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Acromyrmex Leaf-Cutting Ants Have Simple Gut Microbiota with Nitrogen-Fixing Potential

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Ants and termites have independently evolved obligate fungus-farming mutualisms, but their gardening procedures are fundamentally different, as the termites predigest their plant substrate whereas the ants deposit it directly on the fungus garden. Fungus-growing termites retain diverse gut microbiota, but bacterial gut communities in fungus-growing leaf-cutting ants have not been investigated, so it is unknown whether and how they are specialized on an exclusively fungal diet. Here we characterized the gut bacterial community of Panamanian Acromyrmex species, which are dominated by up to four bacterial taxa: Wolbachia, Rhizobiales, and two Entomoplasmatales taxa. We show that the Entomoplasmatales can be both intracellular and extracellular across different gut tissues, Wolbachia is mainly but not exclusively intracellular, and the Rhizobiales species is strictly extracellular and confined to the gut lumen, where it forms biofilms along the hindgut cuticle supported by an adhesive matrix of polysaccharides. Tetracycline diets eliminated the Entomoplasmatales symbionts but hardly affected Wolbachia and only moderately reduced the Rhizobiales, suggesting that the latter are protected by the biofilm matrix. We show that the Rhizobiales symbiont produces bacterial NifH proteins that have been associated with the fixation of nitrogen, suggesting that these compartmentalized hindgut symbionts alleviate nutritional constraints emanating from an exclusive fungus garden diet reared on a substrate of leaves.

Communities of gut bacteria play key roles in nutrient acquisition, vitamin supplementation, and disease resistance. Their diversity often covaries with host diet, both across lineages with different ecological niches and between conspecific populations in different habitats or geographic regions (1–3). Elucidating the significance of single bacterial taxa in omnivores such as humans is dauntingly complex (3, 4), but insects with specialized diets have regularly offered gut microbiota study systems that are dominated by a limited number of species (5–7). Several insect-microbial symbioses are evolutionarily ancient so that extensive functional complementarity between hosts and symbionts could evolve, as in aphids that rely on Buchnera for the production of essential amino acids (8, 9). Other mutualisms have more recent origins, such as bedbugs that rely on Wolbachia for vitamin B production (10, 11) or wood-eating beetles that carry nitrogen-fixing gut bacteria in order to subsist on protein-poor diets (12).

The eusocial insects offer abundant niche space for bacterial symbionts (5, 13–16) because they have peculiar diets and practice liquid food transfer (trophallaxis), which facilitates symbiont transmission within colonies. Higher termites replaced their ancestral protist gut communities by bacterial microbiota (17), while other early studies identified Blochmannia gut symbionts in carpenter ants (18, 19) and a community of gut-pouch symbionts in Tetraponera ants (20, 21). More recently, comparative studies have started to survey the total complexity of the gut microbiota of ants to reveal overall nutritional adaptations associated with predatory and herbivorous feeding habits (6, 14, 19), and comparable studies in termites documented the importance of gut microbes for the conversion of dead plant material into nutrients that can be absorbed (22–24). A similar approach has been successful in honeybees and bumblebees and revealed microorganisms dominated by rather few bacterial species, consistent with bees having more predictable pollen and nectar diets than ants and termites, which have generalist feeding ecologies (5, 25–28).
ria in the fungus gardens of Atta leafcutter ants, but without investigat- ing their gut bacterial communities (32).

We tested these expectations in Acromyrmex leaf-cutting ants. Using 16S-454 and 16S-Miseq sequencing, we determined the major bacterial operational taxonomic units (OTUs) (representing a cluster of bacterial 16S rRNA gene sequences of ≥97% similarity, typically interpreted as representing a bacterial species) associated with the digestive system of these ants. We then used a combination of fluorescence microscopy and electron microscopy to investigate the localization of the major bacterial OTUs across gut tissues, the lumen, and the surrounding fat bodies to make inferences about their putative adaptive roles. We subsequently kept ants on sterile sugar solutions with and without the antibiotic tetracycline and monitored changes in the prevalence of dominant gut bacteria. Finally, we focused on an extracellular Rhizobiales species that was restricted to the hindgut lumen and discovered that these bacteria are embedded in a biofilm-like matrix of polysaccharides and produce NiFH proteins, which are known to mediate the reduction of free nitrogen to the bioavailable NH3.

