Gut microbiota structure differs between honey bees in winter and summer

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Abstract

Adult honey bees harbor a specialized gut microbiota of relatively low complexity. While seasonal differences in community composition have been reported, previous studies have focused on compositional changes rather than differences in absolute bacterial loads. Moreover, little is known about the gut microbiota of winter bees, which live much longer than bees during the foraging season, and which are critical for colony survival. We quantified seven core members of the bee gut microbiota in a single colony over two years and characterized the community composition in 14 colonies during summer and winter. Our data shows that total bacterial loads substantially differ between foragers, nurses, and winter bees. Long-lived winter bees had the highest bacterial loads and the lowest community α−diversity, with a characteristic shift towards high levels of *Bartonella* and *Commensalibacter*, and a reduction of opportunistic colonizers. Using gnotobiotic bee experiments, we show that diet is a major contributor to the observed differences in bacterial loads. Overall, our study reveals that the gut microbiota of winter bees is remarkably different from foragers and nurses. Considering the importance of winter bees for colony survival, future work should focus on the role of the gut microbiota in winter bee health and disease.

42 # Introduction

43 The European honey bee, *Apis mellifera,* is an important pollinator species for natural
44 ecosystems and agricultural production [1]. Its health status is threatened by numerous
45 factors including habitat loss, pesticide exposure, and high parasite and pathogen loads [2–
46 4]. Accumulating evidence suggests that the gut microbiota of adult honey bees plays a
47 critical role for bee health [5]. The bee microbiota converts dietary compounds [6, 7] and
48 produces short chain fatty acids [8] in the gut, enhances sucrose responsiveness of the host
49 [8], and stimulates the immune system [9, 10]. Moreover, disruption of the gut microbiota
50 composition by antibiotic treatment, pesticide exposure, or dietary manipulations has
51 been associated with increased pathogen loads resulting in increased host mortality [11–
52 14].

53 A striking feature of the honey bee gut microbiota is its low taxonomic complexity. In
54 worker bees, the community is dominated by less than ten phylotypes (i.e. clusters of
55 strains sharing ≥97% sequence identity in the 16S rRNA gene), which typically make up
56 >95% of the bacterial cells in the gut [5, 15–18]. These phylotypes have been consistently
57 detected in honey bees, regardless of geographic location, life stage, or season [16, 19, 20],
58 and are acquired horizontally through contact with nest mates and hive components [21].
59 They include five core phylotypes (*Gilliamella, Snodgrassella, Lactobacillus* Firm-4 and
60 Firm-5, and *Bifidobacterium*), which are typically present in every adult worker bee, and a
61 number of non-core phylotypes, e.g. *Frischella*, *Bartonella, Commensalibacter*, or
62 *Bombella*, which are prevalent across colonies, but not necessarily present in every bee
63 [22]. Additional phylotypes have been detected, including *Lactobacillus kunkeii, Serratia*

64 *marcescens* and other Enterobacteriaceae, or *Apibacter*, but they typically account for a
65 relatively small proportion of the bee gut microbiota [23].

66 While many of these phylotypes are consistently present in adult worker bees, their
67 abundance can vary across bees, and may differentially impact the host physiology.
68 Particularly, the type and amount of nutrients (i.e. pollen and nectar) available during the
69 foraging season can have profound effects on the composition of the gut microbiota and
70 may alter its metabolic activity [24]. Likewise, distinct dietary habits or variation in lifespan
71 of worker bees during summer and winter may influence gut microbiota composition. From
72 spring to autumn, young worker bees (nurses) stay inside the hive to take care of larvae,
73 and feed on nutrient-rich pollen, whereas older worker bees become foragers that feed on
74 nectar and honey to fuel their energy-expensive flights [25]. In late autumn, newly emerged
75 adult worker bees become winter bees (also called 'diutinus') that have an extended
76 lifespan (~6 months) and that ensure the colony survival during the cold winter season in
77 the absence of brood [26]. These bees form a tight cluster for thermoregulation inside the
78 hive, feed strictly on food stores (pollen, beebread, and honey) and retain their feces all
79 winter [27], which is likely to impact the ecology of their gut microbiota.

80 A number of studies have looked at the gut microbiota composition of different worker bee
81 types or throughout seasons, with the overall conclusion that the community composition
82 is relatively stable [19, 28–31]. However, previous studies were mostly based on
83 comparative analyses of relative community member abundance using 16S rRNA amplicon
84 sequencing. Such analysis cannot provide insights about the extent or directionality of
85 changes in taxa abundance, especially if microbial loads vary substantially between
86 samples [32]. In fact, a change in the total abundance of the microbiota could by itself be

87 an important characteristic of different bee types (e.g. foragers, nurses, winter bees),
88 season, or environmental exposure. An example is the experimental exposure of bees to
89 antibiotics which did not result in a strong shift in the relative composition, but in an overall
90 reduction of bacterial load, rendering bees more susceptible to pathogen invasion [11]. In
91 addition to the limitations of current studies using relative abundance data, almost nothing
92 is known about the gut microbiota of winter bees as compared to foragers or nurses. This
93 is surprising, as winter bees are critical for colony health and survival during the cold season
94 of the year, when resources are limited and most colony losses occur [33, 34].

95 Characterizing the gut microbiota of winter bees and identifying factors that shape its
96 community composition may help to understand the physiological adaptations that honey
97 bees need to survive the cold season in temperate regions. In this study, we used qPCR and
98 16S rRNA gene amplicon sequencing to assess differences in the gut microbiota of nurses,
99 foragers, and winter bees. We analyzed bacterial loads of major community members in
100 566 individual worker bees sampled from a single hive over two years. We then expanded
101 our analysis to the entire community and analyzed pooled samples from 14 different hives
102 to test if similar community changes occur in winter bees across hives. Finally, we
103 performed experiments with gnotobiotic bees to test the influence of diet on differences
104 in gut microbiota composition. Our study reveals major differences in total bacterial load
105 and in the abundance of specific gut community members in the gut microbiota of nurses,
106 foragers, and winter bees and identifies dietary pollen as a major contributing factor.

107 # Materials and Methods

108 **Sampling of honey bees**

109 Over a period of two years, we sampled ~24 adult worker bees of *A. mellifera* each month
110 from a single hive located on the Dorigny campus of the University of Lausanne,
111 Switzerland. These bees were used to determine seasonal changes in the absolute
112 abundance of seven major community members of the honey bee gut microbiota using
113 qPCR. During the foraging season, we sampled foragers returning to the hive entrance with
114 pollen on their legs, while during the cold winter months, we sampled winter bees on top
115 of the frames from inside the hive. Each sampling time point took place at the middle of
116 each month (+/- 3 days) between April 2015 and April 2017. Samples from July 2015 were
117 not included in the analysis due to an error that occurred during DNA extraction.

118 To identify changes in gut microbiota composition between adult worker bees in summer
119 (i.e. nurses and foragers) and in winter (i.e. winter bees) across colonies, we sampled bees
120 from 14 different hives. Eleven hives were located on the Dorigny campus of the University
121 of Lausanne, and three hives were located in the village of Yens, about 17 km away.
122 Foragers and nurses were sampled in July 2017 and August 2018, and winter bees were
123 sampled in January 2018 and January 2019. Nurses and winter bees were collected inside
124 the hive in the center of the colony. Foragers were collected outside the hive at the same
125 time point as nurses. The bees sampled in July 2017 and January 2018 were used for gut
126 content visualization and correlation of gut weight and 16S rRNA gene copy numbers. The
127 guts of the bees sampled in August 2018 and January 2019 were pooled (20 guts per bee
128 type per hive) and used to monitor the abundance of individual community members by
129 qPCR and to determine the overall community structure by 16S rRNA community analysis.

