

## **Appendix for the paper “ Low resource availability drives feeding niche partitioning between wild bees and honeybees in a European city”**

Joan Casanelles-Abella, Simone Fontana, Bertrand Fournier, David Frey and Marco Moretti

### **Supplementary Text**

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**Section S1.** Seeds of *Raphanus sativus* were sown on 9 March 2016 into 1.5 L pots, which were filled with commercial standard garden soil and placed in a greenhouse. They were transferred to 7.5 L pots on 22 May. The remaining three species were bought as potted plants from certified Swiss wildflower nurseries (P. Willi, 6274 Eschenbach and UFA Samen, 8408 Winterthur) in March 2016. They were transferred into 10 L pots between 20 and 25 April. Sainfoin plants were grown together in one 20 L pot due to their relatively small size. All plants were kept outdoors under cool conditions from the end of March onwards, in order to harden them. All potted plants were transferred to focal gardens on the same day (9 June) around the onset of flowering. In the gardens, the plants were watered at least weekly and more frequently, based on actual signs of wilting, if necessary.

**Section S2.** ITD is a proxy for body size, which is a measure of mobility and thus foraging distance (Cote et al. 2017). While larger bees (i.e. with a larger ITD) can fly longer distances and consequently could be able to switch foraging patches in case of increased competition (Wojcik et al. 2018; see also Walter-Hellwig et al. 2006), they also have higher nutritional requirements to fuel their flights (Zurbuchen et al. 2010) and may have similar nutrient profile preferences to honeybees (Kriesell et al. 2017). Tongue length is another important functional trait, which determines the range of floral resources (in terms of floral morphology) a bee can access. Specifically, longer tongues enable bees to exploit deeper corollas. Feeding specialization degree is a trait related to the number of plant taxa (i.e. family, genus or species level) a bee forages. We classified bees into three categories: polylectic (visiting >10 plant families), oligolectic (visiting 2–10 plant families, usually few species) and monolectic (visiting 1 plant family, usually one or very few species). Phenology start and end are two traits related to the temporal feeding niche, specifically measuring the amount of time (here weeks) during which a bee is mobile. Finally, we used daily activity (the time of day when a bee was actively foraging) as an additional component of the temporal feeding niche. This trait has been found to be an important aspect of honeybee foraging behaviour (Moore et al. 1989).

ITD was measured following Kendall et al. (2019). Tongue length was measured as the sum of the lengths of prementum and glossa with an Olympus SZX12 Microscope and Olympus image analysis software (Version 510; Olympus Soft Imaging Solutions GmbH, Münster, Germany). Relative tongue length was then calculated by dividing tongue length by ITD to obtain a measure independent of body size (i.e. length of the tongue per unit body size). Daily activity was defined as the time window (1 h intervals) when the bee individual was captured

while feeding. Species-level measurements for the remaining traits were extracted from the European trait database (compiler: Stuart Roberts; pollinator loss module of the EU- FP6 ALARM-project) following Fournier et al. (2020).

**Section S3.** We used a detailed map of the habitats and land-cover types of the city of Zurich (Biototypenkartierung der Stadt Zürich 2010), grouped by Braaker et al. (2014) into 11 main categories. In particular, the impervious land-covers include buildings, major roads and gravel. In addition, the green land-covers include urban agriculture (i.e. allotment gardens), meadows, forests, hedges, wetlands and lawn. At each site, we calculated the amount of each category at 50, 100, 250 and 500 m radii. We additionally aggregated the impervious land-covers (i.e. buildings, major roads and gravel) and the green land-covers (agricultural land, meadows, forests, hedges, wetlands and lawn) at the same radii.

**Table S1. Features of the experimental gardens.** For each garden (Site), we provide the geolocation, the number of sampling days, the total sampling effort (i.e. the total amount of time volunteers spend sampling the phytometer), the number of wild bee species, plants species, the abundance of honeybee individuals. Moreover, we provide the amount of green surface around garden at 100 and 500 m radii. Note that a sampling day is equivalent to 9 hours.

Site	Latitude	Longitude	Sampling days	Sampling effort (days)	Wild bee S	Honeybee abundance	N. hives 500 m	Plant S	Green surfaces 100 m	Green surfaces 500 m
2	47.366	8.567	3	5.890	27	10	1	148	0.5768	0.4274
7	47.412	8.550	5	5.330	14	13	0	69	0.1851	0.7771
8	47.411	8.565	4	5.740	20	28	0	79	0.5919	0.5336
11	47.386	8.479	3	6.000	15	15	6	89	0.5226	0.4912
17	47.331	8.515	3	4.810	18	5	0	71	0.5871	0.2957
19	47.371	8.540	4	6.780	19	85	17	114	0.0385	0.9542
25	47.418	8.513	5	6.310	28	13	2	132	0.6544	0.3364
27	47.372	8.524	3	8.000	21	39	20	117	0.0489	0.8891
28	47.365	8.518	3	5.000	20	27	10	110	0.5132	0.7276
30	47.411	8.549	5	5.480	28	11	0	185	0.343	0.8051

40	47.395	8.535	4	5.370	22	17	10	105	0.5253	0.586
41	47.404	8.541	4	5.560	25	47	0	131	0.5716	0.5175
47	47.407	8.577	4	6.460	28	24	0	186	0.5596	0.5083
48	47.371	8.546	4	7.560	15	31	7	102	0.1272	0.8585
52	47.375	8.490	4	5.520	15	24	3	174	0.4205	0.5406
53	47.375	8.523	3	7.000	18	46	21	125	0.0953	0.8974
56	47.416	8.525	5	5.310	23	8	4	171	0.7817	0.2961
59	47.409	8.573	4	6.190	18	24	0	75	0.5824	0.4937
71	47.352	8.582	4	5.650	29	15	5	177	0.7604	0.2754
73	47.384	8.499	3	6.000	20	28	0	76	0.3046	0.7802
83	47.402	8.504	4	5.000	21	21	17	90	0.5793	0.4248
84	47.385	8.576	4	6.370	29	31	1	85	0.4575	0.3293
85	47.391	8.551	3	5.930	22	7	26	82	0.7124	0.2769

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**Table S2. Description of the six functional traits used in the analyses.** For each trait, we provide the level of measurement (individual or species), the type of trait, the unit of measurement (for numeric traits) and the categories used (for categorical traits), and a short description.