MATERIALS AND METHODS

Ant collection and maintenance, sterile diets, DNA extractions, 454 pyrosequencing, and Illumina Miseq sequencing. Ant colonies were collected in Gamboa, Republic of Panama. We used 11 Acromyrmex lab colonies for 454 sequencing (eight A. echinatior, two A. octospinosus, and one A. volucanus) and 13 partly overlapping Acromyrmex colonies for Miseq sequencing: six new colonies (sampled both in the field and after being transferred to the lab) and seven lab colonies, more than 2 years after collection (six of them had already been sequenced with 454). This double procedure was chosen because we were seeking to verify that bacterial gut communities could be reproduced across sequencing platforms and to elucidate their susceptibility to changes in rearing conditions (field versus 3 months in the lab versus >2 years in the lab). An overview of the sampling and experimental procedures is provided in Table S1 in the supplemental material. DNA for both 454 and Miseq sequencing was extracted with the same methods (see details below), and all lab colonies were maintained in rearing rooms at ca. 25°C and 70% relative humidity (RH) under a 12 h photoperiod.

The ant workers that were reared on artificial diets were collected from lab colony Ae150 and were picked from the fungus gardens with forceps and placed in groups of 15 in sterile petri dishes (90 by 15 mm), which had an inverted screw cap in the middle that served as liquid food vial. Control samples per colony.

To obtain an estimate of the gut bacterial diversity of the ants on leaf-cutting ants, but without investigating their gut bacterial communities (32). We retrieved OTU sequences from both data sets using python scripts and compared them to each other and to specific probes using the BLAST algorithm with a 1e-50 value cutoff and 50% identity (39). In order to design primers and probes from the retrieved OTUs, sequences were aligned using the Map to Reference algorithm incorporated in Geneious software v4.8.5 and v7.0.6 (40).

For the ant survival analyses, we used Cox proportional hazards models (with censoring), carried out with the coxph function of the Survival package in R (version 3.1.1), following assessment of proportional hazards using cox.zph (41, 42). The cofactors included the substrate, the presence of yeast, or the presence of tetracycline. Data were plotted using the survival analysis function in JMP 10.0. Effects of the different components of the diets on the presence/absence of certain bacterial groups in the guts and the fecal droplets were compared using pairwise multivariate
correlations across all samples. We constructed 2-by-2 contingency tables examining each of the bacterial species and diet components and evaluated their distribution frequencies using Pearson χ² tests in JMP 10.0. To validate bacterial presence in fecal droplets, we collected samples from the ants in experimental petri dishes at days 7, 14, 21, 26, and 28 and used a Cox proportional hazard model (with censoring) to analyze the data under the assumption that the number of days of bacterial survival in guts as sampled from fecal droplets was equal to the number of days of obtaining positive bacterial signals by dissections during the 4 weeks of monitoring (see Fig. S1C in the supplemental material). The diet groups that had positive bacterial signals in the fecal droplets until the last day of monitoring were considered censored.

**qPCRs.** To identify nifH sequences, we used a previously described protocol (14) and sequences identified in colony Ae150 (accession number KP256164) to design nifH-specific primers (C8_nifH_F/R; see Table S3 in the supplemental material). These were then used either directly or to perform the second step of a nested PCR in combination with primers in the protocol described previously and targeting the same region (14, 32). PCR conditions were as follows: denaturation for 3 min at 94°C, followed by 40 cycles of 30 s at 94°C, 30 s at 60°C, and 30 s at 72°C and a 7-min final extension at 72°C. All PCR products were gel purified (QiAquick gel extraction kit [Qiagen] or Montage gel extraction kit [Millipore]) and sent to Eurofins (Germany) for sequencing. Samples with failing sequencing reactions or chromatographs with multiple peaks were reamplified and cloned using the TOPO TA cloning kit (Invitrogen). At least 20 bacterial colonies from each cloning were checked with PCR using the C8-nifH primers, and 10 positive PCR products from each cloning were sent to MWG for sequencing.