130 Bees were anesthetized with CO_2 for 10 s and the gut including crop, midgut, hindgut, and
131 malpighian tubules carefully removed using sterile forceps. For the monthly sampling of

132 the single bee hive, each gut sample was placed in a drop of PBS, scored for the scab
133 phenotype [35], and placed in a bead beating tube containing ~150 mg of glass beads (0.75-
134 1 mm in diameter, Carl Roth) and 750 µL of CTAB lysis buffer (0.2 M Tris-HCl, pH 8; 1.4 M
135 NaCl; 0.02 M EDTA, pH 8; 2% CTAB, w/v, dissolved at 56°C overnight; 0.25% β-
136 mercaptoethanol, v/v). For the sampling of the 14 colonies in August 2018 and January
137 2019, the dissected guts were pooled into a single Falcon tube (14 hives x 3 bee types = 42
138 pooled samples). Tubes were flash frozen in liquid nitrogen and stored at -80°C until DNA
139 extraction.

140

141 **Experimental colonization of honey bees**

142 Microbiota-depleted bees were generated and colonized as described in Kešnerová et al.
143 [6]. The treatment group of bees fed on pollen and sugar water was the same as in the
144 previous study. The other treatment group (bees fed on sugar water only) was carried out
145 in parallel with the same batch of bees. Bees were fed *ad libitum* with sterilized bee pollen
146 (P) and sterilized sugar water (SW, 50% sucrose, w/v) (SW+P treatment), or with only
147 sterilized sugar water (SW treatment). Bees were sampled 10 days after colonization and
148 the guts were dissected as described before.

149

150 **DNA extraction from honey bee gut tissue**

151 A previously established CTAB/phenol-based extraction protocol [6] was used to extract
152 DNA from individual guts. At the end of the protocol, the precipitated dried pellet was
153 resuspended in 200 µl and split into two samples of 100 µl each. One sample was processed

154 with the Nucleospin PCR Clean-up kit (Macherey-Nagel, Germany) according to the
155 manufacturer's instructions and the resulting DNA was used for qPCR. For the pooled gut
156 samples, 2 ml of glass beads and 15 ml of CTAB lysis buffer were added to each Falcon tube.
157 Samples were then homogenized in a Fast-Prep24^{TM}5G homogenizer at 6 m/s for 40 s,
158 briefly centrifuged, and an aliquot of 750 µl corresponding to the sample volume of one
159 bee gut was transferred to a new 2 ml bead beating tube with glass beads and homogenized
160 again. All further steps of the DNA extraction were performed as previously described [6].

161

162 **Quantitative PCR (qPCR) to determine absolute abundance of community members**

163 Bacterial absolute abundances were determined using qPCR assays targeting the 16S rRNA
164 gene of either specific community members or universally all bacteria, and normalized to
165 the number of host actin gene copies, as described in Kešnerová et al. [6].
166 Standard curves were performed on serial dilutions containing known quantities of plasmid
167 DNA encoding the target sequence as follows: The plasmid copy number was calculated
168 based on the molecular weight of the plasmid and the DNA concentration of the purified
169 plasmid. Dilutions containing 10^1–10^7 plasmid copies per µl were used to generate the
170 standard curves. For *Frischella*, *Snodgrassella*, *Bartonella*, *Lactobacillus* Firm4, and
171 *Lactobacillus* Firm5, the slope and intercept of the standard curve was calculated based on
172 the Cq values (quantification cycle [36]) obtained from the dilutions containing 10^2 - 10^7
173 plasmid copies. For these targets, the Cq value corresponding to 10^2 copies was set as the
174 limit of detection (LOD) of the primer set, because dilutions containing 10^1 copies resulted
175 in Cq values which could not be discriminated from the water control, or the signal was
176 undetected. For all other targets (*Gilliamella*, *Bifidobacterium*, and actin), the slope and

177 intercept of the standard curve was calculated based on the Cq values obtained from all
178 seven dilutions, and the Cq value corresponding to 10^1 copies was used as the LOD.
179 Bacterial targets resulting in Cq values higher than the LOD of a given primer pair were
180 considered to be too low to be quantified in the respective sample (i.e. $<10^2$ or $<10^1$ copies
181 per µl). The *Efficiency of primers (E)* was estimated from the slope according to the
182 equation: $E = 10^{(-1/slope)}$ [37]. Primer characteristics and their performance are summarized
183 in **Table S1**.
184 One individual gut sample had to be excluded from the analysis, because it gave no
185 amplification for any of the bacterial targets and very low amplification for actin. For all
186 other samples we determined the number of bacterial genome equivalents per gut as a
187 proxy for bacterial abundance as follows: We first calculated the 'raw' copy number (n_{raw})
188 of each target in 1 µl of DNA (the volume used in each qPCR reaction) based on the Cq value
189 and the standard curve using the formula $n_{raw} = E^{(intercept - Cq)}$ [38]. Then, we normalized the
190 'raw' copy number by dividing by the number of actin gene copies present in the sample
191 (n_{actin}), which was determined using the same formula. This normalized value of 16S rRNA
192 gene copies was then multiplied by the median number of actin gene copies of the samples
193 of a given dataset and the total volume of extracted DNA (i.e. 200 µl) to obtain normalized
194 copy numbers per gut (n_{abs}): $n_{abs} = (n_{raw}/n_{actin}) \times median(n_{actin}) \times 200$. Normalization with the
195 actin gene was done to reduce the effect of gut size variation and the DNA extraction
196 efficiency. To report the number of genome equivalents (n_{GE}) rather than the normalized
197 16S rRNA gene copy number, we divided n_{abs} by the number of 16S rRNA loci present in the
198 genome of the target bacterium (as listed in **Table S1**). For the qPCR results obtained with
199 the universal bacterial primers, we reported the absolute 16S rRNA gene copies (n_{abs})
200 rather than genome equivalents (n_{GE}), as the number of 16S rRNA gene loci differs between

201 bacteria.

202

203 **16S rRNA gene amplicon sequencing**

204 The V4 region of the 16S rRNA gene was amplified as described in the Illumina 16S
205 metagenomic sequencing preparation guide
206 (https://support.illumina.com/documents/documentation/chemistry_documentation/16
207 s/16s-metagenomic-library-prep-guide-15044223-b.pdf) using primers 515F-Nex
208 (TCGTCGGCAGCGTCAGATGTGTATAAGAGACAGGTGCCAGCMGCCGCGGTAA) and 806R-Nex
209 (GTCTCGTGGGCTCGGAGATGTGTATAAGAGACAGGGACTACHVGGGTWTCTAAT), which
210 contain the adapter sequences for Nextera XT indexes and the primers for the V4 region of
211 the 16S rRNA gene [39]. PCR amplifications were performed in a total volume of 25 µl, using
212 12.5 µl of Invitrogen Platinum SuperFi DNA Polymerase Master Mix, 5 µl MilliQ water, 2.5
213 µl of each primer (5 µM), and 2.5 µl of template DNA. PCR conditions were set to 98°C for
214 30 s followed by 25 cycles of 98°C for 10 s, 55°C for 20 s and 72°C 20 s, and by a final
215 extension step at 72°C for 5 min. Amplifications were verified by 2% agarose gel
216 electrophoresis. The PCR products were next purified using Clean NGS purification beads
217 (CleanNA) in a 1:0.8 ratio of PCR product to beads, and eluted in 27.5 µl of 10 mM Tris pH
218 8.5. Next, we performed a second PCR step to add unique dual-index combinations to each
219 sample using the Nextera XT index kit (Illumina). Second-step PCR amplifications were
220 performed in a total volume of 25 µl using 2.5 µl of the PCR products, 12.5 µl of Invitrogen
221 Platinum SuperFi DNA Polymerase Master Mix, 5 µl MilliQ water, and 2.5 µl each of Nextera
222 XT index primers 1 and 2. Thermal cycle conditions were an initial denaturation step at 95°C
223 for 3 min followed by eight cycles of 30 s at 95°C, 30 s at 55°C, and 30 s at 72°C, and a final
224 extension step at 72°C for 5 min. The final libraries were purified using Clean NGS