Trait	Level of measurement	Type	Unit	Information
Intertegular distance (ITD)	Individual level	Numeric continuous	mm	Reflects body size and thus is a proxy for dispersal and foraging capacity
Relative tongue length	Individual level	Numeric continuous	mm	Indicates the diversity of floral morphologies, and consequently resources, a species can access
Daily activity	Individual level	Numeric continuous	Hour	Time of the day when a bee species was observed foraging
Phenology start	Species level	Numeric discrete	Week	First week of a bee species' active period
Phenology end	Species level	Numeric discrete	Week	Last week of a bee species' active period
Feeding specialization	Species level	Categorical	Monolectic Oligolectic Polylectic	Classification based on the number of plant taxa visited by a bee species, reflecting bee diet specialization

**Table S4.** Selected and alternative Structural Equation Models (SEMs). For each SEM, the formulation of the linear model (LM) of the community niche partitioning, wild bee species richness, plant species richness and number of honeybees is presented. For each SM, we report the Akaike Information Criterion (AIC) and corrected Akaike Information Criterion (AICc), the Bayesian Information Criterion (BIC), the adjusted R<sup>2</sup> for the four LMs included in the SEM, and the Fisher's C value. Plant S = Plant species richness; MI = management intensity; N honeybees = number of honeybee individuals; Wild bee S = number of wild bee species; Green100 = amount of green surface in 100 m; Green500 = amount of green surface in 500 m; Year = years managed; Hives500 = number of hives in 500 m radius; Agriculture100 = amount of agricultural land in 100 m radius

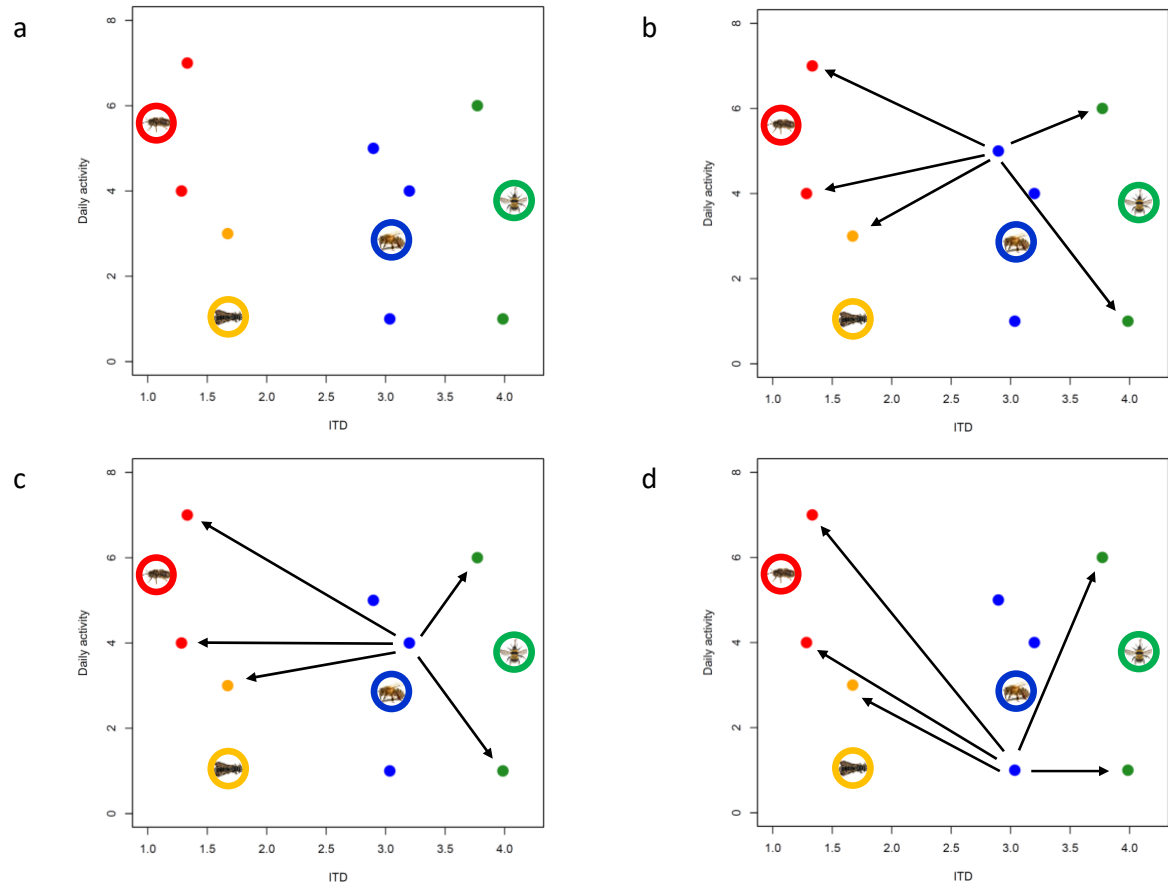
	AIC	AICc	BIC	R <sup>2</sup> Niche partitioning	R <sup>2</sup> Wild bee S	R <sup>2</sup> Plant S	R <sup>2</sup> N honeybees	Fisher's C
<b>Full model</b> <i>Niche partitioning</i> ~ Plant S + Green500 + N honeybees + Wild bee S + Hives500 <i>Wild bee S</i> ~ Plant S + N honeybees + Grey100 + Hives500 + Agriculture100 <i>Plant S</i> ~ MI + Year <i>N honeybees</i> ~ Grey500 + Plant S	83.83	Inf	108.81	0.54	0.57	0.39	0.40	39.83, df=32, p-value=0.161
<b>Model 1</b> <i>Niche partitioning</i> ~ Plant S + Green500 + N honeybees + Wild bee S + Hives500 <i>Wild bee S</i> ~ Plant S + N honeybees + Green100 + Hives500 <i>Plant S</i> ~ MI + Year <i>N honeybees</i> ~ Green500	74.52	856.99	97.23	0.54	0.44	0.39	0.40	34.52, df=28, p-value=0.184
<b>Model 2</b> <i>Niche partitioning</i> ~ Plant S + Green500 + N honeybees + Wild bee S + Hives500 <i>Wild bee S</i> ~ Plant S + N honeybees + Green100 + Hives500 + Agriculture100 <i>Plant S</i> ~ MI + Year <i>N honeybees</i> ~ Green500 + Plant S	82.89	1906.53	106.74	0.54	0.57	0.40	0.39	40.83, df=34, p-value=0.194



