

## **Supplementary information for:**

### **Covariation among reproductive traits in flowering plants determine interactions with floral visitors**

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## Appendix S1

### Description of the traits compiled in this study

Here we describe the different traits of the database used in this study to explore the reproductive spectrum of trait variation and plant-pollinator associations. Note that all species have references or links providing the original source of the information.

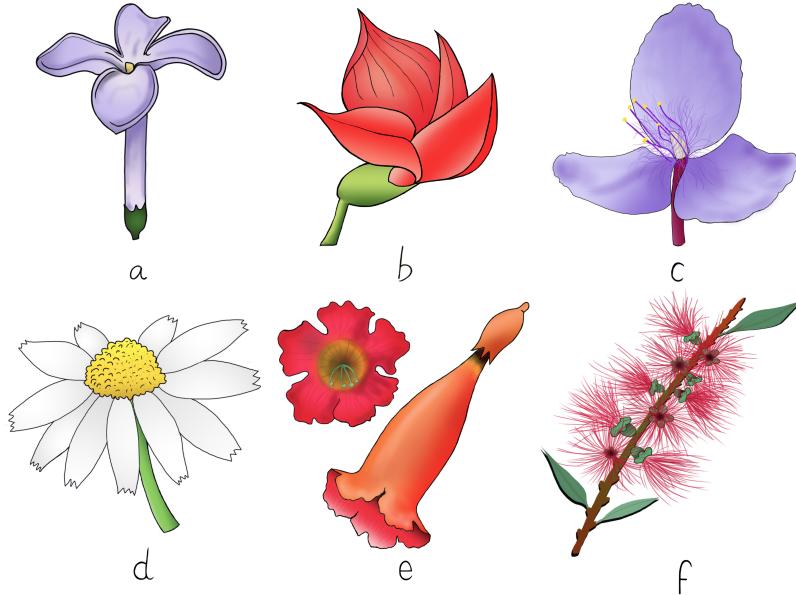
#### *Reproductive traits*

- Breeding system: The different plant species were classified in hermaphrodite, dioecious and monoecious species. Intermediate breeding systems or more complex ones were also annotated but all the species were divided into these three main categories for simplicity of the analysis.
- Selfing level: We recorded the selfing level of the different species with both quantitative and qualitative data. The qualitative data was divided in four main categories, high selfers, medium selfers, low selfers and none which was for the species that were unable to self-pollinate. In addition, quantitative data was also divided into these four categories with the following criteria: from 0% to lower than 1% ‘none’, from 1% to 25% ‘low’, from 26% to 75% ‘medium’ and from 76% to 100% ‘high’. Because quantitative selfing had a high percentage of missing values (68%), we were able to solve this by converting these four categories to representative percentages of each category 0%, 13%, 50.5% and 88%. This reduced the percentage of missing values for this quantitative trait from 68% to 35% and allowed the imputation of this variable.
- Compatibility system: The different species were divided in three main categories in order to know their ability to self-pollinate. These categories were self-compatible, partially self-compatible and self-incompatible species. The field of selfing level is partly complementary to the compatibility system but is important to note that not all the self-compatible species or partially self-compatible species will self-pollinate.

## *Floral traits*

- Flower symmetry: We also recorded if the flowers were bilaterally symmetrical “zygomorphic” or were radially symmetrical “actinomorphic”.
- Flower and inflorescence size: We searched for flower length and flower and inflorescence width (mm) for all species. When possible, we calculated the not found measurements with the help of online images and the software ImageJ. Note that for species with compound flowers (e.g., Asteraceae) or similar floral structures with flower heads with many small flowers we considered the inflorescence as the floral unit. For each species this is indicated in the dataset with the field of “info\_level” where the measurement level is specified as capitulum or flower level. Note that for some Asteraceae species information about the disc and ray floret is also provided in the database but these were not included in our analyses.
- Flower number per plant: We compiled information about the number of flowers per plant for all species. However, this field was rare to find and we also used online images of the different species in order to calculate rough numbers of flowers per plant. We referenced all the filled fields in order to be able to follow the images that were used for these counts. It is important to note, that these numbers are not pretended to be the exact number of flowers per species but an approximate indicator of the reproductive investment for the different species that allow the macroecological analysis of this field.
- Ovule number: We searched for the number of ovules per flower for all the different species. The number of ovules of Asteraceae species are considered as the total number of ovules per capitulum. Many species were filled by genus or family level because the number of ovules in this taxonomic groups is considered to be mostly constant (e.g., Lamiaceae Boraginaceae or Apiaceae).
- Flower morphology: We looked for images and illustrations of the flowers from the different species on the floras and available resources in order to categorize the flower

shape. We divided the flowers in 8 main different categories: open, bowl, tube, campanulate, funnelform, papilionaceous, brush and capitulum. However, we ended up grouppping all flowers on the following 6 morphological groups for analyses: tube, papilionaceous, open, capitulum, campanulate and brush (Supplementary Information Text Fig. 1).



**Supplementary Information Text Fig. 1.** Main floral morphologies considered in this study. All species were grouped within these categories for analysis: (a) tube, (b) papilionaceous, (c) open, (d) capitulum, (e) campanulate and (f) brush.

- Style length: The length of the style (mm) of the different species was also included. When possible, we calculated style length from images and illustrations on the online floras.
- Nectar provision: We recorded the presence and absence of nectar for all species. In addition, we also searched for microlitres and milligrams of nectar per flower and nectar concentration. For species that did not have nectar information but belonged to a family that is considered as ‘nectarless’, this trait was recorded at family level and the species was recorded with ‘absence’ of nectar. This was done exclusively for well documented nectarless taxonomical groups. For the field of microlitres of nectar, we

considered single measurements of nectar standing crop. In general terms, the timing of the measurement and methodology differed across studies. For instance, some studies measured nectar in freshly opened flowers while others in flowers that were bagged for 24 hours. Despite the different methodologies to measure nectar provision, we believe that this is an appropriate way to collate measurements of nectar to explore trait associations at a macroecological scale.

- Pollen grains per flower: We recorded pollen grains per flower for all species but this field was rarely described in the literature. When just the pollen:ovule ratio was found we converted it back to pollen grains by multiplying it by the average ovule number found for each species.

#### *Vegetative traits*

- Life form, life span and plant height: We divided the different plant species in 4 main categories: herbs, vines, shrubs and trees. Moreover, we also divided the species between short-lived species (annual, biennial and short-lived perennials) and perennial species (long-lived). Finally, we also searched for the average height (m) of the different species and annotated the maximum and minimum height when possible. We conducted the average between the maximum and minimum height to get an approximate average height of the species when the average was not indicated.