16S rRNA gene-specific primers were constructed in Geneious for EntAcro2 (Entomoplasmatales), RhizoAcro1 (Rhizobiales), and EntAcro2 (Entomoplasmatales) (see Table S3 in the supplemental material). The specificity of the primers was confirmed by PCR, cloning, and Sanger sequencing of various PCR products from different colonies, which showed that the primers amplify the expected sequences (data not shown). To detect Wolbachia (Wolbachia), we used the wsp-specific primers (43). PCR conditions were as follows: denaturation for 3 min at 94°C, followed by 35 cycles of 30 s at 94°C, 30 s at the annealing temperature (see Table S3 in the supplemental material), and 30 s at 72°C and a 7-min final extension at 72°C.

**Electron microscopy.** Large workers of *A. echinatior* (Ae150) were dissected in 0.1 M phosphate buffer (pH 7.4), and ant digestive tracts were fixed in 4% paraformaldehyde in 0.1 M phosphate buffer (pH 7.4) for 2.5 h. This was followed by washings in the same buffer and postfixation in 1% OsO₄ for 1 h, after which samples were placed in a 1% aqueous solution of uranyl acetate and left for 12 h at 4°C. Samples were then dehydrated in an ethanol series and acetone and embedded in Agar 100 Resin (Agar Scientific Ltd.) or Spurr low-viscosity resin (Ted Pella Inc.). Ultrathin sections were stained with uranyl acetate and Reynolds lead citrate and examined with a transmission electron microscope (TEM) (JEM 100 SX [JEOL] or CM100 [FEI]).

**FISH.** Five to 10 ant workers from colony Ae150 for *A. echinatior* and colony Ao492 for *A. octospinosus* were dissected in PBS, and their guts were placed in 4% paraformaldehyde and left for at least 24 h. For the permeabilization, deproteinization, and hybridization, we followed a previously described protocol (45). For the hybridization step, we used 0.75 µg/µl specific labeled probes (see Table S3 in the supplemental material) targeting bacteria belonging to the class Mollicutes (order Entomoplasmatales) and the class Alphaproteobacteria (orders Rhizobiales and Rickettsiales [Wolbachia]). As negative controls, we used reverse probes for Entomoplasmatales and Rhizobiales (see Table S3 in the supplemental material), which gave faint diffuse signals in the fat bodies that probably originated from lipid droplets of significantly different size and intensity than the bacterium-specific signals (see Fig. S2 in the supplemental material). To check permeabilization of cell membranes, we used DAPI (4′,6-diamidino-2-phenylindole) staining as a positive control in each experiment because it has high cell permeability, and we thereby confirmed that our specific probes were able to cross cell membranes similarly to DAPI. We thus considered a signal as being specific when it was absent from the negative controls and colocalized with the DAPI bacterial staining. The fluorescent in situ hybridization (FISH) images were inspected and photographed using a Zeiss LSM 710 confocal microscope equipped with ZEN 2009 software and a Leica TCS SP2 microscope.