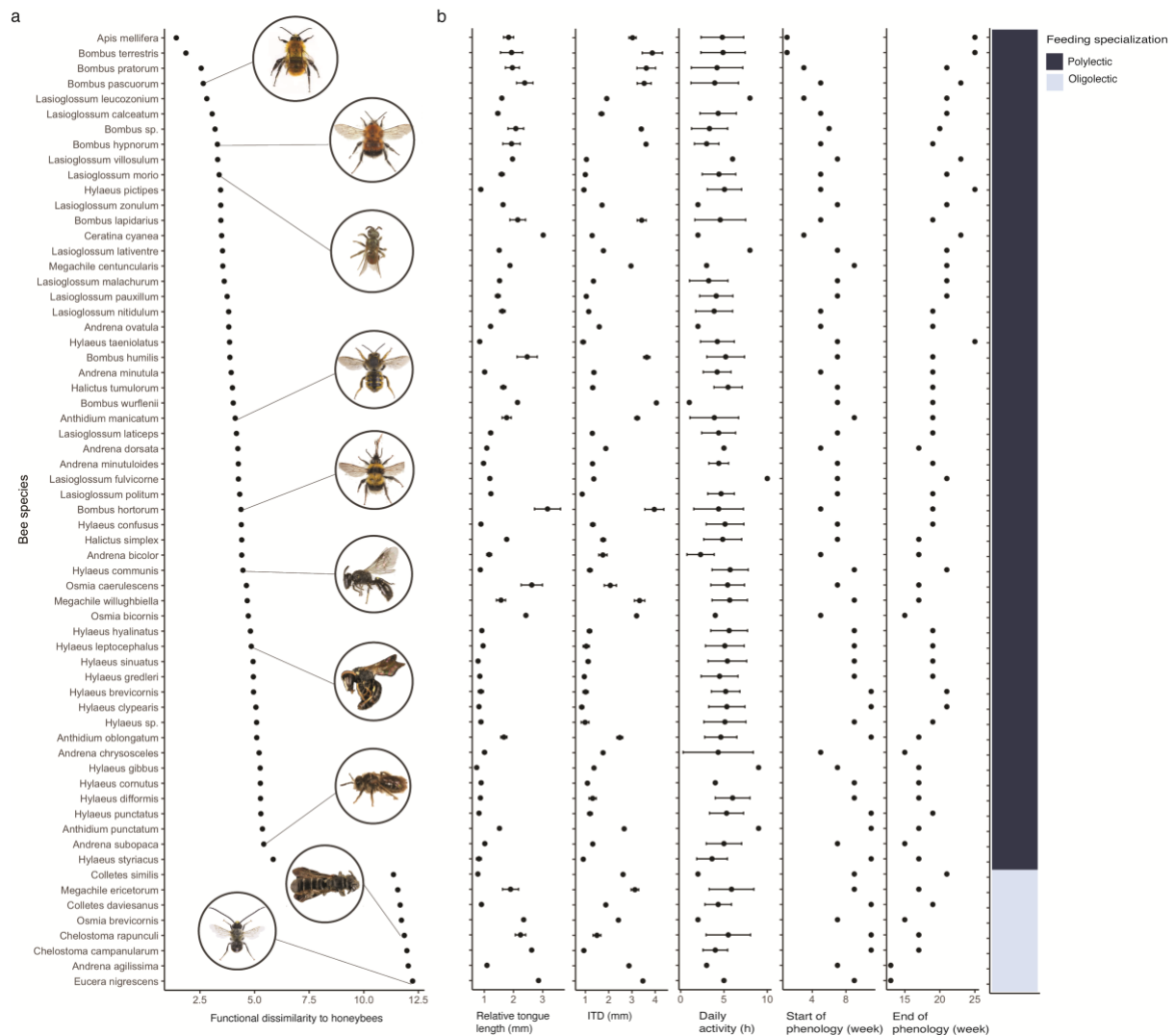




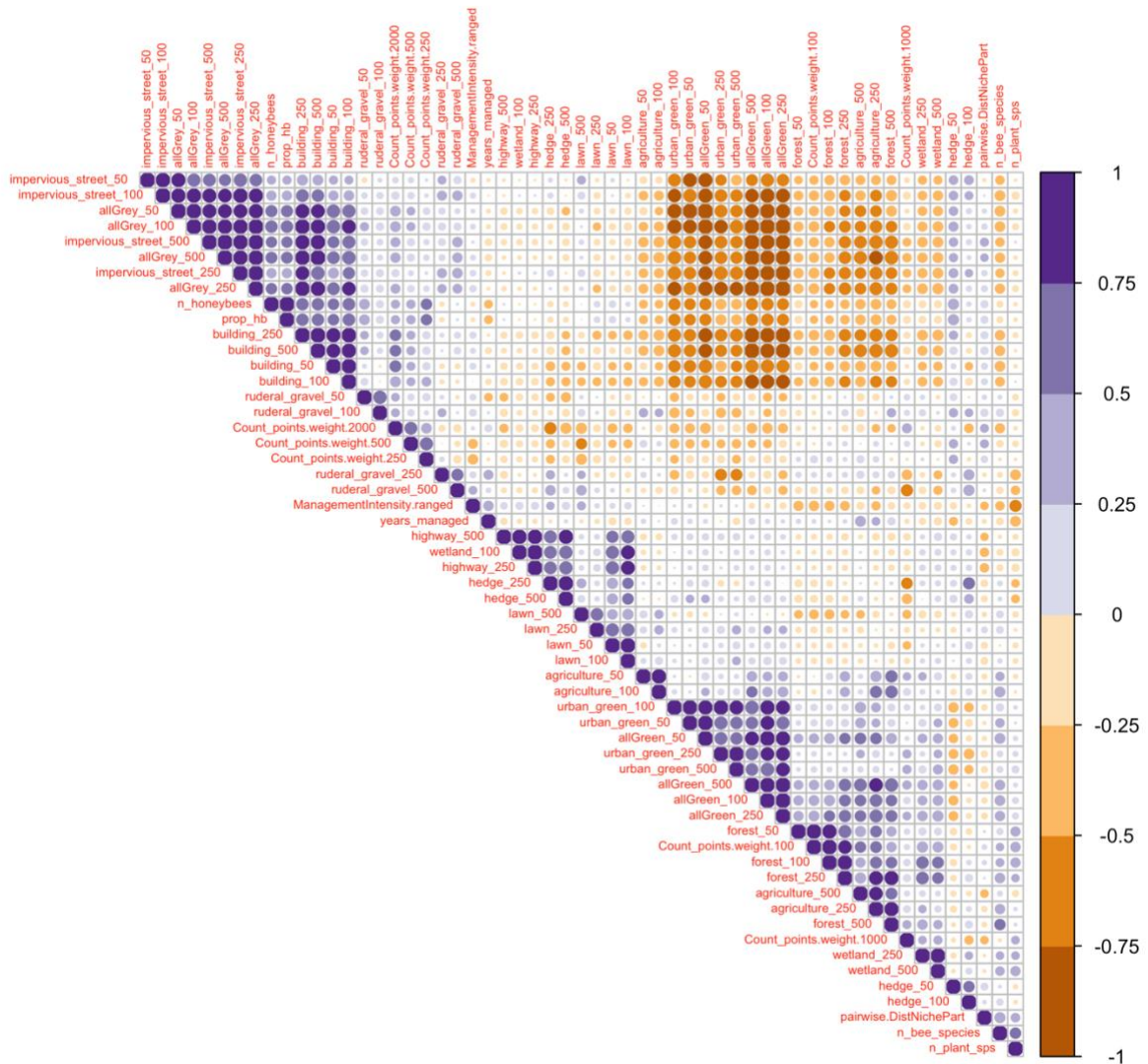
**Figure S1. Experimental set-up.** (a) example of a highly managed garden, with low numbers of plant species, and (b) example of with low management intensity, with high numbers of plant species. Credit: David Frey.