**Table S1.** List of the 28 plant-pollinator studies used to build the plant trait database. Each study is shown with the first author that conducted the study, number of networks or metawebs that contains, type of information that contains (weighted or unweighted), the structure (web or metaweb), year of publication and digital object identifier or permanent link for each study.

| First author  | Year | Web N. | Network type     | DOI   |
|---------------|------|--------|------------------|---|
| Arroyo-Correa | 2019 | 3      | Weighted web     | <a href="https://doi.org/10.1111/1365-2745.13332">https://doi.org/10.1111/1365-2745.13332</a>                       |
| Bartomeus     | 2008 | 6      | Weighted web     | <a href="https://doi.org/10.1007/s00442-007-0946-1">https://doi.org/10.1007/s00442-007-0946-1</a>                   |
| Bartomeus     | 2008 | 16     | Weighted web     | <a href="https://github.com/ibartomeus/BeeFunData">https://github.com/ibartomeus/BeeFunData</a>                     |
| Bek           | 2006 | 1      | Unweighted web   | Unpublished, Master thesis  |
| Bundgaard     | 2003 | 1      | Weighted web     | Unpublished, Master thesis  |
| Burkle        | 2013 | 1      | Weighted web     | <a href="https://doi.org/10.1126/science.1232728">https://doi.org/10.1126/science.1232728</a>                       |
| Dicks         | 2002 | 2      | Weighted web     | <a href="https://doi.org/10.1046/j.0021-8790.2001.00572.x">https://doi.org/10.1046/j.0021-8790.2001.00572.x</a>     |
| Dupont        | 2003 | 3      | Weighted web     | <a href="https://doi.org/10.1111/j.1365-2656.2008.01501.x">https://doi.org/10.1111/j.1365-2656.2008.01501.x</a>     |
| Elberling     | 1999 | 1      | Weighted web     | <a href="https://doi.org/10.1111/j.1600-0587.1999.tb00507.x">https://doi.org/10.1111/j.1600-0587.1999.tb00507.x</a> |
| Fang          | 2008 | 1      | Weighted web     | <a href="https://doi.org/10.1111/1749-4877.12190">https://doi.org/10.1111/1749-4877.12190</a>                       |
| Inouye        | 1988 | 1      | Weighted web     | <a href="https://doi.org/10.1111/j.1442-9993.1988.tb00968.x">https://doi.org/10.1111/j.1442-9993.1988.tb00968.x</a> |
| Inouye        | 1990 | 1      | Weighted metaweb | <a href="http://hdl.handle.net/2433/156099">http://hdl.handle.net/2433/156099</a>                                   |

(continued)

| First author   | Year | Web N. | Network type       | DOI   |
|----------------|------|--------|--------------------|---|
| Kaiser-Bunbury | 2017 | 8      | Weighted web       | <a href="https://doi.org/10.1038/nature21071">https://doi.org/10.1038/nature21071</a>   |
| Kaiser-Bunbury | 2011 | 6      | Weighted web       | <a href="https://doi.org/10.1111/j.1365-2745.2010.01732.x">https://doi.org/10.1111/j.1365-2745.2010.01732.x</a>                               |
| Kaiser-Bunbury | 2010 | 2      | Weighted web       | <a href="https://doi.org/10.1016/j.ppees.2009.04.001">https://doi.org/10.1016/j.ppees.2009.04.001</a>   |
| Kato           | 2000 | 1      | Unweighted web     | <a href="http://hdl.handle.net/2433/156116">http://hdl.handle.net/2433/156116</a>   |
| Kevan          | 1970 | 1      | Unweighted web     | <a href="https://doi.org/10.2307/2258569">https://doi.org/10.2307/2258569</a>   |
| Lundgren       | 2005 | 1      | Weighted web       | <a href="https://doi.org/10.1657/1523-0430(2005)037[0514:TDAHCW]2.0.CO;2">https://doi.org/10.1657/1523-0430(2005)037[0514:TDAHCW]2.0.CO;2</a> |
| McMullen       | 1993 | 1      | Unweighted metaweb | <a href="https://biostor.org/reference/244737">https://biostor.org/reference/244737</a>   |
| Olesen         | 2002 | 2      | Weighted web       | <a href="https://doi.org/10.1046/j.1472-4642.2002.00148.x">https://doi.org/10.1046/j.1472-4642.2002.00148.x</a>                               |
| Peralta        | 2006 | 4      | Weighted web       | <a href="https://doi.org/10.1111/ele.13510">https://doi.org/10.1111/ele.13510</a>   |
| Primack        | 1983 | 3      | Unweighted metaweb | <a href="https://doi.org/10.1080/0028825X.1983.10428561">https://doi.org/10.1080/0028825X.1983.10428561</a>                                   |
| Ramirez        | 1989 | 1      | Unweighted web     | <a href="https://doi.org/10.2307/2388282">https://doi.org/10.2307/2388282</a>   |
| Ramirez        | 1992 | 1      | Unweighted metaweb | <a href="https://doi.org/10.1111/j.1095-8339.1992.tb00294.x">https://doi.org/10.1111/j.1095-8339.1992.tb00294.x</a>                           |
| Robertson      | 1929 | 1      | Unweighted metaweb | <a href="https://doi.org/10.5962/bhl.title.11538">https://doi.org/10.5962/bhl.title.11538</a>   |
| Small          | 1976 | 1      | Weighted web       | <a href="https://doi.org/10.5962/bhl.title.11538">/13960/t4km08d21</a>  |

*(continued)*

| First author | Year | Web N. | Network type     | DOI   |
|--------------|------|--------|------------------|---|
| Souza        | 2017 | 1      | Weighted web     | <a href="https://doi.org/10.1111/1365-2745.12978">https://doi.org/10.1111/1365-2745.12978</a> |
| Traveset     | 2013 | 1      | Weighted metaweb | <a href="https://doi.org/10.1098/rspb.2012.3040">https://doi.org/10.1098/rspb.2012.3040</a>   |

**Table S2.** Statistical association between the different categorical variables and the first three main axes of trait variation with the full set of species.

| Functional traits    | Sum Sq | F value | Pr(>F) | PC  |
|----------------------|--------|---------|--------|-----|
| Breeding system      | 304.59 | 119.50  | 0.00   | PC1 |
| Compatibility system | 89.12  | 23.31   | 0.00   | PC1 |
| Lifespan             | 35.65  | 27.97   | 0.00   | PC1 |
| Life form            | 565.87 | 222.00  | 0.00   | PC1 |
| Flower shape         | 132.24 | 20.75   | 0.00   | PC1 |
| Flower symmetry      | 0.37   | 0.29    | 0.59   | PC1 |
| Nectar provision     | 0.38   | 0.29    | 0.59   | PC1 |
| Breeding system      | 304.59 | 119.50  | 0.00   | PC2 |
| Compatibility system | 89.12  | 23.31   | 0.00   | PC2 |
| Lifespan             | 35.65  | 27.97   | 0.00   | PC2 |
| Life form            | 565.87 | 222.00  | 0.00   | PC2 |
| Flower shape         | 132.24 | 20.75   | 0.00   | PC2 |
| Flower symmetry      | 0.37   | 0.29    | 0.59   | PC2 |
| Nectar provision     | 0.38   | 0.29    | 0.59   | PC2 |

**Table S3.** Loadings of the first three axes of trait variation of the phylogenetic informed principal component analysis with the full set of species.