225 purification beads in a 1:1.12 ratio of PCR product to beads, and eluted in 27.5 µl of 10 mM
226 Tris pH 8.5. The amplicon concentrations, including the negative PCR control, were then
227 quantified by PicoGreen and pooled in equimolar concentrations (with the exception of the
228 negative control). We verified that the final pool was of the right size using a Fragment
229 Analyzer (Advanced Analytical) and performed sequencing on an Illumina MiSeq
230 sequencer, producing 2 x 250 bp reads, at the Genomic Technology Facility of the University
231 of Lausanne.
232
233 **Processing of 16S rRNA gene amplicon sequencing data**
234 Divisive Amplicon Denoising Algorithm 2 (DADA2) pipeline ("dada2" package version 1.12.1
235 in R) was used to process the sequencing data (see script '2_Dada2_Pipeline.R' on Zenodo)
236 [40]. All functions were ran using the recommended parameters
237 (https://benjjneb.github.io/dada2/tutorial.html) except for "expected errors" during the
238 filtering step which was set to (maxEE=1,1) in "filterAndTrim" function. The SILVA database
239 was used for taxonomy assignments. Downstream analyses were performed in R version
240 3.6.0. Reads belonging to mitochondria, chloroplast, and eukaryotes were excluded from
241 further analyses ("phyloseq" package version 1.28.0 [41], "subset_taxa" function). Only
242 reads that are present in at least two samples with a total number of 10 reads were
243 retained for downstream analyses ("genefilter" package version 1.66.0 [42],
244 "filterfun_sample" function, see script '2_Dada2_Pipeline.R' on Zenodo). To complement
245 the taxonomic classification based on the SILVA database, sequence variants were further
246 assigned to major phylotypes of the bee gut microbiota as defined in previous studies
247 based on a BLASTn search against the Nucleotide (nt) database of NCBI
248 (https://www.ncbi.nlm.nih.gov/nucleotide/). To analyze absolute bacterial abundances,

249 we multiplied the proportions of each taxon by the total 16S rRNA gene copy number
250 present in each sample (as measured by qPCR using the universal bacterial primers and
251 normalized by actin copy gene number), and divided this number by the number of 16S
252 rRNA loci for each taxon. The mean 16S rRNA operon copy number for each taxon was
253 obtained from a previous study [11] and completed from rrNDB
254 (https://rrndb.umms.med.umich.edu/).
255

256 **Diversity analysis and statistics**

257 Diversity analyses were performed using "Vegan" package [43]. For both datasets, the
258 qPCR data from the monthly sampling and the 16S rRNA gene amplicon data from the
259 pooled samples, we measured α-diversity using effective number of species [44] that is
260 calculated by taking the exponent of Shannon's diversity index ("diversity" function). For
261 the 16S rRNA gene amplicon sequencing data, permutational multivariate analysis of
262 variance (ADONIS, "adonis" function) based on Bray–Curtis dissimilarities ("vegdist"
263 function) [45] was used to test the effect of bee type on community structure, and
264 "metaMDS" function was used for plotting beta-diversity (see script
265 '3_Plots_Stats_Figures2_S4.R' on Zenodo). To test the dispersion of communities we used
266 the function "betadisper" [46, 47] and compared the distances of individual samples to
267 group centroids in multidimensional space using "permutest". For the qPCR data from the
268 monthly sampling, we performed a principal component analysis (PCA) with the *prcomp*
269 function of the R package "stats" to determine the similarity of the bacterial communities
270 between foragers and winter bees using absolute abundance measures of the seven gut
271 microbiota phylotypes.

All statistical analyses were performed using R (version 3.6.0). We tested the effect of bee type on bacterial loads, diversity indices, and wet gut weight using Student's t-test (in case of two group comparisons) or general linear models (in case of three group comparisons). Since the residuals obtained for certain models showed heteroscedasticity, we used a permutation approach (referred to as Permutation TTEST or ANOVA respectively) to test the significance of the effects as described before [48]. Briefly, we randomized the values of the response variable 10,000 times and computed the F-values/t-values for the tested effect for each randomized dataset. The p-values corresponding to the effects were calculated as the proportion of 10,000 F-values that were equal or higher than the observed one. Pairwise comparisons between different factors were performed by Tukey's HSD using "multcomp" package [49] using *glht* function on the model. P-values were adjusted using the Bonferroni method. Detailed results of statistics are reported in Supplementary tables S2-S5.

286 # Results

287 ***Bacterial loads of core microbiota members differ between foraging and winter season***
288 ***in a honey bee colony monitored over two years.***

289 To characterize the gut microbiota of adult worker bees across seasons, we tracked the
290 total abundance of five core (*Gilliamella*, *Snodgrassella, Bifidobacterium*, *Lactobacillus*
291 Firm4, and *Lactobacillus* Firm5) and two non-core members (*Frischella,* and *Bartonella*;
292 **Table S1**) in adult worker bees from a single hive over two years. Our analyses included 566
293 individual bee samples.

294 The core members *Gilliamella*, *Snodgrassella*, *Lactobacillus* Firm-5 and *Bifidobacterium*
295 were present in all analyzed bees, and the core member *Lactobacillus* Firm-4 was
296 detectable in 98.4% of all bees (**Supplementary Fig. S1A**). Notably, the two designated non-
297 core members *Bartonella and Frischella* were also present at relatively high prevalence
298 with only 5.3% and 26.9% of the samples giving signals below the detection limit,
299 respectively (**Supplementary Figs. S1B** & **C**). Consistent with our previous results, *Frischella*
300 prevalence strongly correlated with the presence of the scab phenotype (**Supplementary**
301 **Fig. S2**), a local melanization response that is induced by *Frischella* upon colonization [35].

302 The absolute abundance of the monitored phylotypes varied little among the bees sampled
303 at the same time point, with the exception of the non-core members *Frischella* and
304 *Bartonella* (**Supplementary Fig. S3**). However, there were clear differences in bacterial
305 abundances between months (Permutation ANOVA P=1e-4) for all monitored community
306 members. In particular, we observed remarkable differences in the bacterial loads between
307 bees sampled during the foraging and the winter season in both years. This became evident
308 from the abundance of individual phylotypes and from the total bacterial load inferred

309 from the summed abundances of all seven phylotypes (**Supplementary Fig. S3, Fig. 1A**).
310 Specifically, we found a 10- to 100-fold increase in the levels of the core members
311 *Lactobacillus* Firm-4, *Lactobacillus* Firm-5, and *Bifidobacterium*, as well as the non-core
312 member *Bartonella* when comparing across all winter bees relative to foragers (**Fig. 1C**,
313 Permutation T-Test P=1e-4). We also observed a small increase of *Snodgrassella* levels in
314 winter bees (**Fig. 1C**, Permutation T-Test P=6e-4), but no difference in the levels of
315 *Gilliamella* (**Fig. 1C**, Permutation T-Test P=0.7). *Frischella* was the only member of the
316 community that displayed the opposite trend, i.e. lower abundance in winter bees (**Fig. 1C**,
317 Permutation T-Test P=1e-4). The overall bacterial load was about 10x larger in winter bees
318 than in foragers based on both the summed abundances of all seven phylotypes (**Fig. 1C**,
319 Permutation T-Test P=1e-4) as well as the number of total 16S rRNA gene copies, which
320 was determined with universal 16S rRNA gene qPCR primers for a subset of the samples
321 (**Fig. 1D**, Permutation T-Test, P=1e-4).