**Immunoﬂuorescence (IF) staining.** Dissected tissues (digestive tract and fat body) of large workers were fixed in cold methanol (20 min, −20°C) and then permeabilized in cold acetone (3 min, −20°C). Samples were subsequently rinsed three times with PBS with 0.1% Triton X-100 (PBST) at room temperature (RT) and incubated for 5 min in PBST. This was followed by incubation of tissues for 1 h with 6 µg/ml affinity-puriﬁed anti-NifH antibody (Agrisera, AS01 021A) diluted in PBS-TBSA (PBS, 0.1% [vol/vol] Triton X-100, 1 mg/ml bovine serum albumin [BSA]). The speciﬁcity of the global NifH protein antibody has been checked with Western blots by the manufacturer against a series of bacterial NifH proteins, and has, among others, predicted specificity for Rhizobium meliloti (Agrisera, AS01 021A). As negative controls, fixed and permeabilized tissues were incubated for 1 h with PBS-TBSA and without primary antibody (see Fig. S2 in the supplemental material). All samples were washed three times with PBST before being incubated in the dark with a goat anti-chicken IgY conjugated to Dylight 488 (Pierce, SA5-10070) for 45 min and being washed twice with PBST. Finally, the tissues were mounted in Vectashield medium containing DAPI (Vector Laboratories, H-1500) and viewed under a SP5 Leica confocal microscope with 10× and 63× objectives.

To check permeabilization of cell membranes, we used DAPI (4′,6-diamidino-2-phenylindole) staining as a positive control in each experiment because it has high cell permeability, and we thereby confirmed that our specific probes were able to cross cell membranes similarly to DAPI. We thus considered a signal as being specific when it was absent from the negative controls and colocalized with the DAPI bacterial staining. The fluorescent in situ hybridization (FISH) images were inspected and photographed using a Zeiss LSM 710 confocal microscope equipped with ZEN 2009 software and a Leica TCS SP2 microscope.

**Electron microscopy.** Large workers of *A. echinatior* (Ae150) were dissected in 0.1 M phosphate buffer (pH 7.4), and ant digestive tracts were fixed in 2.5% glutaraldehyde (Sigma) in 0.1 M sodium cacodylate buffer (pH 7.4) for 2.5 h. This was followed by washings in the same buffer and postfixation in 1% OsO₄ for 1 h, after which samples were placed in a 1% aqueous solution of uranyl acetate and left for 12 h at 4°C. Samples were then dehydrated in an ethanol series and acetone and embedded in Agar 100 Resin (Agar Scientific Ltd.) or Spurr low-viscosity resin (Ted Pella Inc.). Ultrathin sections were stained with uranyl acetate and Reynolds lead citrate and examined with a transmission electron microscope (TEM) (JEM 100 SX [JEOL] or CM100 [FEI]).

**Periodic acid-Schiff (PAS) staining.** Digestive tracts from large workers of *A. octospinosus* (Ao492), taken either directly from their colony’s fungus garden or after having spent 2 weeks on sterile sucrose diets, were fixed in 4% paraformaldehyde in 0.1 M phosphate buffer (pH 7.4) overnight at +4°C and subsequently dehydrated via a graded alcohol series and Histoclear (Sigma), followed by embedding in Paraplast Plus (Sigma). Sections were cut at 3 to 4 µm and dried on a hot plate at 36°C. After dewaxing and rehydration, sections were stained with uranyl acetate and Reynolds lead citrate and examined with a transmission electron microscope (TEM) (JEM 100 SX [JEOL] or CM100 [FEI]).
in ethanol and Histoclear and mounted in DPX to be viewed with a Leica DM 5000 B microscope.

Nucleotide sequence accession numbers. The sequence data have been deposited in the NCBI databases under accession numbers SRR1956953 to SRR1956970, SRR1705540, SRR1705717, SRR1707353, SRR1707463 to SRR1707466, SRR1707501, SRR1707550, SRR1707570, SRR1707571, KF613173, KP256159 to KP256169, and KR336617 to KR336619.