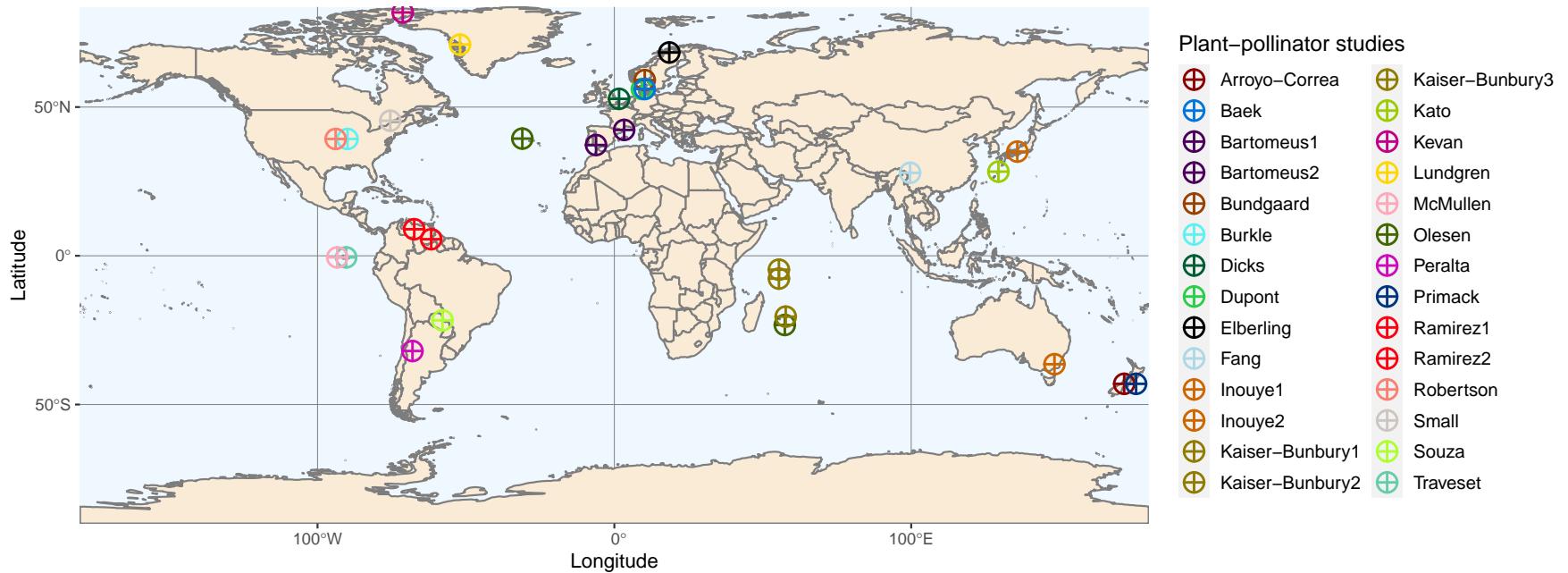
|                     | PC1   | PC2   | PC3   |
|---------------------|-------|-------|-------|
| Autonomous selfing  | 0.03  | 0.85  | -0.51 |
| Flowers per plant   | 0.75  | -0.27 | -0.24 |
| Flower width        | -0.67 | -0.38 | -0.30 |
| Style length        | -0.34 | -0.37 | -0.66 |
| Ovule number        | -0.53 | 0.00  | -0.02 |
| Plant height        | 0.56  | -0.40 | -0.46 |
| Explained variation | 26.72 | 25.08 | 19.17 |

**Table S4.** Loadings of the first three axes of trait variation of the phylogenetic informed principal component analysis with the subset of species with data of nectar and pollen quantity.

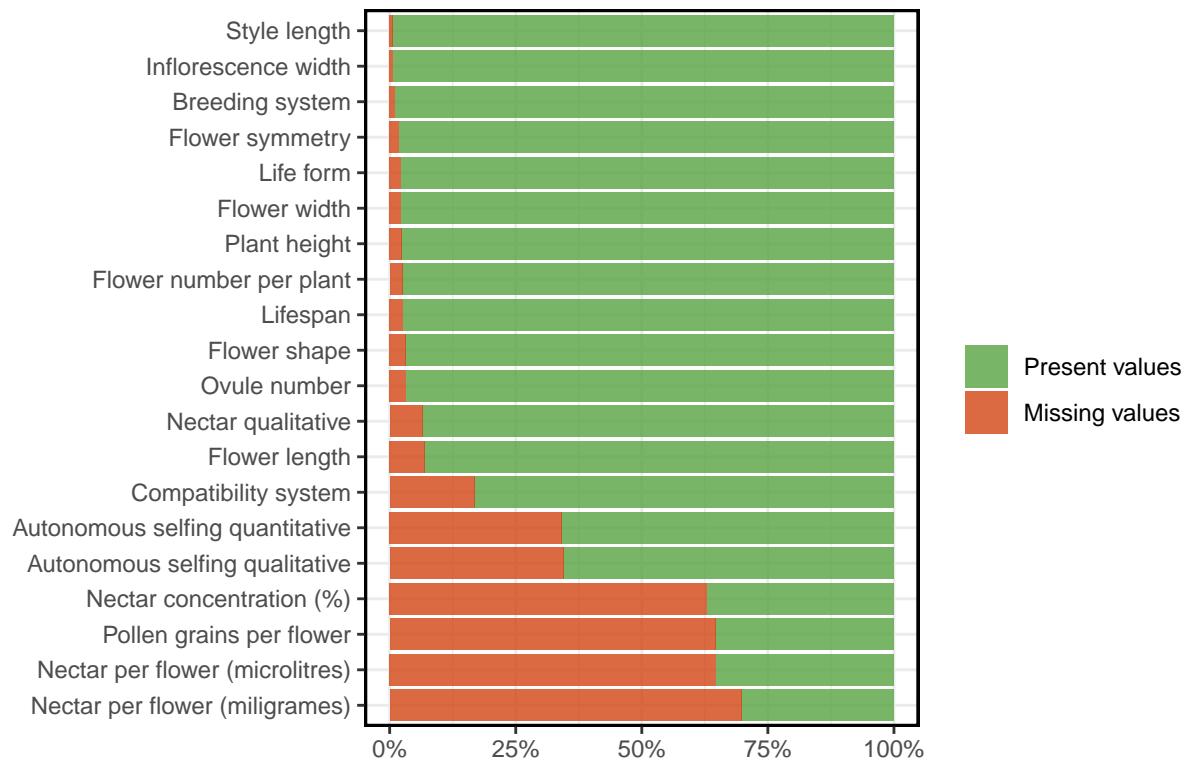
|                                  | PC1   | PC2   | PC3   |
|----------------------------------|-------|-------|-------|
| Autonomous selfing               | -0.05 | 0.78  | 0.37  |
| Flowers per plant                | 0.53  | -0.49 | 0.42  |
| Flower width                     | -0.74 | -0.27 | -0.13 |
| Style length                     | -0.60 | -0.30 | 0.11  |
| Ovule number                     | -0.59 | 0.11  | -0.08 |
| Plant height                     | 0.26  | -0.60 | 0.47  |
| Microlitres of Nectar per flower | -0.49 | 0.05  | 0.71  |
| Pollen per flower                | -0.29 | -0.45 | -0.13 |
| Explained variation              | 23.42 | 21.13 | 14.84 |