322 Considering that the monitored phylotypes typically comprise the majority of the bacteria
323 present in the honey bee gut, we neglected the possible presence of additional, non-
324 targeted members and analyzed the relative composition of the community based on our
325 data. In both years, the communities of winter bees were largely dominated by the
326 phylotypes *Lactobacillus* Firm-5 and *Bartonella.* In contrast, forager bees seem to have
327 more even community compositions (**Fig. 1B**). The dominance of *Lactobacillus* Firm-5 and
328 *Bartonella* in winter bees was reflected by a reduction in α-diversity in winter bees
329 compared to foragers, as determined by the effective number of species (**Fig. 1E**,
330 Permutation T-Test, P=1e-4). Moreover, PCA revealed a clear separation between foragers
331 and winter bees (**Fig. 1F,** MANOVA Wilks =0.6 $F_{(7, 392)}$=39.4, P<2.2e-4) along the principal

332 component 1 (PC1). This separation was mainly driven by *Lactobacillus* Firm-4,
333 *Lactobacillus* Firm-5, *Bartonella* and *Bifidobacterium*, the four phylotypes with the largest
334 differences in abundance between the two types of bees (**Fig. 1C**).

335 Taken together, these results suggest that the gut microbiota of winter bees and foragers
336 markedly differs from each other in the monitored hive, both in terms of the total bacterial
337 abundance and in the levels of individual microbiota members.

338

339 ***Consistent difference in bacterial loads and community composition between foragers,***
340 ***nurses, and winter bees across colonies***

341 The observed differences in bacterial loads between foragers and winter bees in the
342 monitored hive prompted us to check for similar patterns across 14 different hives in a
343 subsequent year. In addition to foragers and winter bees, we also analyzed nurses, to help
344 understand whether microbiota differences between foragers and winter bees are linked
345 to seasonal changes or to behavioral or dietary differences. Moreover, we combined our
346 qPCR approach with 16S rRNA gene amplicon sequencing to expand our analysis to the
347 complete community of the honey bee gut microbiota.

348 Performing universal 16S rRNA qPCR, we found that total bacterial loads differed between
349 the three bee types across the sampled hives. Both winter bees and nurses had higher
350 bacterial loads than foragers (**Fig. 2A,** Permutation ANOVA P=1e-4, followed by Tukey HSD
351 test, P=5.1e-9 and 1.66e-6 respectively) confirming our previous results from the single
352 hive. Winter bees also showed a trend towards higher bacterial loads than nurses, but this
353 difference was not statistically significant (**Fig. 2A,** Permutation ANOVA followed by Tukey
354 HSD test, P=0.224).

355 16S rRNA amplicon sequencing yielded 70 amplicon sequence variants across the 42
356 samples, with a minimum of 26,993 reads per sample after quality and abundance filtering
357 (See methods and Supplementary Table S6 for details). These sequence variants were
358 further clustered by assigning them to the major phylotypes of the bee gut microbiota as
359 defined in previous studies, resulting in 28 operational taxonomic units (OTUs). To account
360 for the differences in total bacterial load, we calculated absolute abundance of each OTU
361 based on its proportion in the community, the number of rRNA loci in the genome, and the
362 total bacterial load per sample.
363 Diversity analyses of the amplicon sequencing data revealed marked differences in
364 community composition between the three bee types. We found a significant reduction in
365 α-diversity in winter bees compared to foragers and nurses, as determined by effective
366 number of species (ANOVA $F(2,39) = 35.9$, $p = 1.60e-9$, Tukey HSD test $P<0.005$ for all
367 comparisons, **Fig. 2B**). This indicates that gut communities in these bees are less rich and
368 less even. Moreover, nonmetric multidimensional scaling (NMDS) based on Bray-Curtis
369 dissimilarities revealed a significant separation of samples according to bee type indicating
370 that the communities of nurses, foragers, and winter bees are different from each other
371 (**Fig. 2C**). Consistently, ADONIS on Bray-Curtis dissimilarities showed a statistically
372 significant difference according to bee type ($P=0.001$). Differences in community structure
373 were also evident from the relative proportion of different taxa across the samples, with a
374 clear reduction of the relative abundance of *Snodgrassella* and *Frischella* and an increase
375 of *Bartonella* and *Commensalibacter* in winter bees relative to foragers and nurses (**Figure**
376 **2D**). However, we did not detect any difference in community dispersal between nurses,
377 foragers, and winter bees. Distances to group centroids based on Bray-Curtis dissimilarities
378 were not different between bee types (Permutest $F_{(2,39)}=0.41$, $P=0.68$ (**Supplementary Fig.**

379 **4A**). Therefore, while the gut communities of the three bee types differed from each other,
380 they seemed to be similarly variable among each other.
381 We next assessed differences in the absolute abundance of individual community members
382 to reveal the directionality of community changes. We first looked at the seven phylotypes
383 that were monitored by qPCR over two years (**Fig. 2E**). Consistent with our previous results
384 (**Fig. 1C**), *Bifidobacterium*, *Lactobacillus* Firm4, *Lactobacillus* Firm5, and *Bartonella* had
385 increased levels (Permutation ANOVA on three groups P=1e-4, followed by Tukey, P<2e-4),
386 while *Frischella* had decreased levels in winter bees compared to foragers (**Fig. 2E,**
387 Permutation ANOVA p=2e-04 followed by Tukey HSD test P=2.79e-3). The only two
388 phylotypes showing abundance patterns inconsistent with the results from the two year
389 sampling were *Snodgrassella* and *Gilliamella*. *Snodgrassella* did not experience any
390 differences in absolute abundance (**Fig. 2E,** Permutation ANOVA P=1.87e-1), illustrating
391 that a proportional change in the community, as found when looking at the relative
392 community composition (**Fig. 2D),** does not necessarily imply a change in abundance. When
393 comparing nurses and winter bees, only *Bartonella* and *Frischella* showed differences in
394 their absolute abundance. While *Bartonella* had markedly increased levels, *Frischella*
395 abundance went down in winter bees as compared to nurses (**Figure 2E**). We confirmed
396 these changes by carrying out qPCR on the same samples with the phylotype-specific
397 primers used for the monthly sampling as presented above (**Supplementary Fig. S5**). Except
398 for *Lactobacillus* Firm5, which showed a significant difference between nurses and winter
399 bees in the qPCR but not in the amplicon sequencing data, the results of the two
400 approaches were surprisingly congruent corroborating our conclusion that the microbiota
401 of nurses, foragers, and winter bees markedly differs in the composition of these seven
402 major community members.

403 We also looked at abundance changes of other community members than those assessed
404 by qPCR the two-year sampling from a single hive (**Fig. 2F** and **Supplementary Fig. S4B)**. As
405 expected, other bacteria made up a relatively small fraction of the overall community (4-
406 25%) with *Commensalibacter* being the most prevalent (100% of the pooled gut samples)
407 and abundant one (2-14% of the community). *Commensalibacter* was also the only
408 additional community member that showed a significant increase in winter bees compared
409 to foragers and nurses (Permutation ANOVA P=1e-04, followed by Tukey P=7.68e-08). In
410 contrast, all other additional community members were only detected in a subset of the
411 samples, and at relatively low abundance, suggesting that they represent opportunistic or
412 transient colonizers. Moreover, many of these community members showed a trend
413 towards lower prevalence and/or abundance in winter bees than in foragers and nurses
414 (**Fig. 2F**). For example, while *Apibacter* was detected in all forager and nurse samples, it
415 was only detected in five out of the 14 sampled hives in winter bees and at lower levels
416 than in foragers and nurses (Permutation ANOVA P=1e-04, followed by Tukey HSD test P<2e-
417 8). Likewise, while *Lacotbacillus kunkeii* was detected in nurses and foragers from some
418 hives, it was not detected in any hive during winter. These differences are likely responsible
419 for the reduction in α-diversity in winter bees as compared to foragers and nurses.
420 Interestingly, several *Enterobacteriaceae* (*Klebsiella*, *Pantoea*, *Serratia*, or *Tatumella*) were
421 prevalent among nurse samples but absent from nearly all foragers and winter bee samples
422 (**Fig. 2F** and **Supplementary Fig. S4B**), suggesting a specific association of these bacteria
423 with nurse bees.
424 Taken together, these results show that winter bees and nurses across hives have increased
425 bacterial loads compared to foragers, and that winter bees have particularly high levels of
426 *Bartonella* and *Commensalibacter*, but low levels of opportunistic colonizers.