RESULTS

16S-454 and 16S-Miseq sequencing. Using a 97% sequence identity cutoff, we identified a total of 180 bacterial OTUs from the 454-pyrosequencing (see Table S4A in the supplemental material). Rarefaction curves were approaching saturation in all but one sample (Ao492), indicating that coverage was generally sufficient for community structure analyses. The four most abundant OTUs belonged to the Mollicutes (Entomoplasmatales [EntAcro1, and EntAcro2]) and Alphaproteobacteria (Rhizobiales [RhiAcro1] and Wolbachia [WolAcro1]) and jointly accounted for >97% of the reads per sample (Fig. 1A; see Table S4A in the supplemental material). Although the rarefaction curve for Ao492 did not plateau (see Fig. S3A in the supplemental material), this OTU also was included in the analyses because the four dominant OTUs were all present.

The ranked sample prevalences of OTUs 5 to 14 never exceeded 0.71%, while none of the other OTUs exceeded 0.07% per sample (see Table S4A in the supplemental material). RhiAcro1 and WolAcro1 were present in all 11 samples, and all samples had at least one of the Entomoplasmatales species, as EntAcro1 was found in nine samples, EntAcro2 was found in six samples, and five samples had both. OTU 5 was also an Entomoplasmatales (EntAcro3, found in 9 samples), but OTU 6 (ActAcro1) was an Actinomycetales (Pseudonocardia) that was 99% identical to one of the two vertically transmitted cuticular actinomyete symbionts (Ps1) of A. echinatior and A. octospinosus (33, 46, 47). This OTU was found in the single gut sample of A. volcanus and in one of the two A. octospinosus gut samples but not in the eight A. echinatior samples. None of the other OTUs was restricted to or specific for any of the three Acromyrmex ant species (see Table S4A in the supplemental material). We further characterized the RhiAcro1, EntAcro1, and EntAcro2 OTUs using Sanger sequencing and obtained 982-bp, 1,282-bp, and 1,340-bp sequences, respectively, while the WolAcro1 OTU has been characterized previously (48, 49). Maximum-likelihood phylogenetic trees showed that RhiAcro1 is closely related to Rhizobiales strains identified in Trachymyrmex urichi of the attine lineage (see Fig. S4A in the supplemental material), while EntAcro1 appeared to be closely related to Mesoplasma lactucae and EntAcro2 to Entomoplasm Freundtii (see Fig. S4B in the supplemental material).

To validate whether the overall rank order of dominant gut OTUs was independent of lab or field conditions during sampling, we sequenced a comparable set of dissected guts from field and lab colonies on a Miseq platform. Rarefaction curves were approaching saturation for all samples (see Fig. S3B in the supplemental material), indicating that coverage was sufficient for community structure analyses. Wolbachia was similarly dominant in A. echinatior and A. octospinosus gut samples from
the field, whereas EntAcro1 and RhiAcro1 were abundant in field guts of A. octospinosus but rare in field guts of A. echinatior (EntAcro1 was abundant in one but <1% in two other field colonies, and RhiAcro1 was <1% in all three field colonies). Once again, EntAcro1, EntAcro2, WolAcro1, and RhiAcro1 accounted jointly for >97% of the reads per sample (Fig. 1; see Table S4B in the supplemental material), but this time there were two exceptions, Ao708(F) and Ao710(3m), that had an additional Entomoplasmatales OTU (EntAcro10), in respective abundances of 31% and 24%.

The gut microbiota of these A. echinatior field colonies were often excessively dominated by Wolbachia (45.7%, 98.1%, and 99.6%) (Fig. 1) and showed consistent directional change toward Rhizobiales 3 months after colonies were moved to the lab to become similar to the gut microbiota of A. octospinosus (see Fig. S5 in the supplemental material).