**Table S5. Phylogenetic signal of the different quantitative traits.**

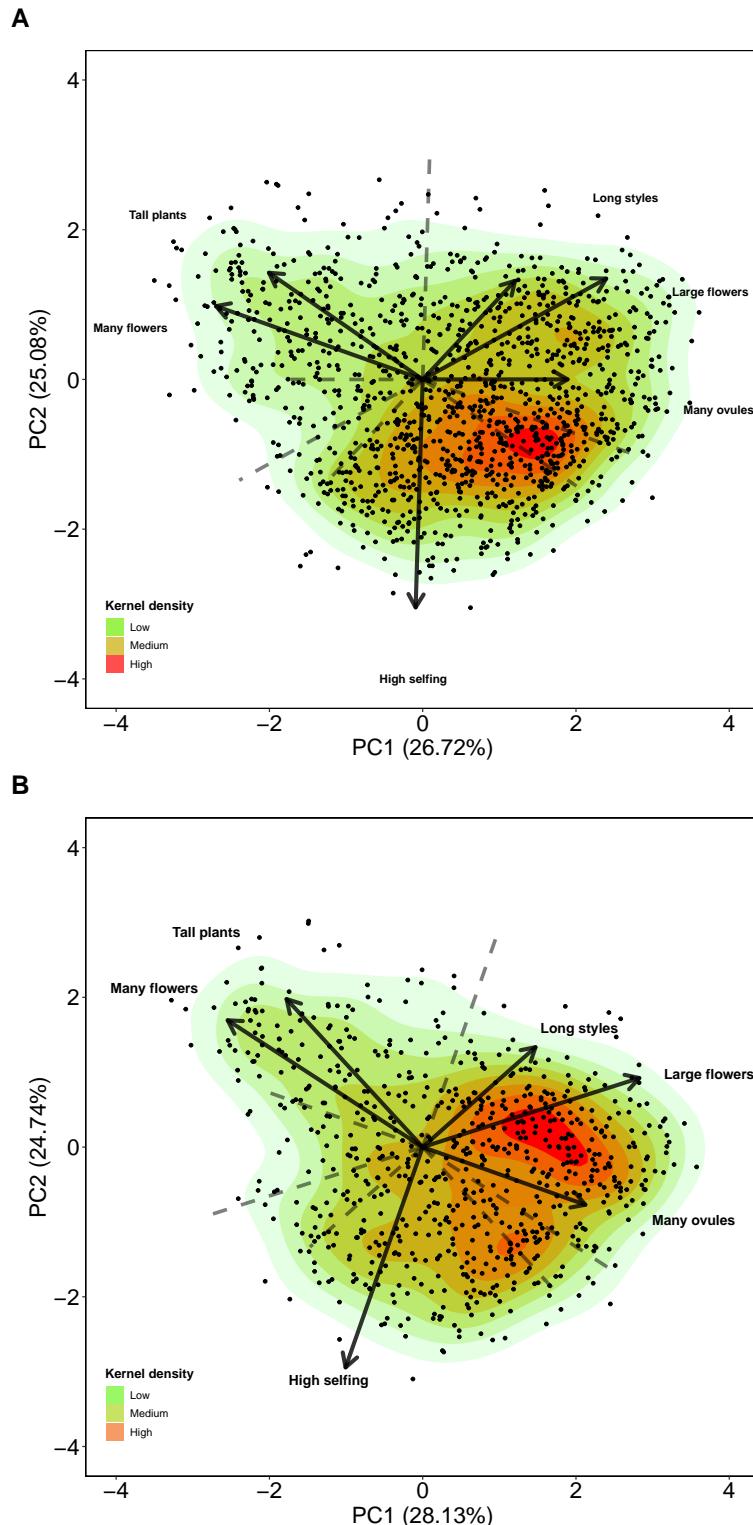
| Functional traits            | Lambda | P-value |
|------------------------------|--------|---------|
| Autonomous selfing           | 0.34   | 0.00    |
| Flower number                | 0.69   | 0.00    |
| Inflorescence width          | 0.57   | 0.00    |
| Flower width                 | 0.73   | 0.00    |
| Flower length                | 0.75   | 0.00    |
| Style length                 | 0.49   | 0.00    |
| Ovule number                 | 1.00   | 0.00    |
| Plant height                 | 0.96   | 0.00    |
| Nectar per flower ( $\mu$ l) | 0.14   | 0.00    |
| Nectar concentration (%)     | 0.65   | 0.00    |
| Pollen grains per flower     | 1.00   | 0.00    |



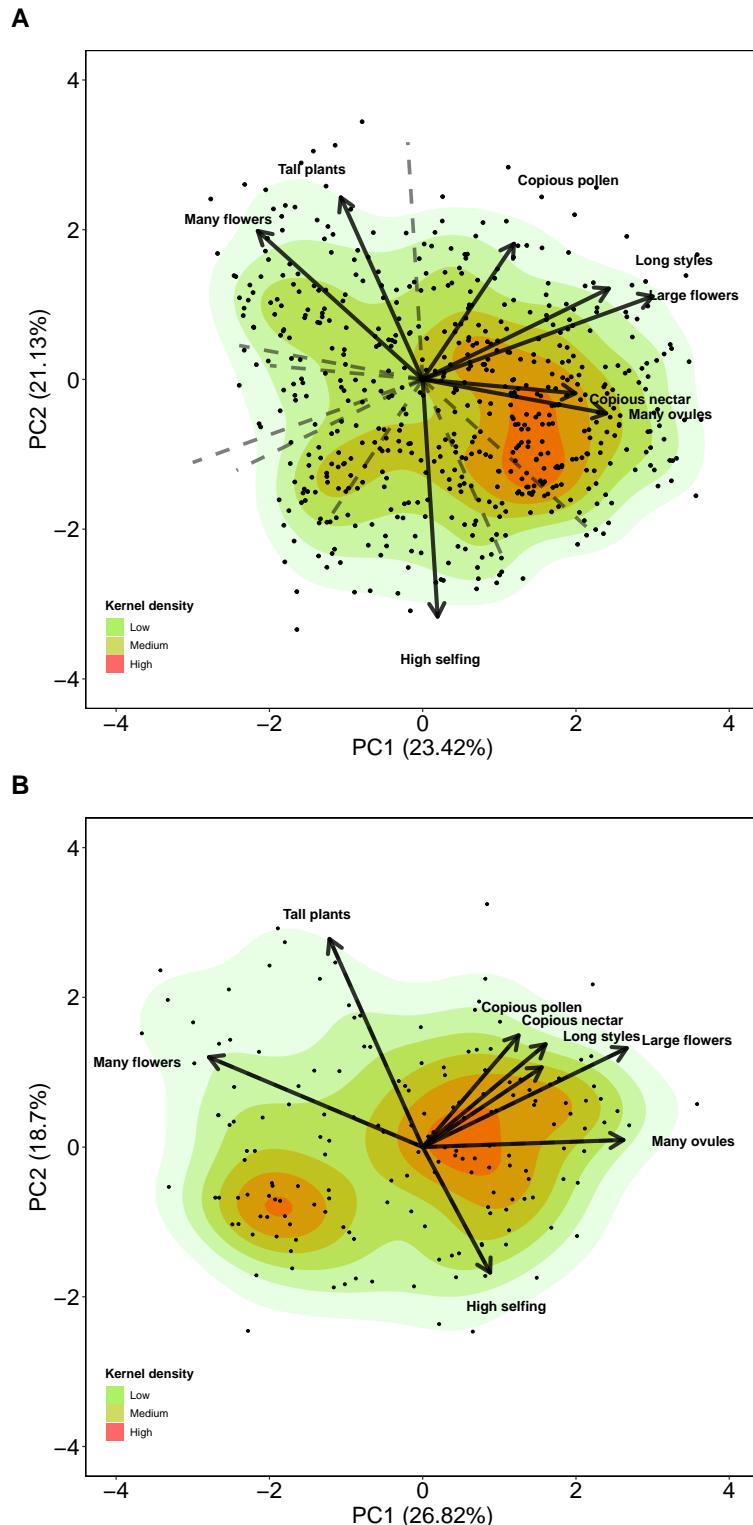
**Fig. S1.** Map with the different locations of the plant-pollinator studies used in this work to explore worldwide patterns at the meso-scale level. Note that for visualization purposes studies from the same authors are shown with the same colour.



