broad-level interaction patterns (presence-absence of interactions and visitation rate), we found changes

in the interaction patterns among and within floral visitor guilds across these axes that suggest plant life-history strategies strongly influence plant-pollinator interactions. For example, all floral visitor guilds visited plant species with higher pollinator dependence more frequently, and high pollinator dependence was associated with large floral displays and greater pollen quantities (Fig. 1 and Supplementary Fig. S6). This trend is consistent with previous studies that show plant species with higher reproductive investment tend to be visited by pollinators more frequently<sup>37,45,46</sup>. In regard to the flower number - flower size and style length trade-offs, different pollinator guilds showed contrasting visitation rates across the continuum of trait variation, which could be associated with different pollination syndromes at a macroecological scale. For instance, bees and syrphid flies were clearly associated with opposing life-strategies on PC1 and PC3 (Fig. 3) suggesting possible niche partitioning<sup>47,48</sup> between these two guilds. However, despite floral rewards, related traits were among the best at characterising species functional roles (Fig. 4), yet the association between reproductive trade-offs and floral visitors did not account for floral rewards because there was insufficient data available. More detailed exploration of reproductive trade-offs in conjunction with floral rewards is needed to help elucidate plant-pollinator associations. In any case, it is worth noting that other local factors such as species relative abundances, surely explain part of the observed variability<sup>17,49,50</sup> that reproductive trade-offs do not.

To conclude, we provide the first description of plant reproductive trade-offs using a large global dataset of plant traits. We identified the major reproductive strategies of flowering plants and how these strategies influence interactions with different floral visitor guilds. Although the explained variation that we found in the first two axes is lower than previous studies of vegetative traits<sup>24,25</sup> it is consistent with the largest and most recent study that has characterised plant life strategies with vegetative and reproductive traits<sup>12</sup>. Future work needs to integrate the reproductive compromises that we have identified with vegetative and physiological trade-offs to create a more comprehensive spectrum of plant trait variation. Further, the varying level of phylogenetic signal among traits deserves further attention to understand evolutionary changes

on mating and flower morphology in response to pollinators<sup>51,52</sup>. Finally, including plant-pollinator networks from unrepresented areas of the world and a more complete description of plant reproductive trade-offs is essential for a better understanding of the global patterns in plant-pollinator interactions.

## MATERIALS AND METHODS

**Plant-pollinator network studies.** We selected 28 studies from 18 different countries that constituted a total of 64 plant-pollinator networks. These studies recorded plant-pollinator interactions in natural systems and were selected so that we had broad geographical representation. Although these studies differ in sampling effort and methodology, all studies provided information about plant-pollinator interactions (weighted and non-weighted), which we used to build a database of plant species that are likely to be animal pollinated. Many of these networks are freely available either as published studies<sup>53,54</sup> or available in online archives (e.g., ‘The Web of Life’<sup>53</sup> and ‘Mangal’<sup>55</sup>). In total, our network dataset (see Supplementary Table S1) constituted 60 weighted (interaction frequency) and 4 unweighted (presence/absence of the interaction) networks, each sampled at a unique location and year, as well as eight meta-webs where interactions were pooled across several locations and multiple years.

**Taxonomy of plants and pollinators.** All species names, genera, families and orders were retrieved and standardized from the taxonomy data sources NCBI (<https://www.ncbi.nlm.nih.gov/taxonomy>) for plants and ITIS (<https://www.itis.gov/>) for pollinators, using the R package *taxize*<sup>56</sup>. We filled the ‘not found’ searches manually using <http://www.theplantlist.org/> and <http://www.mobot.org/> for plants and <http://www.catalogueoflife.org/> for floral visitors.