427

428 ***Pollen diet increases gut community size in gnotobiotic bees***

429 One of the drivers of the observed differences in bacterial load and community
430 composition between winter bees, foragers, and nurses could be diet. Dietary differences
431 between the three types of bees were evident from visual inspection of the dissected guts
432 (**Fig. 3A-C**). The rectums of winter bees and nurses appeared yellow indicating the presence
433 of pollen, while those of foragers were translucent. Moreover, the wet weight of the guts
434 was significantly different between the three types of bees (ANOVA $F_{(2,68)}$ = 24.13, P=1.21e-
435 8), with foragers having on average two times lighter guts than nurses (Tukey HSD test
436 P=1.14e-6) and winter bees (Tukey HSD test P=6.81e-8) (**Fig. 3D**). When plotting normalized
437 16S rRNA gene copy numbers as a function of gut weight, we found that gut weight
438 positively correlated with total microbiota abundances across the three bee types (**Fig. 3E**).

439 In order to demonstrate that pollen diet is directly associated with increased bacterial loads
440 in honey bees, we experimentally colonized newly emerged bees with a community of 11
441 bacterial strains representing the seven major bacterial phylotypes of the bee gut
442 microbiota [6]. The colonized bees were kept in the laboratory for ten days and fed *ad*
443 *libitum* either sterile sugar water and pollen (SW+P treatment), or sugar water only (SW
444 treatment). We found a significant difference in gut weight between the two treatments
445 (**Fig. 3F**, Welch's T-Test *t*=9.433, P=1.452e-11). While the gut weights of the bees of the SW
446 treatment were comparable to those of forager bees, the gut weights of the bees of the
447 SW+P treatment were markedly higher, exceeding even those of winter bees (**Fig. 3D** &
448 **3F**). We observed a positive correlation between gut weight and microbiota abundance for
449 both the experimentally colonized bees in the laboratory (**Fig. 3G**) and the conventional

450 worker bees sampled from the hive (**Fig. 3E**). Moreover, differences in bacterial loads of
451 individual community members between the two experimental treatments mirrored, to a
452 large extent, the differences found between nurses, foragers, and winter bees: most
453 phylotypes were more abundant in bees fed pollen as compared to bees fed sugar water
454 only (**Fig. 3H**, see **Supplementary Table S4** for statistics). Two exceptions were *Bartonella*
455 and *Frischella.* While *Bartonella* had similar levels between the two experimental
456 treatments **(Fig. 3H)**, its abundance was higher in winter bees and nurses as compared to
457 foragers **(Fig. 2A)**. Notably, *Bartonella* was able to colonize only 75% of all bees when pollen
458 was absent. The dependence on pollen for gut colonization was even more pronounced for
459 *Frischella.* Less than 50% of the experimentally colonized bees of the SW treatment had
460 detectable levels of *Frischella,* and the loads in bees that were colonized were relatively
461 low. In contrast, bees of the SW+P treatment were all colonized and had relatively high and
462 consistent loads of *Frischella* **(Fig. 3H)**.

463 Taken together, these results show that a pollen diet leads to an increase in gut weight and
464 overall bacterial load providing a plausible explanation for some of the differences in the
465 loads observed between foragers, nurses, and winter bees.

466 ## Discussion

467 Here, we used a combined approach of qPCR and 16S rRNA gene amplicon sequencing to
468 show that the gut microbiota of adult worker bees markedly differs between nurses,
469 foragers, and winter bees. Nurses and winter bees harbored a larger number of bacteria in
470 the gut than foragers, with most of the dominant community members (except for
471 *Frischella* and *Snodgrassella*) contributing to the increased bacterial loads. Winter bees had
472 the lowest α−diversity of the three bee types, which is explained by the presence of fewer
473 opportunistic colonizers such as *Apibacter, Bombella, or L. kunkeii*. Moreover, a
474 characteristic shift towards high levels of *Bartonella* and *Commensalibacter* was observed
475 in winter bees. These differences in community structure were found across fourteen
476 different colonies and in three different years, suggesting that the "reconfiguration" of the
477 microbiota in winter bees is a conserved feature in colonies in Western Switzerland.

478 However, regional differences in floral diversity [24] or climate may influence this pattern.
479 Therefore, additional surveys of winter bees in other geographic regions are needed to test
480 for the conservation of this pattern. A recent study carried out in Germany on the effects
481 of winter supplementation feeds found that the relative abundance of certain community
482 members (e.g. *Lactobacillus* Firm-5 and *Bartonella*) increases in winter bees compared to
483 foragers [19], resulting in marked community shifts. The results of this study were also
484 consistent with our findings in that the levels of *Frischella* were significantly lower in winter
485 bees as compared to forager bees. However, this previous study was based on relative
486 abundance data only, i.e. 16S rRNA gene amplicon sequencing.

487 In contrast to 16S rRNA gene amplicon sequencing, qPCR provides information about the
488 absolute abundance of bacteria and allows determining whether individual community

489 members increase, decrease, or remain the same in terms of bacterial cell number across
490 samples. For example, in our study, the relative abundance of *Snodgrassella* went down in
491 winter bees as compared to foragers and nurses (**Fig. 2D**). However, this effect was not due
492 to a decrease of the total number of *Snodgrassella*, but rather an increase of other
493 community members as identified by qPCR. In fact, the total abundance of *Snodgrassella*
494 remained the same in foragers, nurses, and winter bees **(Fig. 2E)**. Such quantitative
495 microbiome profiling approaches can reveal important associations between gut bacteria
496 and the host, as previously demonstrated for the human microbiota [32] or the microbiota
497 of caterpillars [50]. We argue that absolute abundances should be routinely assessed when
498 analyzing microbial communities, as changes in absolute abundance – but not necessarily
499 relative abundance – may change the impact of a given bacterium on its environment.
500 Notably, qPCR is a targeted approach, i.e. one can only quantify specific community
501 members for which corresponding primers have been designed, or assess the total amount
502 of bacteria using universal primers. Therefore, a combined approach of qPCR (or any other
503 quantitative method, e.g. flow cytometry) and relative composition analysis (such 16S rRNA
504 gene sequencing or shotgun metagenomics) is preferred, as it provides information about
505 the quantity and directionality of changes in a microbial community.

506

507 What drives the observed changes in bacterial loads and community composition in winter
508 bees, nurses, and foragers? A possible explanation could be dietary differences between
509 the analyzed bee types. Foragers mainly feed on nectar and honey, while nurses and winter
510 bees also consume pollen [51]. These dietary differences were also evident in our study, as
511 we found consistent changes in appearance and weight of the dissected guts of foragers,

512 nurses, and winter bees (**Fig. 3A-C**). Strikingly, our experimental colonization of microbiota-
513 depleted bees with a defined bacterial community showed that pollen in the diet
514 substantially increases gut weight and bacterial loads to levels comparable to those in
515 winter bees. In contrast, bacterial levels in bees fed on sugar water only were more similar
516 to those of foragers (**Fig. 3F-H**). Therefore, we conclude that diet is an important factor that
517 can explain many of the differences observed between worker bee types. Seasonal changes
518 in gut microbiota composition in wild rodent populations [52] and humans [53, 54] have
519 also been found to coincide with dietary shifts, which is in agreement with the general
520 notion that dietary preferences is the main driver of community differences across a wide
521 range of animals [55–57].