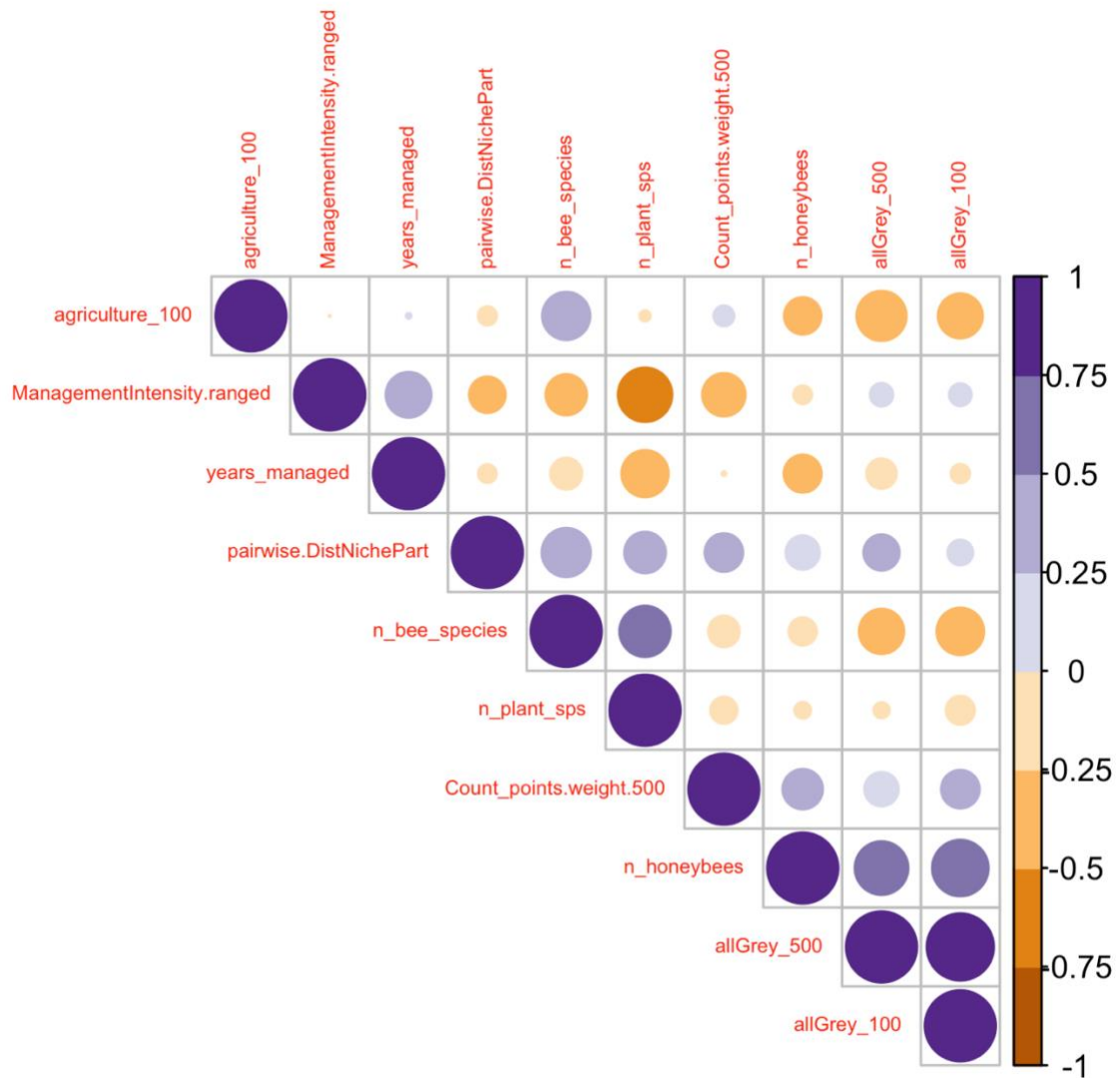
**Figure S2. Graphical summary of the calculation of feeding niche partitioning.** In a given site, feeding niche partitioning between wild bees and honeybees is calculated as the mean of the pairwise distances between all wild bee individuals and all honeybee individuals in the multidimensional trait space (six functional traits in this case, i.e. intertegular distance (ITD), relative tongue length, daily activity, phenology start and end, and feeding specialization). Plots (a–d) show a simplified graphical representation of the calculation considering two traits (two dimensions in the functional trait space, in this case ITD and daily activity), three wild bee species with two, two and one individuals, respectively, and the honeybees with three individuals. Wild bee individuals of the three species are coloured red, yellow and green, and honeybee individuals are coloured blue. Arrows in (b–d) represent the distances between each of the three honeybee individuals and the wild bee individuals of the three species. The average length of the arrows (15 in total in this case) represents feeding niche partitioning.



**Figure S3.** Characterization of the studied species. (a) Functional dissimilarity to honeybees, as shown in Figure 2. (b) Values of the six functional traits used to compute the functional dissimilarity per species. For relative tongue length, intertegular distance and day activity, the measurements are at the individual level; dots indicate the mean value per species and bars the standard deviation. The start and end of phenology and feeding specialization (lecty) are measured at the species level. Images retrieved from: <https://www.flickr.com/people/usgsbiml/>

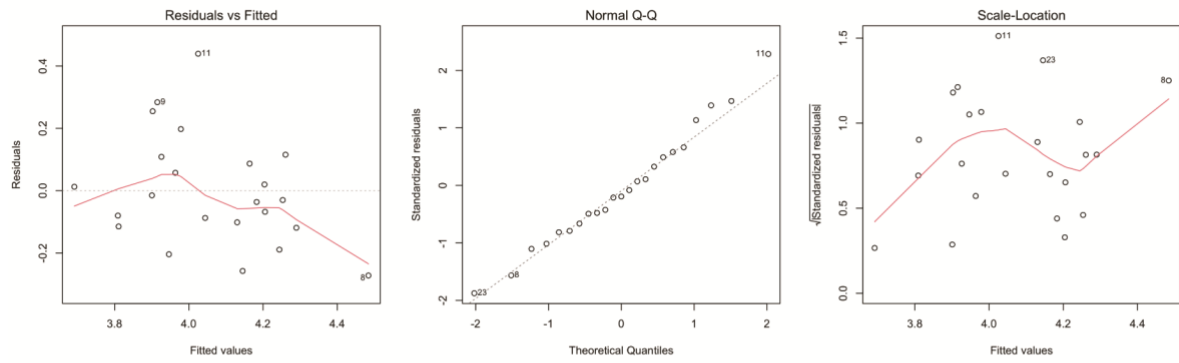


**Figure S4. Correlations among all variables.** ManagementIntensity.ranged = management intensity; n\_honeybees = number of honeybee individuals; n\_bee\_species = number of wild bee species; allGrey50,100,250,500 = amount of grey surface in 50, 100, 250, 500 m; allGrey50,100,250,500 = amount of grey surface in 50, 100, 250, 500 m; Count\_points.weight.50, .100, .250, .500 = number of hives in 50, 100, 250, 500 m radius; agriculture\_50, \_100, \_250, \_500 = amount of agricultural land in 50, 100, 250, 500 m radius; years\_managed = years managed