**Functional traits.** We selected 20 different functional traits based on their relevance to plant reproduction and data availability (Table 1). These included twelve quantitative

and eight categorical traits belonging to three broader trait groupings (13 floral, 4 reproductive biology and 3 vegetative, Supplementary Information). For each plant species, we undertook an extensive literature and online search across a wide range of resources (plant databases, online floras, books, journals and images). From a total of 30,120 cells (20 columns  $\times$  1,506 species) we were able to fill 24,341 cells (80.8% of the dataset, see Supplementary Fig. S1 for missing values information for each trait).

**Phylogenetic Distance.** We calculated the phylogenetic distance between different plant species using the function *get\_tree* from the package *rtrees* (<https://github.com/daijiang/rtrees>), which downloads phylogenetic distances from the extended R implementation of the Open Tree of Life<sup>57,58</sup>.

**Data Imputation.** Trait missing values were imputed with the function *missForest*<sup>59</sup> which allows imputation of data sets with continuous and categorical variables. We accounted for the phylogenetic distance among species on the imputation process by including the eigenvectors of a principal component analysis of the phylogenetic distance (PCoA) which has been shown to improve the performance of *missForest*<sup>60</sup>. To extract the eigenvectors, we used the function *PVRdecomp* from the package *PVR*<sup>61</sup> based on a previous conceptual framework that considers phylogenetic eigenvectors<sup>62</sup>. Although the variable of autonomous selfing had a high percentage of missing values (68%), we were able to solve this by back transforming the qualitative column of autonomous selfing to numerical. The categories of ‘none’, ‘low’, ‘medium’ and ‘high’ were converted to representative percentages of each category 0%, 13%, 50.5% and 88% respectively. This reduced the percentage of missing values for this column from 68% to 35% and allowed the imputation of this variable. However, we were unable to include nectar and pollen traits on the imputation process because of the high percentage of missing values (Supplementary Fig. S1). Hence, the imputed dataset had 1,506 species, seven categorical and eight numerical variables and 5.79% of missing values. Further, we conducted an additional imputation on the filtered raw data by filled cells of either



**Table 1 | Quantitative and categorical traits used in this study.**

Quantitative traits		Categorical traits		
Type	Traits	Type	Traits	Categories
<b>Vegetative</b>	Plant height (m)	<b>Vegetative</b>	Lifepan	Short-lived Perennial
<b>Floral</b>	Flower width (mm)	<b>Vegetative</b>	Life form	Herb Shrub Tree
<b>Floral</b>	Flower length (mm)	<b>Floral</b>	Flower shape	Brush Campanulate Capitulum Open Papilionaceous Tube
<b>Floral</b>	Inflorescence width (mm)	<b>Floral</b>	Flower symmetry	Actinomorphic Zygomorphic
<b>Floral</b>	Style length (mm)	<b>Floral</b>	Nectar	Presence Absence
<b>Floral</b>	Ovules per flower	<b>Reproductive biology</b>	Autonomous selfing	None Low Medium High
<b>Floral</b>	Flowers per plant	<b>Reproductive biology</b>	Compatibility system	Self-incomp. Part. self-comp. Self-comp.
<b>Floral</b>	Nectar ( $\mu$ l)	<b>Reproductive biology</b>	Breeding system	Hermaphrodite Monoecious Dioecious
<b>Floral</b>	Nectar (mg)			
<b>Floral</b>	Nectar concentration (%)			
<b>Floral</b>	Pollen grains per flower			
<b>Reproductive biology</b>	Autonomous selfing (fruit set)			

pollen grains per flower or microlitres of nectar. This subset comprised 755 species, 8.01% missing values and all traits but milligrams of nectar (~50% of missing values) were included in the imputation process.