522 In the case of honey bees, the larger amount of food in the gut is likely to increase the
523 carrying capacity for the gut microbiota. In addition, pollen is a more nutrient-rich diet than
524 nectar, honey, or sucrose offering a larger diversity of different metabolic niches for gut
525 bacteria. Both factors are likely to contribute to the increased bacterial loads in bees fed
526 on pollen as compared to those fed on sugar water only. Recent reports in mice and fly
527 models have shown that an increase in nutritional richness, especially protein quantity, is
528 associated with an increase in overall abundance of the microbiota but a decrease in α-
529 diversity [58, 59]. This is supported by our findings, because we observed an increase in
530 bacterial loads and a decrease in effective number of species in nurses and winter bees
531 that feed on pollen (**Fig. 2A and 2B**). Consistently, most of the phylotypes that increased in
532 total abundance (*Lactobacillus* Firm5, *Lactobacillus* Firm4, *Bifidobacterium*, *Bartonella*) are
533 located in the rectum, which is the last part of the hindgut where pollen accumulates until
534 bees defecate. In line with this, a previous report showed that the abundances of total

535 bacteria, as well as certain individual phylotypes (*Lactobacillus* Firm-5, *Bifidobacterium*)
536 increase in rectum upon pollen consumption [60]. However, this increase was dependent
537 on the age, and it was not significant when autoclaved pollen was used instead of stored
538 pollen [60]. In contrast to our study, the experimental bees were not inoculated by a
539 defined bacterial community [60], which may greatly impact community growth and
540 dynamics. Overall, despite certain experimental differences, our results seem to be
541 consistent with the data that have been published before.

542

543 However, not all changes observed in winter bees could be recapitulated in our
544 colonization experiment. For example, the differences observed *in Bartonella* levels
545 between foragers, nurses, and winter bees (**Fig. 2E**) were not observed in the experimental
546 bees that were fed with or without pollen (**Fig. 3H**). Another example is *Frischella*. While
547 this bacterium was less abundant in winter bees than in foragers and nurses, the
548 colonization success of *Frischella* was largely dependent on the presence of pollen in the
549 experimental bees. This suggests that other factors may contribute to community
550 differences found in winter bees as compared to foragers or nurses.

551 Winter bees have an extended lifespan with an average life expectancy of ~6 months as
552 compared to ~4 weeks in the case of summer bees (i.e. nurses and foragers)[61]. In
553 contrast, the bees of the colonization experiment were age-matched and sampled ten days
554 after emergence. In the fruit fly, *Drosophila melanogaster*, the physicochemical state of the
555 gut changes with age, resulting in shifts in the composition of microbial communities,
556 mainly characterized by the invasion of certain gut bacterial taxa [62–64]. Therefore, the
557 observed expansion of *Bartonella* and *Commensalibacter* in the gut of winter bees may be

558 related to age. However, despite their old age, winter bees do not display signs of
559 senescence [65, 66] and these differences are likely not due to functional decay in intestinal
560 tissue as reported in flies [64, 67].

561 Winter bees feed on pollen that has been stored in the hive for several weeks to months.
562 It has previously been shown that the consumption of an aged pollen-diet affects the gut
563 microbiota composition of nurses [12]. It will be important to characterize metabolic
564 differences between the pollen diet of winter and summer bees and to associate such
565 differences with the metabolic capabilities of the different bee microbiota members. For
566 example, *Commensalibacter* and *Bartonella*, the two community members that increased
567 the most in winter bees, carry out aerobic respiration, while most of the other microbiota
568 members are saccharolytic fermenters [22, 68]. Notably, winter bees retain their feces in
569 the gut for extended periods of time, which is likely to affect the physico-chemical
570 conditions and the availability of nutrients in the gut. Moreover, in the absence of
571 defecation, bacteria may accumulate over time in the gut of winter bees, while in nurses
572 or foragers more frequent defecation may result in a faster turnover of the microbiota.
573 Together with differences in the body temperature of bees - in winter it is at ~21°C and in
574 summer at ~35°C [69] - this may influence bacterial growth rates. Indeed, in a recent
575 metagenomic study, it was shown that gut bacteria have lower average population
576 replication in old winter bees as compared to young nurse bees, which is indicative of
577 decreased replication rates [18]. Another important point to consider, when carrying our
578 non-culture based community analysis is that these methods usually cannot discriminate
579 between dead and live bacterial cells. Therefore, some of the observed differences could
580 also be attributed to the accumulation of environmental DNA from lysed bacterial cells.

581 Finally, winter bees show reduced expression of immune genes [70–73], and have an
582 altered protein metabolism [74] as compared to nurses and foragers, another factor which
583 may influence the total bacterial loads and the community composition in the gut.

584 In the case of *Frischella,* it is tempting to speculate that the decrease in colonization levels
585 in old winter bees may be a consequence of the specific immune response elicited by the
586 host towards this bacterium [10], eliminating it from the gut as the bee ages. In the case of
587 *Snodgrassella*, it is interesting to note that the levels of *Snodgrassella* barely changed
588 across worker bee type or the two diet treatments in the experiment. This suggests that
589 the colonization of *Snodgrassella* is not modulated by the dietary state, the
590 physicochemical conditions in the gut, or the abundance of other community members. A
591 possible explanation could be that the niche of *Snodgrassella* is dependent on the host
592 rather than the diet, because it selectively colonizes the epithelial lining of the ileum, which
593 presents a physically restricted niche [8, 75, 76].

594

595 Beside the increase of *Commensalibacter* and *Bartonella*, another intriguing characteristic
596 of the winter bee gut microbiota was the disappearance of minor, non-core community
597 members in the bee gut microbiota. We can exclude that these differences in community
598 composition are due to a community sampling bias, because nurses had similar bacterial
599 loads as winter bees, but showed the opposite trend in respect to the presence of minor
600 community members. We hypothesize that these minor community members are transient
601 colonizers that cannot persist in the bee gut environment over longer periods of time and
602 hence disappear in old winter bees. As some of these bacteria, e.g. *Serratia or Klebsiella,*
603 present potential pathogens of bees, there may be also mechanisms in place that increase

604 colonization resistance against such opportunistic colonizers in winter bees. Moreover,
605 during the foraging season adult worker bees are more likely to pick up environmental
606 bacteria from e.g. flowers, facilitating their dissemination in the hive environment during
607 the summer but not in winter.

608

609 Most of the recent colony losses have occurred during the winter months [33, 34].
610 Consequently, winter bees are highly critical for colony survival and a better understanding
611 of the factors influencing their health status - including the gut microbiota - is needed. In
612 summary, our analysis revealed that the gut microbiota of winter bees undergoes
613 characteristic shifts. These changes may have important consequences for the host.
614 Therefore, future studies should specifically focus on the functional role of the gut
615 microbiota in winter bees, and colony health.

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Competing Interests

Authors declare to have no conflicts of interest.

Data accessibility

All scripts and datasets will be deposited to Zenodo upon acceptance. For the revision they can be found on: https://drive.switch.ch/index.php/s/zHsqyMOztvAr8Vu.

Sequencing data is deposited on NCBI under BioProject ID PRJNA578869.

Supplementary Material

Supplementary Figures: Contains Figures S1-S3

Supplementary Table S1: Primers used in this study and stndard curve characteristics.

Supplementary Table S2: Details of statistics used in Fig 1.

Supplementary Table S3: Details of statistics used in Fig 2.

636 **Supplementary Table S4:** Details of statistics used in Fig 3.

637 **Supplementary Table S5**: Details of statistics used in Supplementary Fig S5.

638 **Supplementary Table S6:** Data related to the number of reads obtained from 16S rRNA

639 gene sequencing and after each step of filtration.