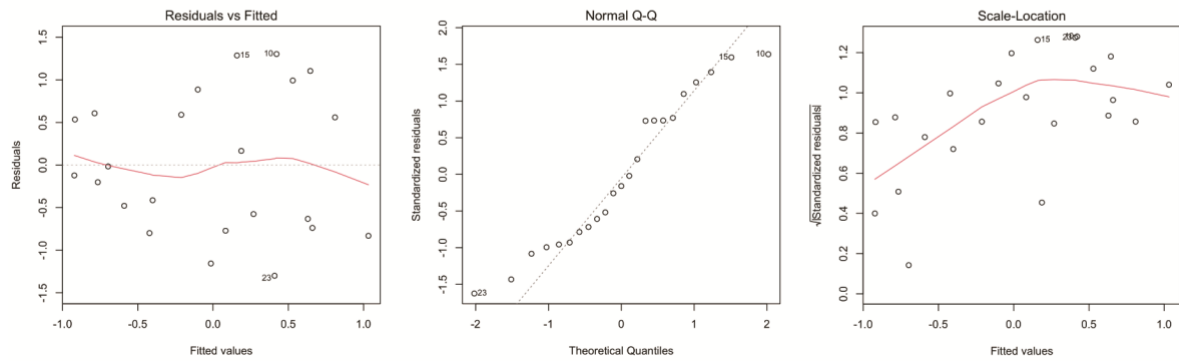


**Figure S5.** Correlations among response variables and explanatory variables included in the SEM. ManagementIntensity.ranged = management intensity; n\_honeybees = number of honeybee individuals; n\_bee\_species = number of wild bee species; allGrey100 = amount of grey surface in 100 m; allGrey500 = amount of grey surface in 500 m; Count\_points.weight.500 = number of hives in 500 m radius; agriculture\_100 = amount of agricultural land in 100 m radius; years\_managed = years managed