**Plant strategies.** We explored the trade-offs between different quantitative plant functional traits with a phylogenetically informed Principal Component Analysis (pPCA). We did not include the quantitative variables of flower length and inflorescence width because they were highly and moderately correlated to flower width respectively (Pearson's correlation = 0.72,  $P < 0.01$  and Pearson's correlation = 0.36,  $P < 0.01$  respectively), and thus we avoided overemphasizing flower size on the spectrum of trait variation. Although qualitative traits were not included in the dimensionality reduction analysis, we also investigated the association of the different qualitative traits with the main axes of trait variation. Prior to the analyses, we excluded outliers and standardized the data. Due to the high sensitivity of dimensionality reduction to outliers, we excluded values within the 2.5th–97.5th percentile range<sup>63</sup>, and thus our final dataset had 1,236 species. Then, we log transformed the variables to reduce the influence of outliers and z-transformed ( $X = 0$ ,  $SD = 1$ ) so that all variables were within the same numerical range. We performed the pPCA using the function *phyl.pca* from the package *phytools*<sup>64</sup> with the method lambda ( $\lambda$ ) that calculates the phylogenetic correlation between 0 (phylogenetic independence) and 1 (shared evolutionary history) and we implemented the mode covariance because values for each variables were on the same scale following transformation<sup>65</sup>. Moreover, to corroborate that our imputation of missing values did not affect our results, we conducted a pPCA on the full dataset without missing values (see Supplementary Fig. S2). We found little difference between the explained variance with the imputed dataset (51.08%) and the dataset without missing values (52.87%). In addition, the loadings on each principal component had a similar contribution and correlation patterns, with the exception of plant height which showed slight variations between the imputed and non-imputed dataset. Finally, we conducted an additional phylogenetic informed principal component analysis for the subset of species with pollen and nectar quantity. For this, we included all quantitative traits considered in

the main pPCA plus pollen grains and microlitres of nectar per flower.

**Phylogenetic signal of traits.** We calculated the phylogenetic signal of the different quantitative traits on the imputed dataset with the full set of species ( $N = 1,506$ ) with the package *phytools* version 0.7-70<sup>64</sup> and we used Pagel's  $\lambda$  as a measurement of the phylogenetic signal. However, for pollen and nectar traits, phylogenetic signal was calculated only on the subset of species that had quantitative information for these traits ( $N = 755$ ).

**Network analyses.** Analyses were conducted on the subset of 60 weighted networks sampled in a unique flowering season and site, which included 556 plant and 1,126 pollinator species. These networks were analysed in their qualitative (presence-absence) and quantitative (interaction frequency) form. First, we analysed the binary version of these weighted networks with presence-absence information that assumes equal weight across interactions. Second, we analysed the untransformed weighted networks with interaction frequency that accounts for the intensity of the interaction. Although floral visitors are not always pollinators and interaction frequency does not consider each pollinator species efficiency<sup>66</sup>, interaction frequency can provide valuable information of the contribution of floral visitors to pollination<sup>67,68</sup>. In total, our network dataset (excluding meta-webs and non-weighted networks) included 2,256 interactions of Anthophila-Hymenoptera (i.e., bees) with plants, 1,768 non-Syrphidae-Diptera interactions, 845 Syrphidae interactions, 437 Lepidoptera interactions, 432 Coleoptera interactions and 362 non-Anthophila-Hymenoptera interactions. Sampling methods varied across networks but this was accounted for in analyses by considering them in the random effects of the modelling process. All analyses were conducted in R version 4.0.3.

**Visitation patterns.** We used Bayesian modelling (see below for details) to explore the effect of floral visitor groups and the main axes of trait variation (pPCA with imputed dataset) on both qualitative (presence/absence) and quantitative (visitation rate)