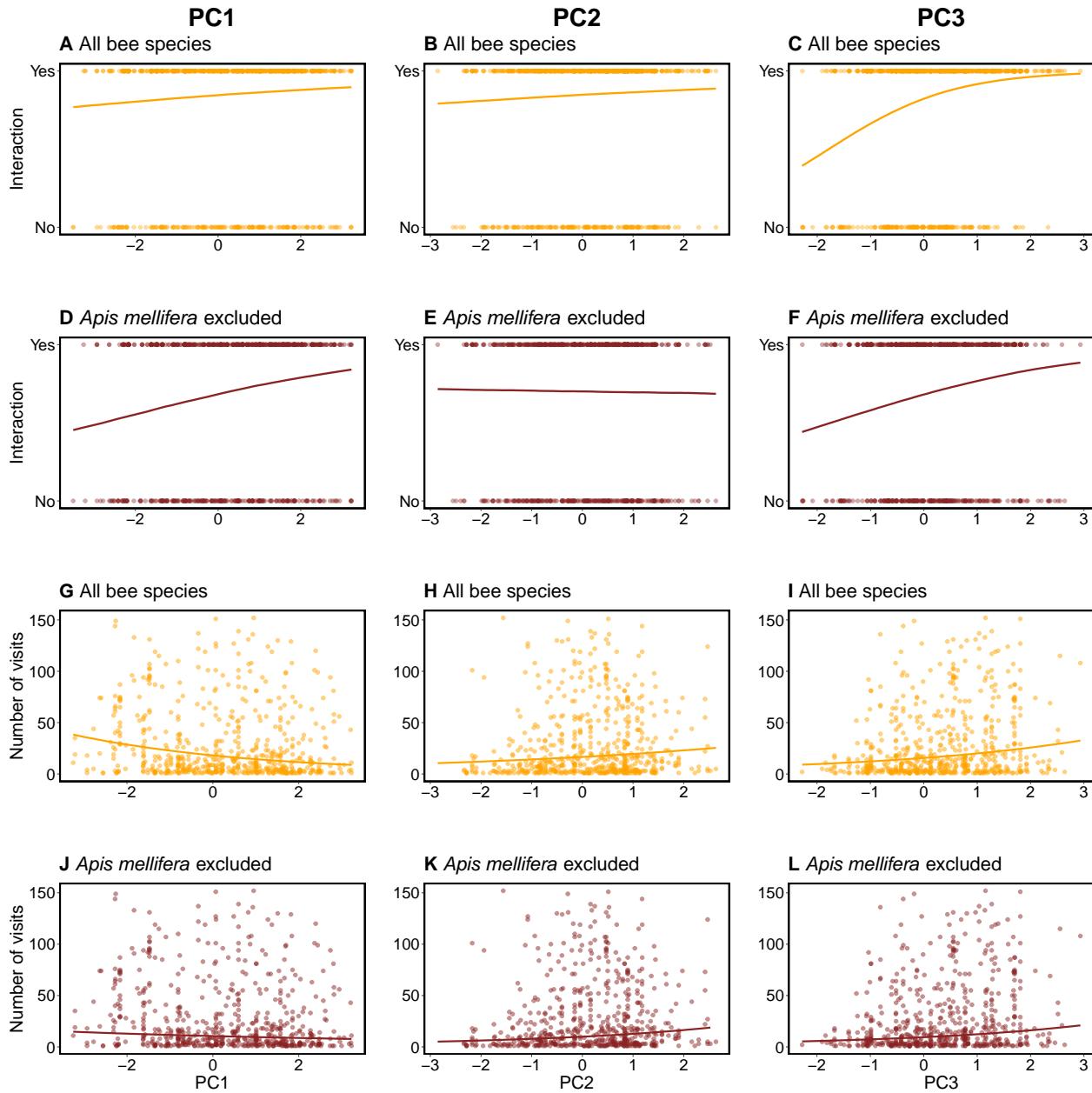
**Fig. S2.** Percentage of present and missing values of the different plant traits.



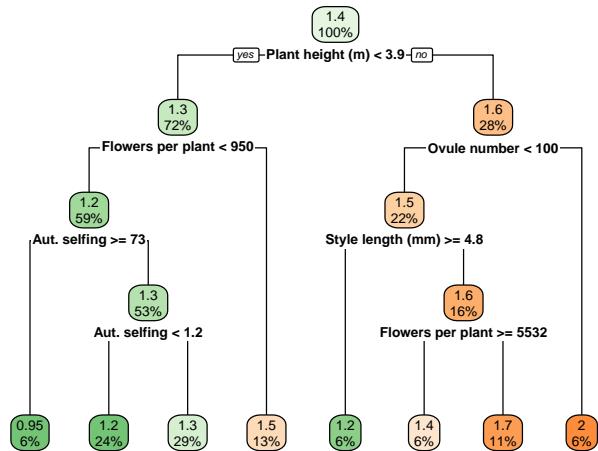
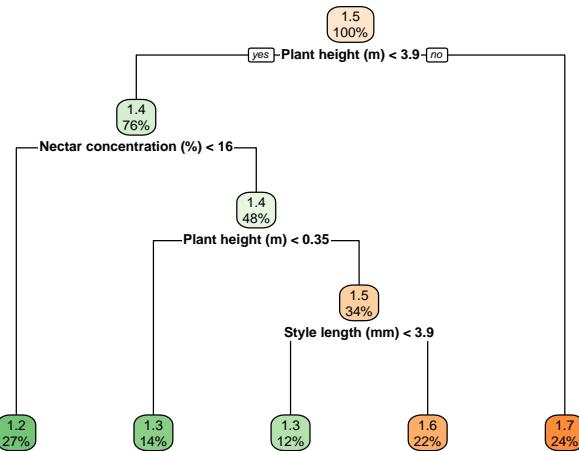
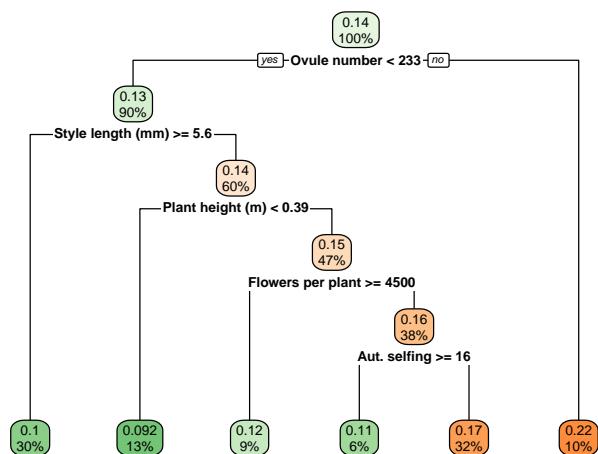
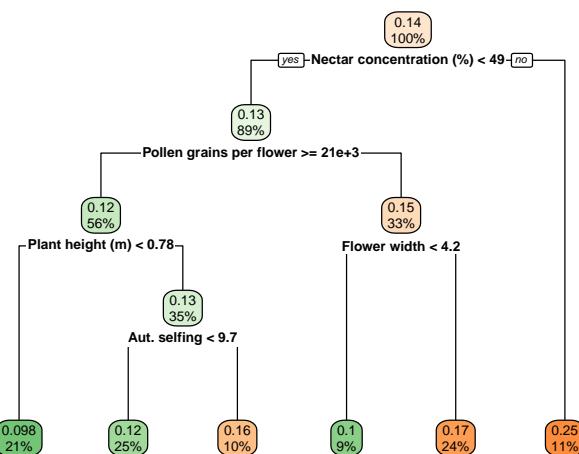
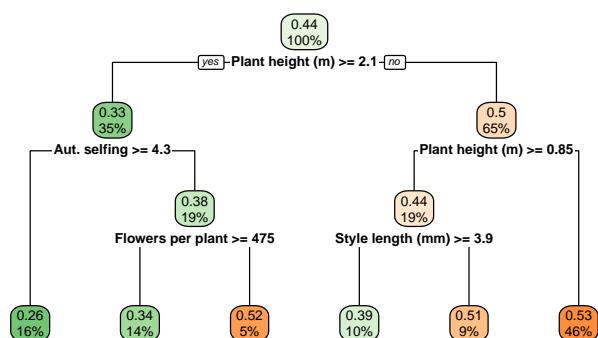
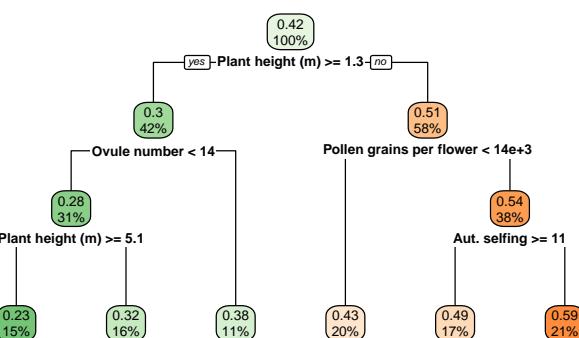
**Fig. S3.** Comparison of the phylogenetic informed principal component analysis for the dataset with data imputation and without data imputation. Panel A shows the reproductive spectrum of trait variation for the full dataset with data imputation and panel B shows the reproductive spectrum for the dataset without data imputation where the species with missing trait data were excluded from the analysis.