640 **Supplementary Table S7:** Number of rRNA gene loci for each taxonomic group

641

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Figures

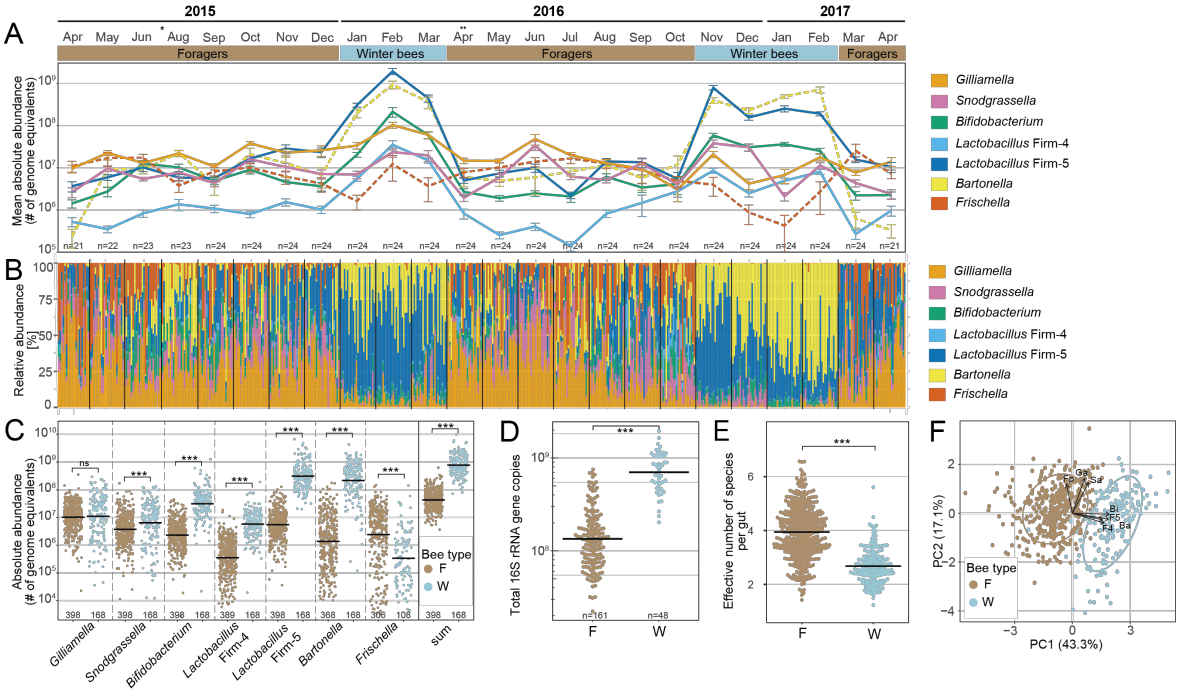

Fig. 1. Gut bacterial communities differ between foraging and winter season in a single colony monitored over two years. (A) Monthly changes in the absolute abundance assessed by qPCR, as determined by number of genome equivalents per sample, of seven phylotypes monitored over a period of two years, depicted as mean values (±SE) of the analyzed bees. The number of bees per month is indicated at the bottom of the plot. * indicates missing data for July 2015 due to DNA extraction failure. ** indicates that the queen of the colony was replaced in the corresponding month. **(B)** Relative community composition of the gut microbiota of bees sampled in each month as based on the seven monitored phylotypes. **(C)** Absolute bacterial abundance of each phylotype per gut in foragers (F) and winter bees (W), as determined by the number of genome equivalents. The sum of the abundances of the seven monitored phylotypes is also plotted. Mean values are shown as black horizontal lines. Only bees with detectable levels were plotted (the number of bees is given at the bottom of the plot; for prevalence see **Supplementary Fig.**

843 **S1**). **(D)** Copy number of the 16S rRNA gene in gut samples of a subset of the analyzed
844 months (Apr 2015, Aug 2015, Oct 2015, Jan 2016, Apr 2016, Jul 2016, Oct 2016, Jan 2017,
845 Apr 2017). **(E)** Effective number of species calculated from cell numbers of different
846 bacterial phylotypes in foragers (F) and winter bees (W). **(F)** Projection of the abundances
847 of monitored phylotypes into first and second principal components in all analyzed bees,
848 together with correlation vectors representing variables driving the separation on both
849 axes. Permutation T-Test was used for pairwise comparisons. ns, non-significant; ***, P <
850 0.001.

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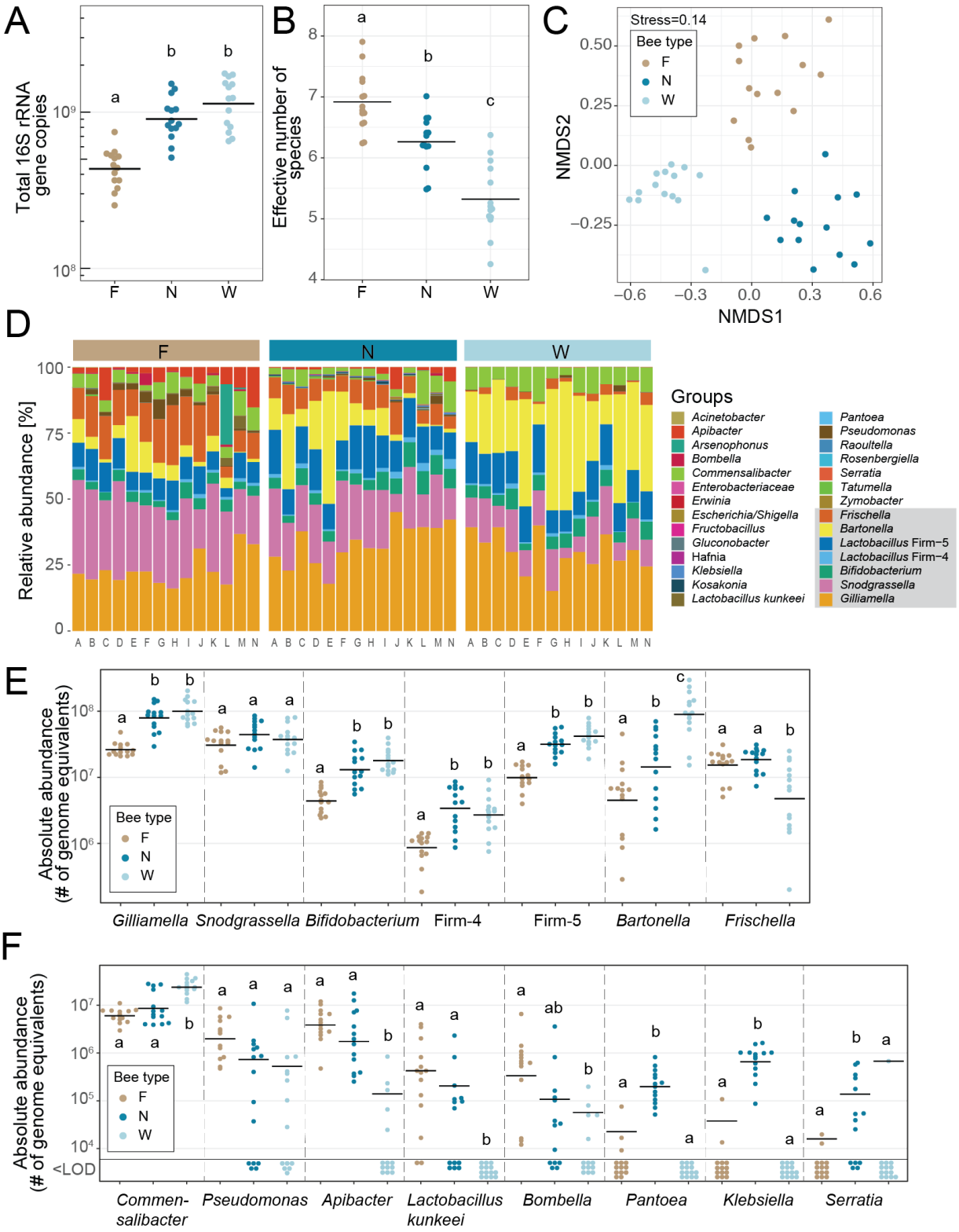