floral interactions per plant species. For this, we divided floral visitors into six main guilds that differ in life form, behaviour and are likely to play a similar ecological role: (i) Hymenoptera-Anthophila (bees), (ii) Hymenoptera-non-Anthophila (non-bee Hymenoptera), (iii) Syrphidae-Diptera, (iv) non-Syrphidae-Diptera, (v) Lepidoptera and (vi) Coleoptera. Moreover, because Hymenoptera-Anthophila was the most represented group with 2,256 records and had the highest frequency of visits of all groups, we also explored the presence-absence of interaction and visitation rate of the main Hymenoptera-Anthophila families (Andrenidae, Apidae, Colletidae, Halictidae and Megachilidae) on the trait space. In addition, we found that *Apis mellifera* was the floral visitor with the largest proportion of records counted (7.55% of the total). This finding is consistent with previous research showing that *A. mellifera* was the most frequent floral visitor in a similar dataset of 80 plant-pollinator networks in natural ecosystems<sup>69</sup>. Hence, to control for the effect of *A. mellifera* on the observed visitation patterns of bees, we conducted an analogous analysis with presence-absence of interaction and visitation rate excluding *A. mellifera*. We found that *A. mellifera*, was partly driving some of the observed trends on PC1 (Supplementary Fig. S3). However, we did not detect major differences on PC2 and PC3.

We implemented Bayesian generalized linear mixed models using the R package *brms*<sup>70</sup>. We modelled the frequency of visits as a function of the main axes of plant trait variation and their interactions with floral visitor functional groups ( $\text{Visits} \sim \text{PC1} \times \text{FGs} + \text{PC2} \times \text{FGs} + \text{PC3} \times \text{FGs}$ ). Because we were interested in possible differences in the visitation patterns among floral visitors groups to plants with different strategies, we included interactions between the main axes of trait variation (PC1, PC2 and PC3) and the floral visitor guilds. In this model, we added a nested random effect of networks nested within the study system to capture the variation in networks among studies and within networks. Moreover, we included the phylogenetic covariance matrix as a random factor due to the possible shared evolutionary histories of species and therefore lack of independence across them. We specified this model with a zero inflated negative binomial distribution and weakly informative priors from the *brms* function. We run

this model for 3,000 iterations and with previous 1,000 warm up iterations. We set delta ( $\Delta$ ) to 0.99 to avoid divergent transitions and visualized the posterior predictive checks with the function *pp\_check* using the *bayesplot* package<sup>71</sup>.

**Plant species functional roles.** We investigated whether different quantitative traits determined plant species functional roles using Bayesian modelling and regression trees. For this, we selected simple and complementary species-level network metrics commonly applied in bipartite network studies<sup>72</sup> with a straightforward ecological interpretation relevant to our research goals. The different plant species-level metrics were: (i) sum of visits per plant species; (ii) normalized degree, calculated as the number of links per plant species divided by the total possible number of partners; and (iii) specialization<sup>73</sup>, which measures the deviation of an expected random choice of the available interaction partners and ranges between 0 (maximum generalization) and 1 (maximum specialization). Normalized degree and specialization were calculated with the *specieslevel* function from the R package *bipartite*<sup>72</sup>.

First, we modelled the distinct plant species metrics (sum of visits, normalized degree and plant specialization) as a function of the three main axes of trait variation (plant species level metric  $\sim$  PC1 + PC2 + PC3). For each response variable (i.e., each plant species level metric), we used different distribution families (zero inflated negative binomial for the sum of visits, weibull for normalized degree and zero one inflated beta for specialization). Finally, we used the same random factors, model settings and conducted the same posterior predictive checks for each model as detailed above in the ‘visitation patterns section’.

Second, to better understand these complex trait relationships, we used regression trees. Regression trees are recursive algorithms which can detect complex relationships among predictors and allow identification of the relevance of specific trait combinations on species functional roles. We focused exclusively on quantitative traits because almost all categorical traits were statistically associated with the first two axes of trait variation

(Supplementary Table S2). We conducted this analysis using the *rpart* package<sup>74</sup> version 4.1-15 with method ‘*anova*’ with a minimum of 50 observations per terminal node and we used the *rpart.plot* package<sup>75</sup> version 3.0.9 to plot the regression trees. We considered the species level indices as response variables (interaction frequency, normalized degree and specialization) and we performed one regression tree per metric using the different quantitative traits as predictors. We calculated two regression trees per plant species-level metric, one for the full set of species and another for the subset of species for which we had pollen and nectar traits. We focused on regression trees that included floral rewards because they consistently showed pollen and nectar traits as being the best for explaining the different species-level metrics (see Supplementary Fig. S4).