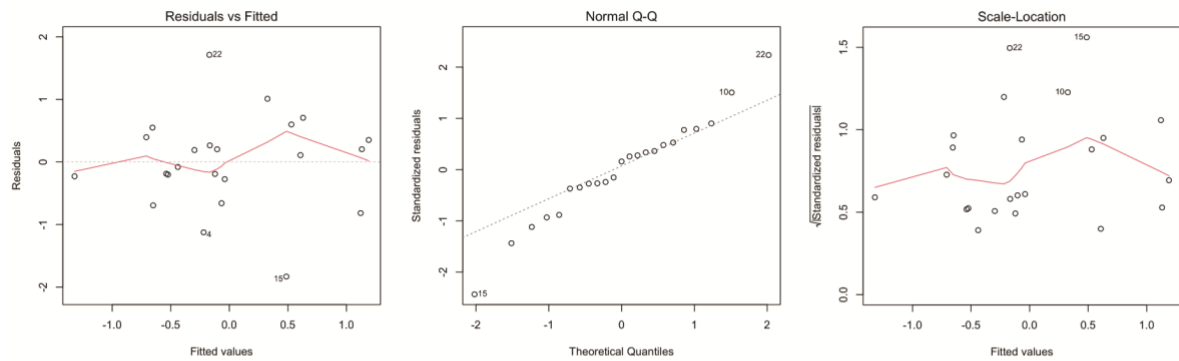
## SEM: Community niche partitioning



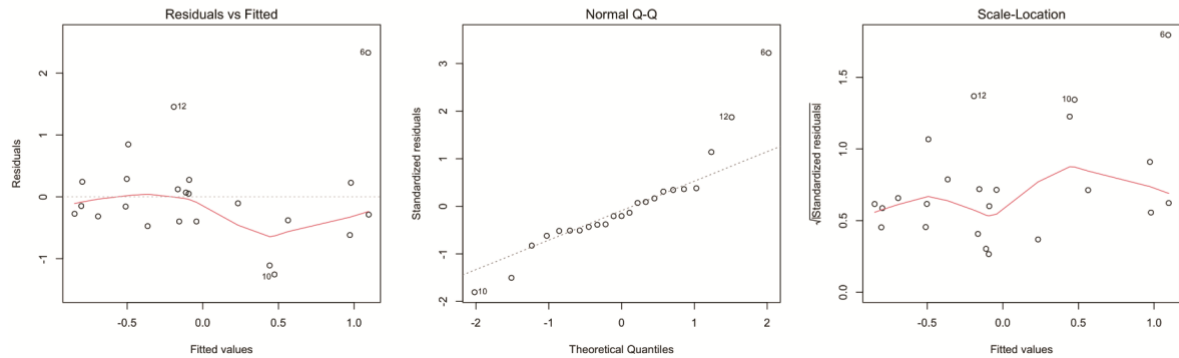
## SEM: Plant S



## SEM: Wild bee S



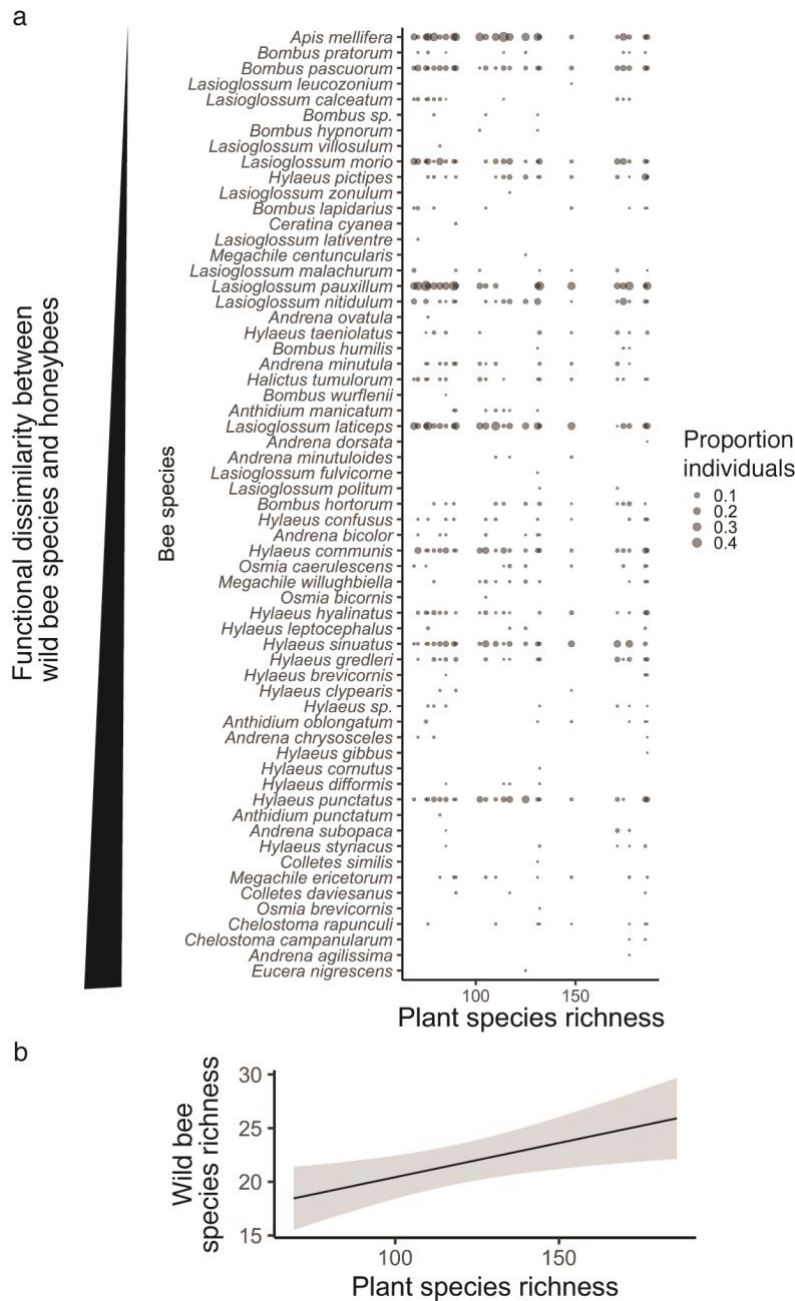
## SEM: Number of honeybees



**Figure S6.** Residual plots for assessing model assumptions of the LMs used in the SEM framework. Response variables for the LMs with community niche partitioning, plant species

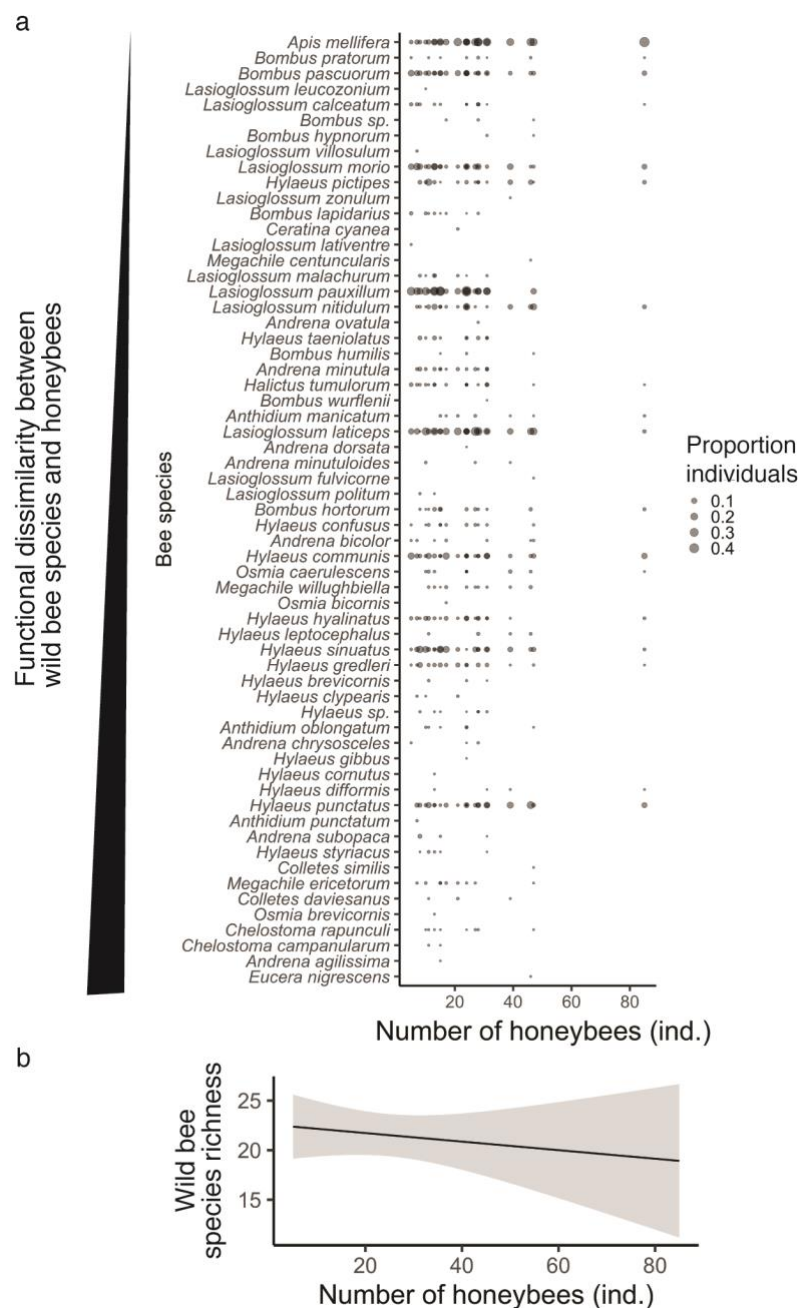
richness, wild bee species richness and honeybee abundance are plotted (see Table 2 for complete model compositions). Very few measurements do not fit well with the model, as recognizable in the Q-Q plots of the residuals, and the majority of the observations seem to fulfil the model assumptions well.  $S$  = species richness