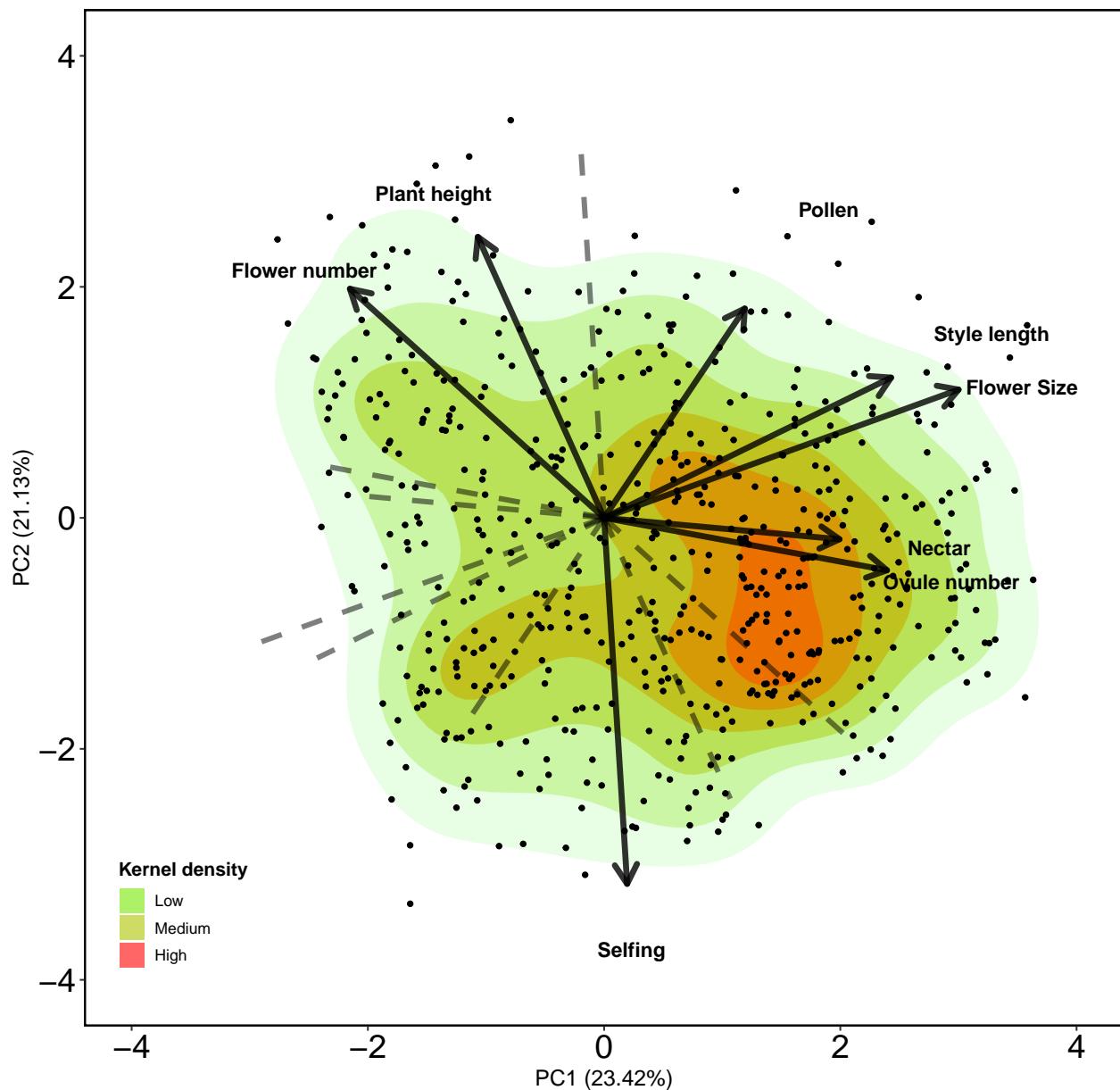
**Fig. S4.** Comparison of the phylogenetic informed principal component analysis for the subset of species that had information of floral rewards with data imputation and without data imputation. Panel A shows the reproductive spectrum of trait variation for the dataset with data imputation and panel B shows the reproductive spectrum for the dataset excluding species with missing trait data