## References

1. Barrett, S. C. H. The evolution of plant sexual diversity. *Nat. Rev. Genet.* **3**, 274–284 (2002).
2. Schiestl, F. P. & Johnson, S. D. Pollinator-mediated evolution of floral signals. *Trends Ecol. Evol.* **28**, 307–315 (2013).
3. Fenster, C. B., Armbruster, W. S., Wilson, P., Dudash, M. R. & Thomson, J. D. Pollination Syndromes and Floral Specialization. *Annu. Rev. Ecol. Evol. Syst.* **35**, 375–403 (2004).
4. Dellinger, A. S. Pollination syndromes in the 21st century: Where do we stand and where may we go? *New Phytol.* **228**, 1193–1213 (2020).
5. Roddy, A. B. *et al.* Towards the flower economics spectrum. *New Phytol.* **229**, 665–672 (2021).
6. Baude, M. *et al.* Historical nectar assessment reveals the fall and rise of floral resources

- 447 in britain. *Nature* **530**, 85–88 (2016).
- 448 7. Munoz, F., Violle, C. & Cheptou, P.-O. CSR ecological strategies and plant mating  
449 systems: Outcrossing increases with competitiveness but stress-tolerance is related to  
450 mixed mating. *Oikos* **125**, 1296–1303 (2016).
- 451 8. Grossenbacher, D. L. *et al.* Self-compatibility is over-represented on islands. *New*  
452 *Phytol.* **215**, 469–478 (2017).
- 453 9. Moeller, D. A. *et al.* Global biogeography of mating system variation in seed plants.  
454 *Ecol. Lett.* **20**, 375–384 (2017).
- 455 10. Sargent, R. D. & Ackerly, D. D. Plant–pollinator interactions and the assembly of  
456 plant communities. *Trends Ecol. Evol.* **23**, 123–130 (2008).
- 457 11. Rech, A. R. *et al.* The macroecology of animal versus wind pollination: Ecological  
458 factors are more important than historical climate stability. *Plant Ecol. Divers.* **9**, 253–262  
459 (2016).
- 460 12. Salguero-Gómez, R. *et al.* Fast-slow continuum and reproductive strategies structure  
461 plant life-history variation worldwide. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 230–235 (2016).
- 462 13. Rüger, N. *et al.* Beyond the fastSlow continuum: Demographic dimensions structur-  
463 ing a tropical tree community. *Ecol. Lett.* **21**, 1075–1084 (2018).
- 464 14. Dehling, D. M., Jordano, P., Schaefer, H. M., Böhning-Gaese, K. & Schleuning, M.  
465 Morphology predicts species’ functional roles and their degree of specialization in  
466 plant–frugivore interactions. *Proc. Royal Soc. B* **283**, 20152444 (2016).
- 467 15. Rosas-Guerrero, V. *et al.* A quantitative review of pollination syndromes: Do floral  
468 traits predict effective pollinators? *Ecol. Lett.* **17**, 388–400 (2014).
- 469 16. Stang, M., Klinkhamer, P. G. L., Waser, N. M., Stang, I. & van der Meijden, E.