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854 **Figure 2. Bacterial load and community composition differ between foragers, nurses, and**

855 **winter bees across 14 colonies.** (**A**) Average 16S rRNA gene copy number per gut in

856 foragers, nurses, and winter bees as determined from the pooled gut samples from the 14
857 different colonies. **(B)** Differences in α-diversity, i.e. effective number of species, in the gut
858 microbiota of foragers, nurses, and winter bees based on 16S rRNA gene amplicon
859 sequencing. **(C)** NMDS based on Bray-Curtis dissimilarities on the gut communities of
860 foragers, nurses, and winter bees based on 16S rRNA gene amplicon sequencing. **(D)**
861 Relative community composition of the gut microbiota based on 16S rRNA gene amplicon
862 sequencing. The seven phylotypes monitored by qPCR (see **Fig. 1** and **Supplementary Fig.**
863 **S4**) which make up the vast majority of the community are highlighted by a grey box in the
864 legend. Capital letters below the stacked bars indicate the hive of origin. **(E)** Absolute
865 abundance of each of the seven major phylotype in foragers (F), nurses (N), and winter
866 bees (W) across hives, as determined based on the number of genome equivalents per gut
867 calculated by multiplying the relative abundance of each phylotype by the total 16S rRNA
868 gene copy number. **(F)** Absolute abundance of a subset of the minor community members
869 in foragers (F), nurses (N), and winter bees (W) across hives, as determined based on the
870 number of genome equivalents per gut calculated by multiplying the relative abundance of
871 each phylotype by the total 16S rRNA gene copy number. <LOD, below limit of detection of
872 the 16S rRNA amplicon sequencing, i.e. no reads were obtained for that particular taxa in
873 the respective sample. Absolute abundance of the remaining phylotypes are depicted in
874 **Supplementary Fig. S4B**. In panels A, B, E and F, levels (bee types) not connected by the
875 same letter are significantly different as based on ANOVA followed by Tukey's HSD test (see
876 **Supplementary Table S3**).
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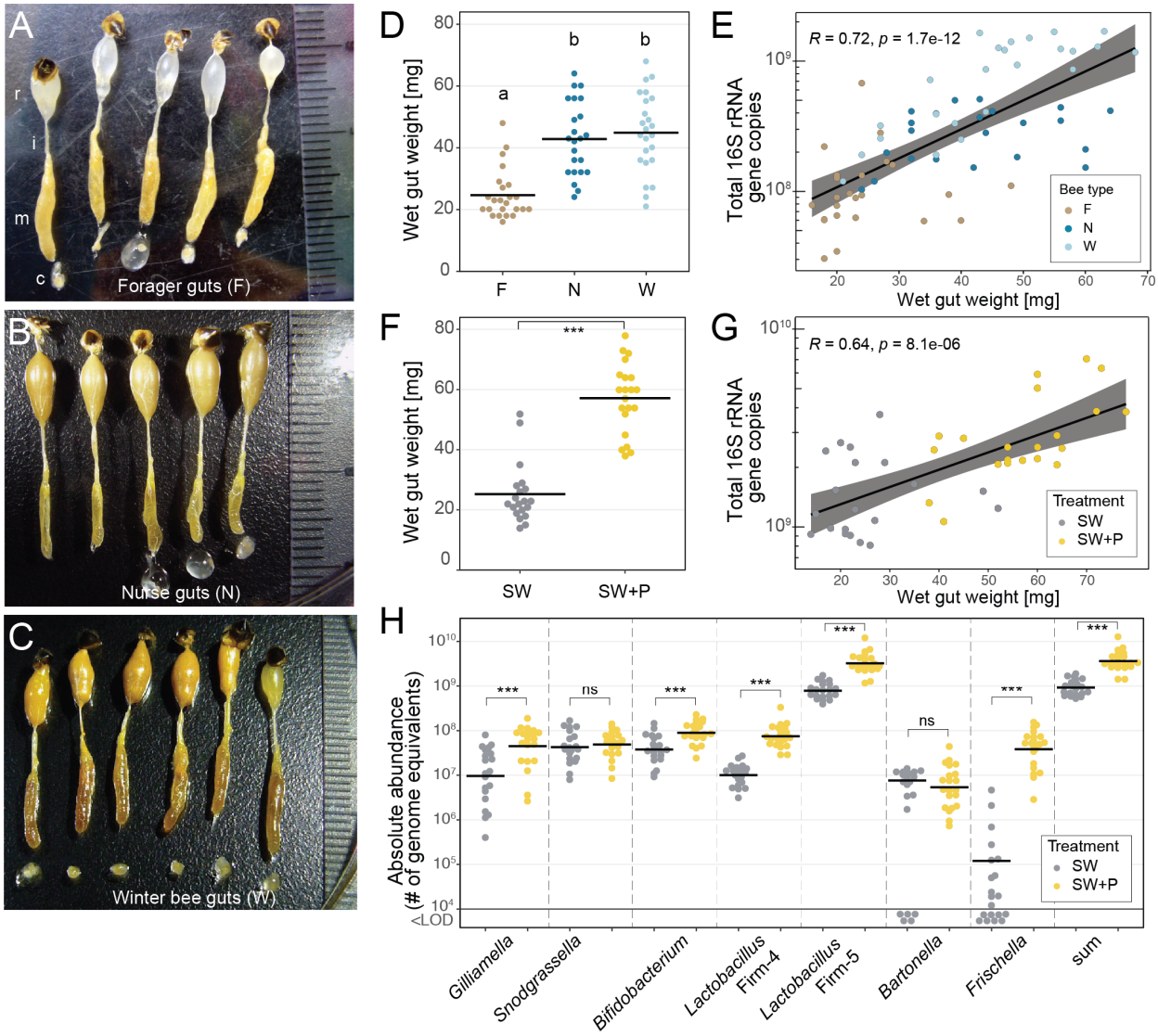

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879 **Figure 3. Diet is a major factor shaping the gut microbiota of honey bees**. **(A-C)** Dissected
880 guts of foragers **(A)**, nurses **(B)**, and winter bees **(C)** consisting of the crop (c) (missing in
881 some samples), the midgut (m), the ileum (i), and the rectum (r) with attached stinger and
882 last abdominal tergite. **(D)** Wet gut weight of individual foragers (F), nurses (N), and winter
883 bees (W). Different letters indicate groups that are significantly different from each other
884 based on ANOVA followed by Tukey's HSD test (See Supplementary Table S4 for details).
885 **(E)** Spearman correlation between gut weight and bacterial loads (assessed with universal
886 bacterial 16S rRNA primers) across all bee types. The grey area indicates the 95%

887 confidence interval. **(F)** Wet gut weight of experimentally colonized bees that were fed
888 either sugar water (SW) or sugar water and pollen (SW+P). **(G)** Spearman correlation
889 between gut weight and bacterial loads (assessed with universal bacterial 16S rRNA gene
890 primers) across the two treatment groups of colonized bees. **(H)** Total abundances of the
891 seven monitored phylotypes in the two treatment groups of colonized bees, as determined
892 by genome equivalents per gut using phylotype-specific qPCR primers. The sum of the
893 abundances of the seven monitored phylotypes is also depicted. Bees with bacterial loads
894 below the limit of detection (<LOD) of the qPCR method are shown below the cut of the
895 axis at 10^4. Two-group comparisons were done by Permutation T-Test. ns, non-significant;
896 ***, $P < 0.001$.