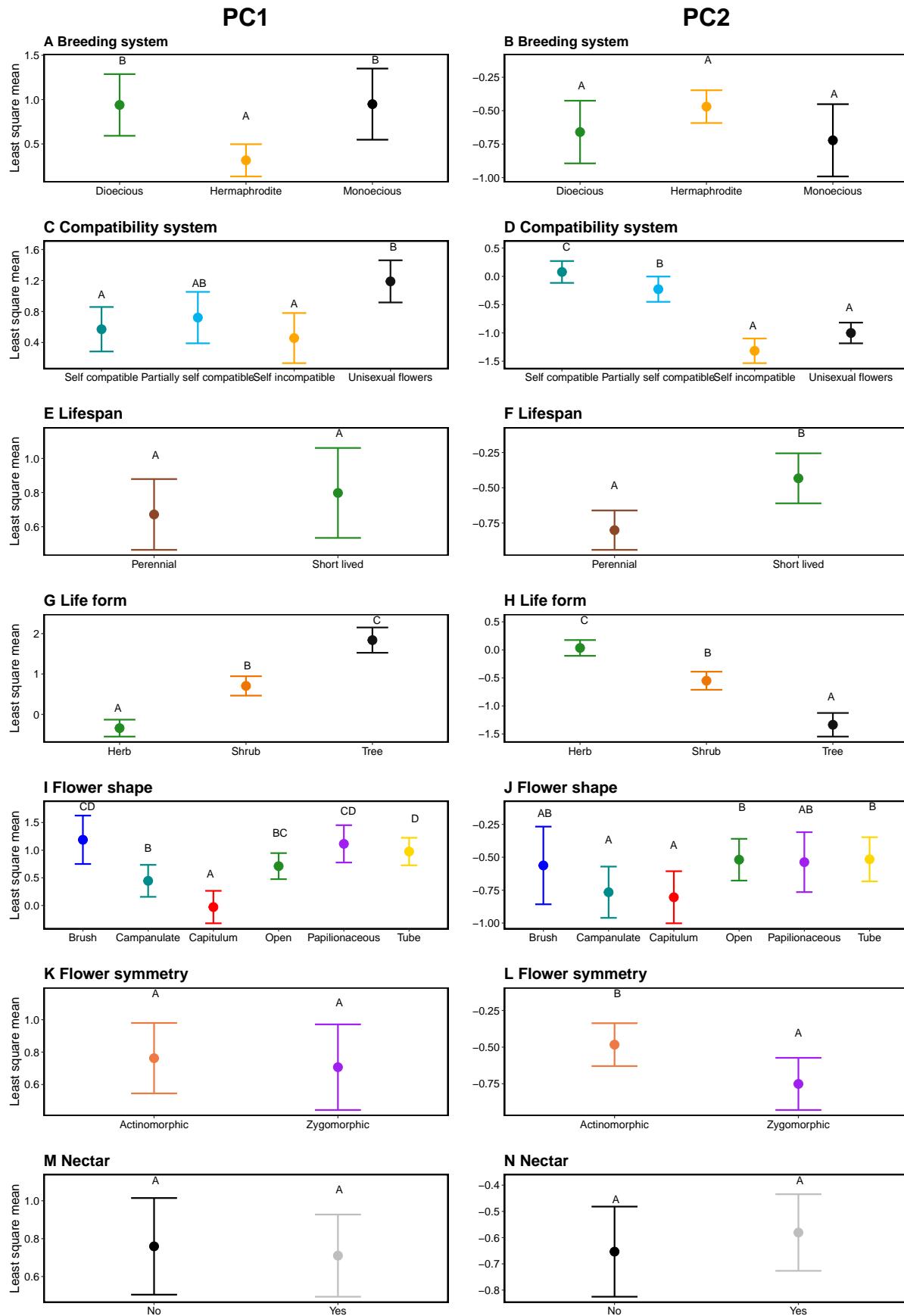
**Fig. S5.** Fitted posterior estimates of the interaction (yes/no) and number of visits made by bees including and excluding honey bees on the main axes of trait variation. The superior panel (plots a, b c, d, e and f) shows the comparison for presence-absence and the lower panel (plots g, h, i, j, k and l) the comparison for visitation rates.

**A Interaction frequency for all species****B Interaction frequency for subset with floral rewards****C Normalized degree for all species****D Normalized degree for subset with floral rewards****E Specialization for all species****F Specialization for subset with floral rewards**

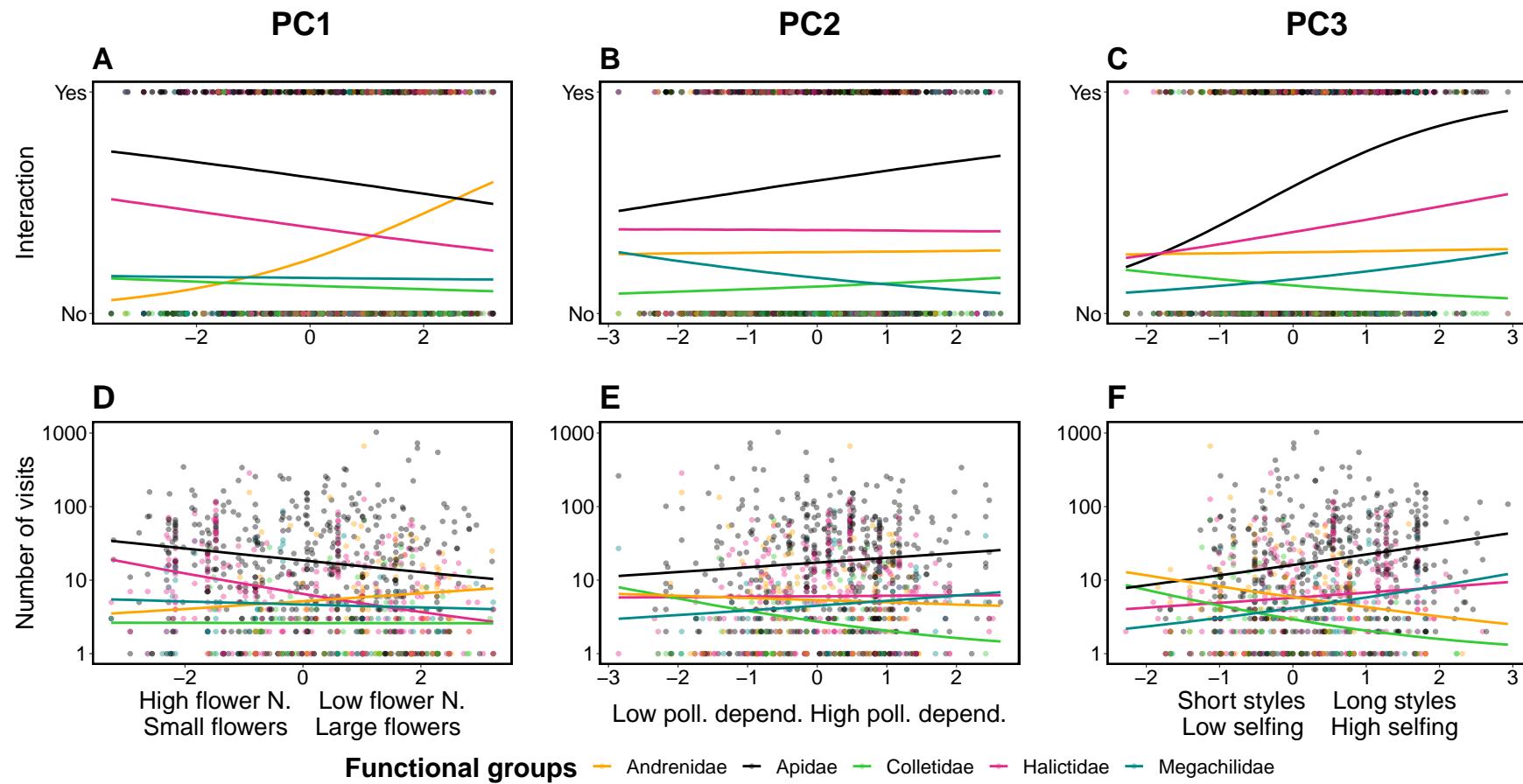
**Fig. S6.** Regression tree analyses. Comparison of the regression tree analyses between the full set of species and the subset of species with floral rewards for each plant species level metric.