- 470 Size-specific interaction patterns and size matching in a plantPollinator interaction web.  
471 *Ann. Bot.* **103**, 1459–1469 (2009).
- 472 17. Bartomeus, I. *et al.* A common framework for identifying linkage rules across  
473 different types of interactions. *Funct. Ecol.* **30**, 1894–1903 (2016).
- 474 18. Waser, N. M., Chittka, L., Price, M. V., Williams, N. M. & Ollerton, J. Generalization  
475 in pollination systems, and why it matters. *Ecology* **77**, 1043–1060 (1996).
- 476 19. Olesen, J. M. & Jordano, P. Geographic patterns in plant–pollinator mutualistic  
477 networks. *Ecology* **83**, 2416–2424 (2002).
- 478 20. Tur, C., Castro-Urgal, R. & Traveset, A. Linking Plant Specialization to Dependence  
479 in Interactions for Seed Set in Pollination Networks. *PLoS One* **8**, e78294 (2013).
- 480 21. Devaux, C., Lepers, C. & Porcher, E. Constraints imposed by pollinator behaviour  
481 on the ecology and evolution of plant mating systems. *J. Evol. Biol.* **27**, 1413–1430 (2014).
- 482 22. Kattge, J. *et al.* TRY a global database of plant traits. *Glob. Chang. Biol.* **17**, 2905–2935  
483 (2011).
- 484 23. Salguero-Gómez, R. *et al.* The compadre Plant Matrix Database: An open online  
485 repository for plant demography. *J. Ecol.* **103**, 202–218 (2015).
- 486 24. Díaz, S. *et al.* The global spectrum of plant form and function. *Nature* **529**, 167–171  
487 (2016).
- 488 25. Carmona, C. P. *et al.* Erosion of global functional diversity across the tree of life. *Sci.*  
489 *Adv.* **7**, eabf2675 (2021).
- 490 26. Wright, I. J. *et al.* The worldwide leaf economics spectrum. *Nature* **428**, 821–827  
491 (2004).
- 492 27. Chave, J. *et al.* Towards a worldwide wood economics spectrum. *Ecol. Lett.* **12**,



- 493 351–366 (2009).
- 494 28. Laughlin, D. C. *et al.* Root traits explain plant species distributions along climatic  
495 gradients yet challenge the nature of ecological trade-offs. *Nat. Ecol. Evol.* 1–12 (2021).
- 496 29. E-Vojtkó, A., Bello, F. de, Durka, W., Kühn, I. & Götzenberger, L. The neglected  
497 importance of floral traits in trait-based plant community assembly. *J. Veg. Sci.* **31**,  
498 529–539 (2020).
- 499 30. Barrett, S. C. H. Mating strategies in flowering plants: The outcrossing-selfing  
500 paradigm and beyond. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **358**, 991–1004 (2003).
- 501 31. Goodwillie, C. *et al.* Correlated evolution of mating system and floral display traits  
502 in flowering plants and its implications for the distribution of mating system variation.  
503 *New Phytol.* **185**, 311–321 (2010).
- 504 32. Ollerton, J., Winfree, R. & Tarrant, S. How many flowering plants are pollinated by  
505 animals? *Oikos* **120**, 321–326 (2011).
- 506 33. Rodger, J. G. *et al.* Widespread vulnerability of flowering plant seed production to  
507 pollinator declines. *Science Advances* **7**, eabd3524 (2021).
- 508 34. Bartomeus, I. Understanding Linkage Rules in Plant-Pollinator Networks by Using  
509 Hierarchical Models That Incorporate Pollinator Detectability and Plant Traits. *PLoS*  
510 *One* **8**, e69200 (2013).
- 511 35. Olito, C. & Fox, J. W. Species traits and abundances predict metrics of plantPollinator  
512 network structure, but not pairwise interactions. *Oikos* **124**, 428–436 (2015).
- 513 36. Rowe, L. *et al.* Flower traits associated with the visitation patterns of bees. *Oecologia*  
514 **193**, 511–522 (2020).
- 515 37. Lázaro, A., Jakobsson, A. & Totland, Ø. How do pollinator visitation rate and seed