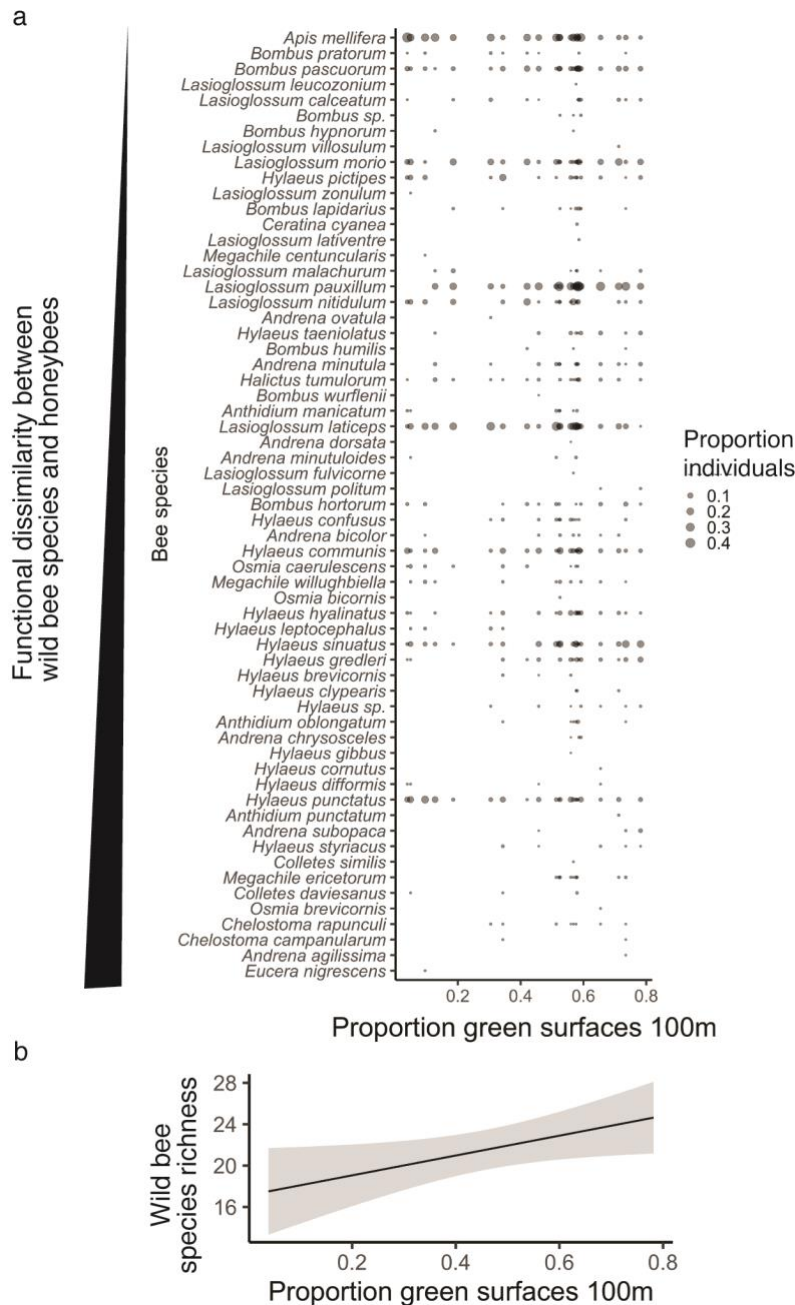


**Figure S7. Influence of resource availability at the local scale on wild bee community composition.** (a) Wild bee species composition in relation to plant richness at each site, which is used as a proxy of resource availability at the local scale. Wild bee species are sorted according to their functional dissimilarity with honeybees, with functionally similar species on the top and functionally dissimilar species on the bottom. The size of each dot represents the proportion of individuals collected at a given site. (b) Linear model depicting the relationship between the wild bee species richness and plant species richness. The grey band indicates the 95% confidence interval.