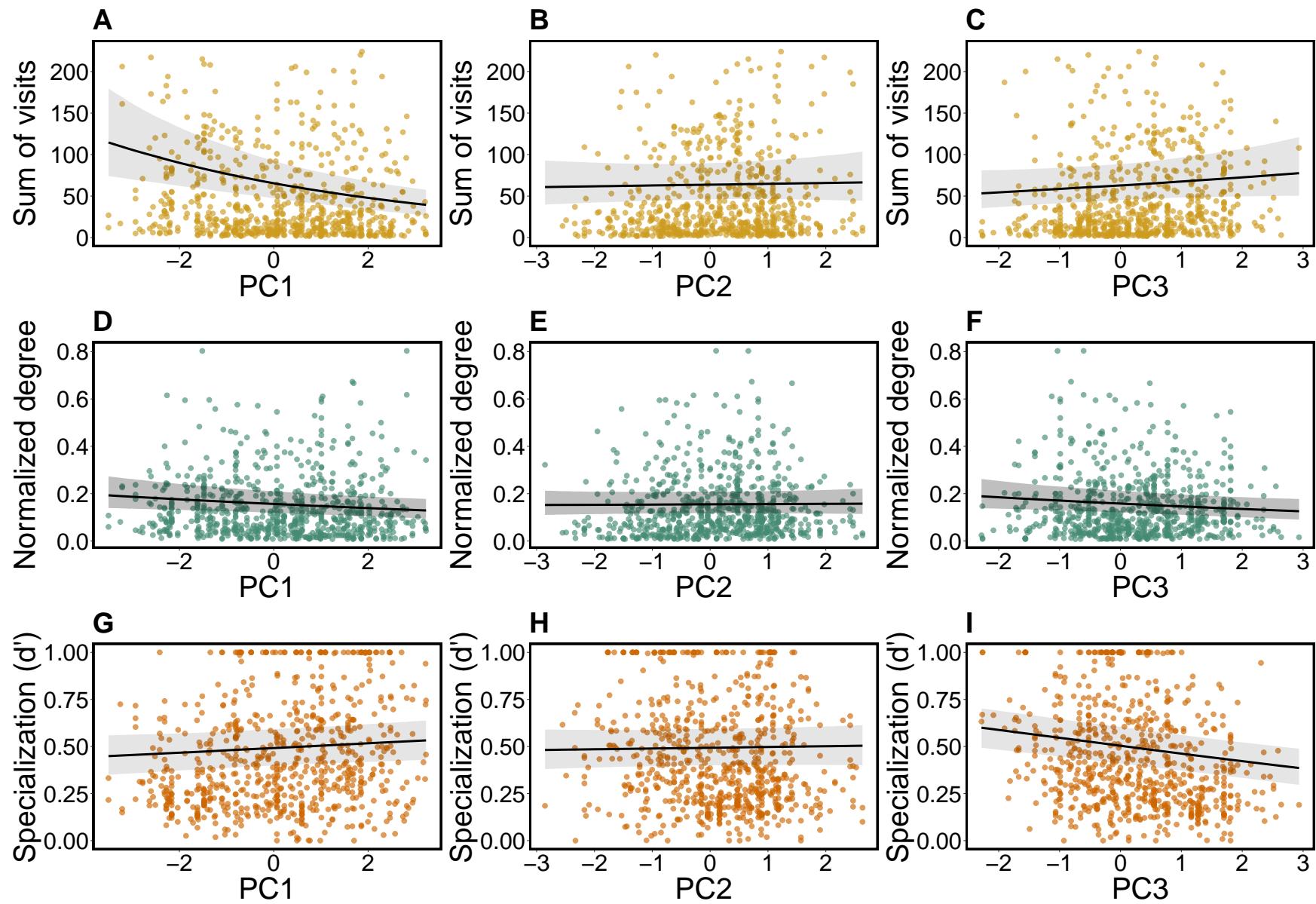
**Fig. S7.** Phylogenetic informed principal component analysis for the subset of species with floral rewards.



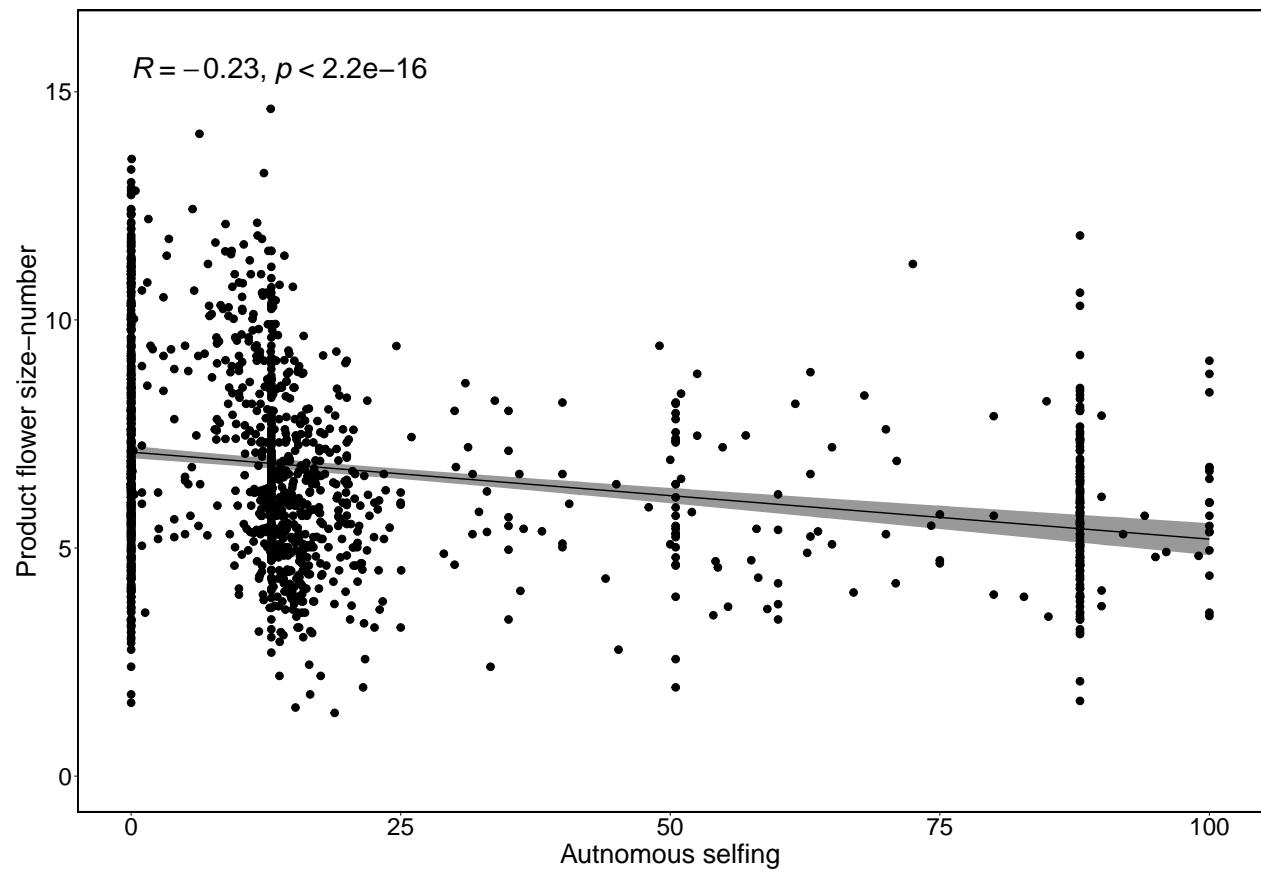
**Fig. S8.** Statistical comparison of the different categories of qualitative traits on the main two axes of trait variation with the full set of species. Categories that differ significantly are denoted with a different letter.



**Fig. S9.** Interaction (yes/no) and visitation rate of the main bee families on the main axes of trait variation. Fitted posterior estimates of the presence-absence of interaction (plots a, b and c) and visitation rate (plots e, f and g) of Andrenidae, Apidae, Colletidae, Halictidae and Megachilidae across PC1, PC2 and PC3. For visualization purposes, the response variable of number of visits was log-transformed (Y-axis of lower panel)



**Fig. S10.** Plant species level metrics across the three main axes of trait variation.



**Fig. S11.** Pearson correlation between the product of flower number-flower size and autonomous selfing level.