- 516 set relate to species' floral traits and community context? *Oecologia* **173**, 881–893 (2013).
- 517 38. Junker, R. R. *et al.* Specialization on traits as basis for the niche-breadth of flower  
518 visitors and as structuring mechanism of ecological networks. *Funct. Ecol.* **27**, 329–341  
519 (2013).
- 520 39. Coux, C., Rader, R., Bartomeus, I. & Tylianakis, J. M. Linking species functional  
521 roles to their network roles. *Ecol. Lett.* **19**, 762–770 (2016).
- 522 40. Ibanez, S. Optimizing size thresholds in a plant-pollinator interaction web: Towards  
523 a mechanistic understanding of ecological networks. *Oecologia* **170**, 233–242 (2012).
- 524 41. Eklöf, A. *et al.* The dimensionality of ecological networks. *Ecol. Lett.* **16**, 577–583  
525 (2013).
- 526 42. Sargent, R. D., Goodwillie, C., Kalisz, S. & Ree, R. H. Phylogenetic evidence for a  
527 flower size and number trade-off. *Am. J. Bot.* **94**, 2059–2062 (2007).
- 528 43. Kettle, C. J. *et al.* Ecological Implications of a Flower Size/Number Trade-Off in  
529 Tropical Forest Trees. *PLoS One* **6**, e16111 (2011).
- 530 44. Healy, K., Ezard, T. H. G., Jones, O. R., Salguero-Gómez, R. & Buckley, Y. M. Animal  
531 life history is shaped by the pace of life and the distribution of age-specific mortality  
532 and reproduction. *Nat. Ecol. Evol.* **3**, 1217–1224 (2019).
- 533 45. Hegland, S. J. & Totland, Ø. Relationships between species' floral traits and pollina-  
534 tor visitation in a temperate grassland. *Oecologia* **145**, 586–594 (2005).
- 535 46. Kaiser-Bunbury, C. N., Vázquez, D. P., Stang, M. & Ghazoul, J. Determinants of the  
536 microstructure of plantPollinator networks. *Ecology* **95**, 3314–3324 (2014).
- 537 47. Palmer, T. M., Stanton, M. L. & Young, T. P. Competition and coexistence: Exploring  
538 mechanisms that restrict and maintain diversity within mutualist guilds. *Am. Nat.* **162**,

539 S63–S79 (2003).

540 48. Phillips, R. D., Peakall, R., van der Niet, T. & Johnson, S. D. Niche perspectives on  
541 plantPollinator interactions. *Trends Plant Sci.* **25**, 779–793 (2020).

542 49. Vázquez, D. P. *et al.* Species abundance and asymmetric interaction strength in  
543 ecological networks. *Oikos* **116**, 1120–1127 (2007).

544 50. Encinas-Viso, F., Revilla, T. A. & Etienne, R. S. Phenology drives mutualistic network  
545 structure and diversity. *Ecol. Lett.* **15**, 198–208 (2012).

546 51. Gervasi, D. D. L. & Schiestl, F. P. Real-time divergent evolution in plants driven by  
547 pollinators. *Nat. Commun.* **8**, 14691 (2017).

548 52. Mackin, C. R., Peña, J. F., Blanco, M. A., Balfour, N. J. & Castellanos, M. C. Rapid  
549 evolution of a floral trait following acquisition of novel pollinators. *J. Ecol.* **109**, 2234–  
550 2246 (2021).

551 53. Fortuna, M. A. *et al.* Nestedness versus modularity in ecological networks: Two  
552 sides of the same coin? *J. Anim. Ecol.* **79**, 811–817 (2010).

553 54. Carvalheiro, L. G. *et al.* The potential for indirect effects between co-flowering plants  
554 via shared pollinators depends on resource abundance, accessibility and relatedness.  
555 *Ecol. Lett.* **17**, 1389–1399 (2014).

556 55. Poisot, T. *et al.* Mangal making ecological network analysis simple. *Ecography* **39**,  
557 384–390 (2016).

558 56. Chamberlain, S. *et al.* Taxize: Taxonomic information from around the web. r  
559 package version 0.9.99 (2020). at <https://cran.R-project.org/package=taxize>.

560 57. Smith, S. A. & Brown, J. W. Constructing a broadly inclusive seed plant phylogeny.