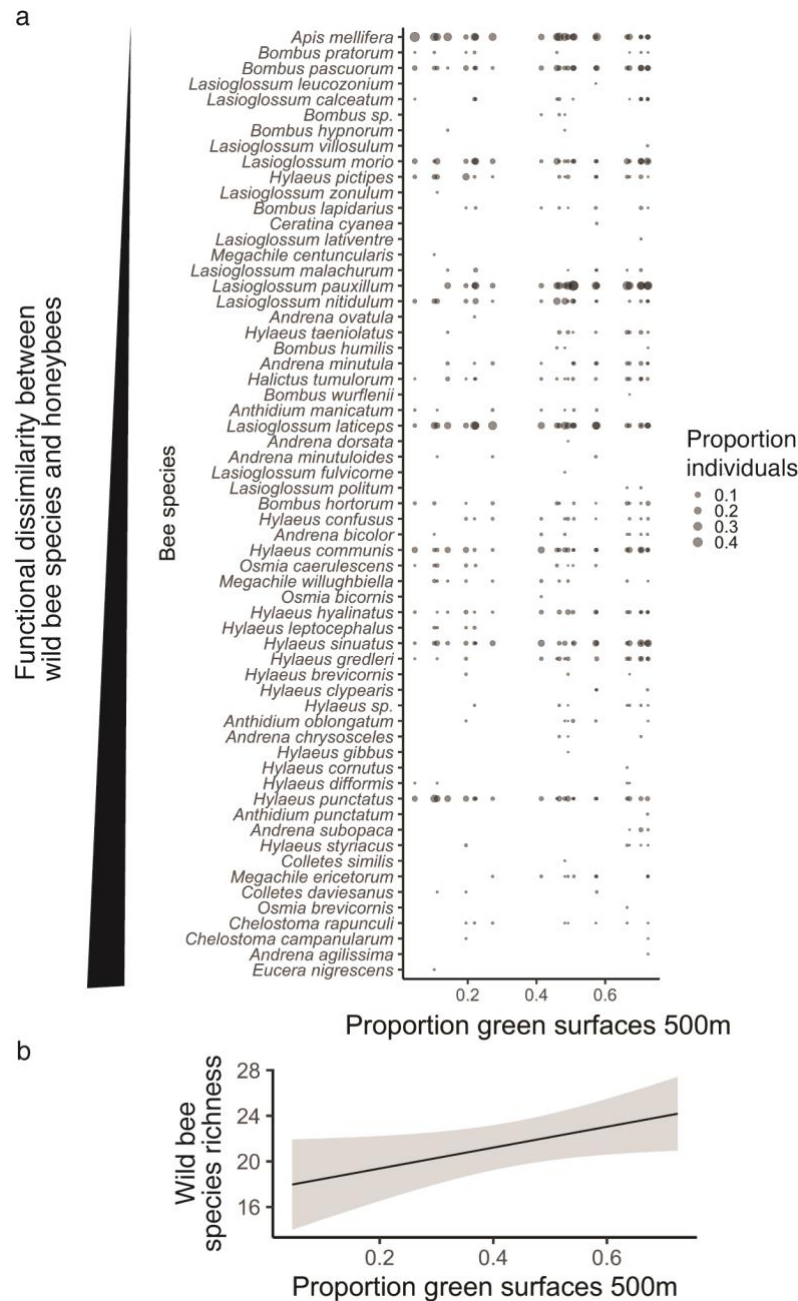




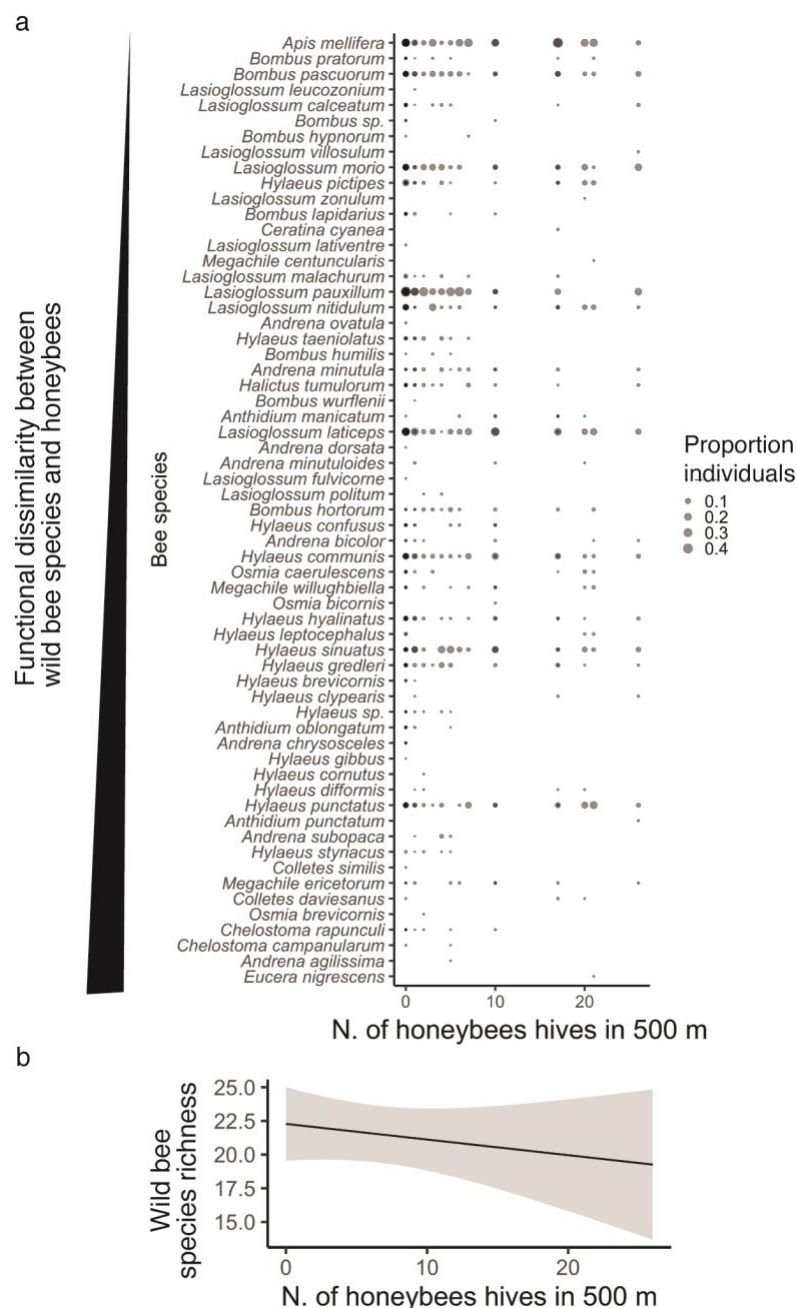
**Figure S8. Influence of beekeeping intensity at the local scale on wild bee community composition.** (a) Wild bee species composition in relation to the number of honeybees at each site, used as a proxy of beekeeping intensity at the local scale. Wild bee species are sorted according to their functional dissimilarity with honeybees, with functionally similar species on the top and functionally dissimilar species on the bottom. The size of each dot represents the proportion of individuals collected at a given site. (b) Linear model depicting the relationship between wild bee species richness and the number of honeybees. The grey band indicates the 95% confidence interval.



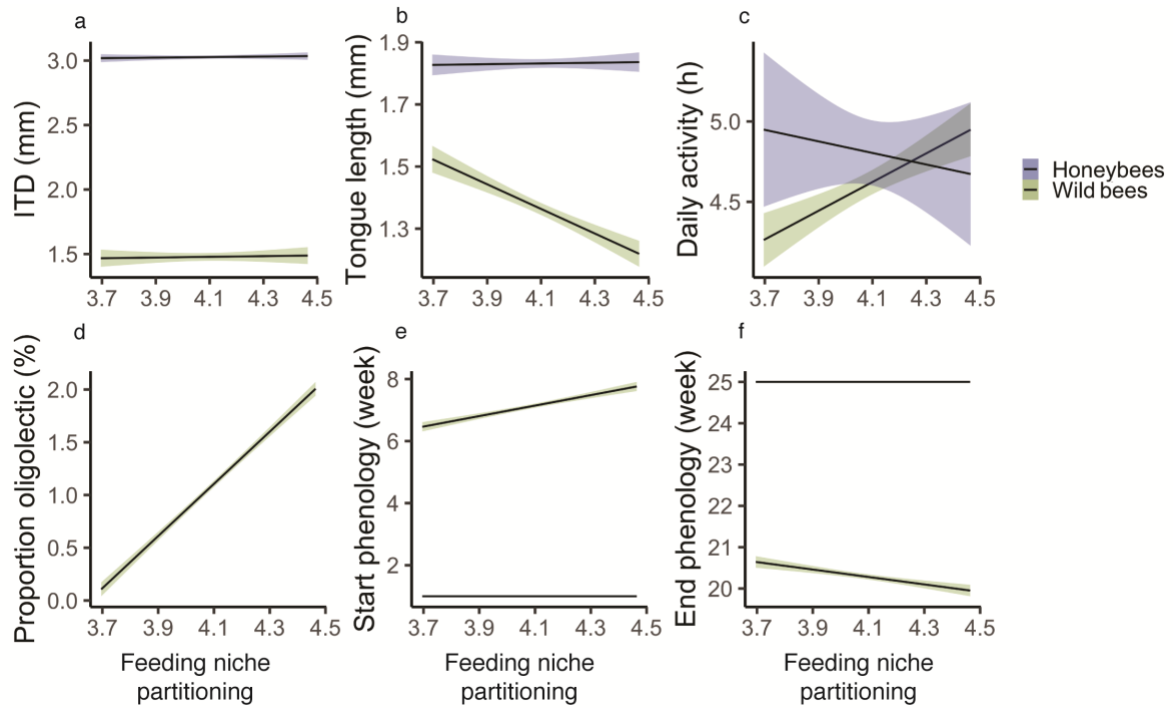
**Figure S9. Influence of the resource availability at the landscape scale on wild bee community composition.** (a) Wild bee species composition in relation to the proportion of grey surfaces in a 100 m radius at each site, used as a proxy of resource availability at the landscape scale. Wild bee species are sorted according to their functional dissimilarity with honeybees, with functionally similar species on the top and functionally dissimilar species on the bottom. The size of each dot represents the proportion of individuals collected at a given site. (b) Linear model depicting the relationship between wild bee species richness and the proportion of green surfaces in a 100 m radius, as also shown in Figure 5d. The grey band indicates the 95% confidence interval.



**Figure S10. Influence of the resource availability at the landscape scale on wild bee community composition.** (a) Wild bee species composition in relation to the proportion of green surfaces in a 500 m radius at each site, used as a proxy of resource availability at the landscape scale. Wild bee species are sorted according to their functional dissimilarity with honeybees, with functionally similar species on the top and functionally dissimilar species on the bottom. The size of each dot represents the proportion of individuals collected at a given site. (b) Linear model depicting the relationship between the wild bee species richness and the proportion of green surfaces in a 500 m radius, as also shown in Figure 5b. The grey band indicates the 95% confidence interval.



**Figure S11. Influence of beekeeping intensity at the landscape scale on wild bee community composition.** (a) Wild bee species composition in relation to the number of honeybees hives in 500 m, used as a proxy of beekeeping intensity at the landscape scale. Wild bee species are sorted according to their functional dissimilarity with honeybees, with functionally similar species on the top and functionally dissimilar species on the bottom. The size of each dot represents the proportion of individuals collected at a given site. (b) Linear model depicting the relationship between wild bee species richness and the number of honeybees. The grey band indicates the 95% confidence interval.



**Figure S12 Change in the values of the six functional traits in relation to feeding niche partitioning.** For each trait, we present the linear model (a, c, d, e, f) or the generalized additive model (b) in relation to feeding niche partitioning for honeybees (green) and wild bees (blue). Green and blue bands represent 95% confidence intervals. Note that for feeding specialization we present the proportion of oligolectic species.

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