- 561 *Am. J. Bot.* **105**, 302–314 (2018).
- 562 58. Jin, Y. & Qian, H. V. PhylMaker: An R package that can generate very large  
563 phylogenies for vascular plants. *Ecography* **42**, 1353–1359 (2019).
- 564 59. Stekhoven, D. J. & Bühlmann, P. MissForestNon-parametric missing value imputa-  
565 tion for mixed-type data. *Bioinformatics* **28**, 112–118 (2012).
- 566 60. Penone, C. *et al.* Imputation of missing data in life-history trait datasets: Which  
567 approach performs the best? *Methods Ecol. Evol.* **5**, 961–970 (2014).
- 568 61. Chamberlain, S. *et al.* Package ‘PVR’. r package version 0.3 (2018). at [https://cran.R-](https://cran.R-project.org/package=PVR)  
569 [project.org/package=PVR](https://cran.R-project.org/package=PVR).
- 570 62. Diniz-Filho, J. A. F. *et al.* On the selection of phylogenetic eigenvectors for ecological  
571 analyses. *Ecography* **35**, 239–249 (2012).
- 572 63. Legendre, P. & Legendre, L. *Numerical ecology*. (Elsevier, Amsterdam, 2012).
- 573 64. Revell, L. J. Phytools: An R package for phylogenetic comparative biology (and  
574 other things). *Methods Ecol. Evol.* **3**, 217–223 (2012).
- 575 65. Abdi, H. & Williams, L. J. Principal component analysis. *WIREs Comp. Stats.* **2**,  
576 433–459 (2010).
- 577 66. Ballantyne, G., Baldock, K. C. R. & Willmer, P. G. Constructing more informative  
578 plantPollinator networks: Visitation and pollen deposition networks in a heathland  
579 plant community. *Proc. Royal Soc. B* **282**, 20151130 (2015).
- 580 67. Vázquez, D. P., Morris, W. F. & Jordano, P. Interaction frequency as a surrogate for  
581 the total effect of animal mutualists on plants. *Ecol. Lett.* **8**, 1088–1094 (2005).
- 582 68. Vázquez, D. P. *et al.* The strength of plantPollinator interactions. *Ecology* **93**, 719–725

583 (2012).

584 69. Hung, K.-L. J., Kingston, J. M., Albrecht, M., Holway, D. A. & Kohn, J. R. The  
585 worldwide importance of honey bees as pollinators in natural habitats. *Proc. Royal Soc.*  
586 *B* **285**, 20172140 (2018).

587 70. Bürkner, P.-C. Brms: An R package for Bayesian multilevel models using Stan. *J.*  
588 *Stat. Softw.* **80**, 1–28 (2017).

589 71. Gabry, J., Simpson, D., Vehtari, A., Betancourt, M. & Gelman, A. Visualization in  
590 Bayesian workflow. *J. R. Stat. Soc. Ser. A Stat. Soc.* **182**, 389–402 (2019).

591 72. Dormann, C. F., Gruber, B. & Fründ, J. Introducing the bipartite package: Analysing  
592 ecological networks. *interaction* **1**, (2008).

593 73. Blüthgen, N., Menzel, F. & Blüthgen, N. Measuring specialization in species interac-  
594 tion networks. *BMC Ecol.* **6**, 9 (2006).

595 74. Therneau, T., Atkinson, B., Ripley, B. & Ripley, M. B. Package ‘rpart’. r package  
596 version 4.1-15 (2015). at <https://cran.R-project.org/package=rpart>.

597 75. Milborrow, S. Rpart. plot: Plot rpart Models. An Enhanced Version of plot. rpart. r  
598 package version 3.0.9 (2015). at <https://cran.R-project.org/package=rpart.plot>.

## 599 Acknowledgements

600 We thank all researchers that made their data available for our analysis. We thank  
601 Bryony Wilcox, Greg Bible, Mercedes Sanchez-Lanuza and David Ragel for their help  
602 with data collection. We also thank Jason Tylianakis for his comments on the manuscript  
603 before submission. JBL thanks the University of New England for the funding provided  
604 to carry out this work.