Principal-coordinate analysis (PCoA) based on weighted Euclidean distances obtained from both the 454 and Miseq runs confirmed that the microbiota differed in a quantitative rather than a qualitative manner across sampling categories (Fig. 1; see Fig. S5 in the supplemental material). The relative abundances of EntAcro1 and EntAcro2 were significantly negatively correlated (Spearman ρ = -0.858; P = 0.0007), whereas a number of other prevalences also showed signs of positive or negative correlation (see Fig. S6 in the supplemental material) but without reaching significance. PCoA comparison of the four focal OTUs in the six samples that were sequenced on both platforms further showed that OTUs were highly reproducible in four cases and satisfactorily reproducible in the two other cases (see Fig. S5 in the supplemental material). To validate our relative abundance estimates, we performed qPCR using 16S rRNA gene-specific primers on a subset of the samples sequenced with Miseq, which showed that relative abundances obtained from the Miseq samples satisfactorily predicted the bacterial 16S rRNA gene copy numbers for EntAcro1, EntAcro2, and RhiAcro1 (see Fig. S7 in the supplemental material).

Localization, morphology, and robustness of Mollicutes and Alphaproteobacteria against tetracycline. We designed probes specific for Mollicutes and Alphaproteobacteria OTUs (see Table S3 in the supplemental material for probe specificity details) and used fluorescent in situ hybridization (FISH) and confocal microscopy to examine different gut tissues of worker ants from colonies Ae150 and Ae492 (Fig. 2A). This showed that Entomoplasmatales were present in the fat body cells (Fig. 2B) and all gut tissues (Fig. 2C, E, and F) of A. echinatior and A. octospinosus: the Malpighian tubules (Fig. 2C), the ileum (Fig. 2E), and the rectum (Fig. 2F). However, RhiAcro1 appeared to be restricted to the hindgut (ileum and rectum) (Fig. 2G and H), while WolAcro1 was present sparsely in the hindgut (Fig. 2G) and more abundantly in the fat body cells (Fig. 2D), the latter confirming results from a previous A. octospinosus study (44).

We further investigated the morphology and localization of these bacteria using transmission electron microscopy (TEM) in A. echinatior. This showed that the Entomoplasmatales had a cocoid shape, an approximate diameter of 0.7 μm, and no bacterial cell wall (Fig. 2I and J) and that rod-shaped Rhizobiales could be recognized by dense cytoplasm, an average diameter of 0.4 μm, and a length range of 0.8 to 2.7 μm (Fig. 2K). Wolbachia was also distinct because of its typical three-layer envelope and heterogeneous cytoplasm (Fig. 2L). TEM analysis confirmed the distribution patterns that we found by FISH microscopy (Fig. 2 B to H) and refined the resolution of the cellular localization of the bacteria. Mollicutes could thus be seen to occur across almost all gut tissues, both intracellularly (Fig. 2I) and extracellularly in the gut, where dividing cells could sometimes be observed (Fig. 2J), while Rhizobiales occurred only extracellularly in the hindgut lumen (Fig. 2G and H) and Wolbachia mostly intracellularly in the fat body cells (Fig. 2D), as also shown previously (44).

To assess the robustness of bacterial symbionts in and around the guts (in fat body cells and gut tissues), ants were deprived of their fungus gardens and fed on different artificial sugar diets, which showed that WolAcro1 prevalence was not, and RhiAcro1 prevalence was only moderately, affected by tetracycline, whereas EntAcro1 and EntAcro2 disappeared from all gut and fat body tissues when ants spent 28 days on such diets (see Fig. S1 in the supplemental material). We also examined the presence of bacteria in the ant fecal droplets with PCR, as the antibiotic treatment should make them disappear when free living in the gut lumen. This showed that the two Entomoplasmatales, which are normally found in Acromyrmex fecal droplets, could no longer be retrieved after ants had been kept on tetracycline for 14 days, while RhiAcro1 prevalence in fecal droplets decreased much more slowly, a decline that was mostly due to the nonfungal diet with only a minor additional effect of tetracycline (see Fig. S1 in the supplemental material). Similar patterns of decline were found in the guts, with tetracycline accelerating the disappearance of the Entomoplasmatales species but only slightly affecting RhiAcro1 until more than a month had passed. Wolbachia has previously been reported, albeit in highly variable cell numbers, from fecal droplets of both A. echinatior and A. octospinosus (44, 50) and was only sporadically found in the feces of the ants that we took directly from fungus gardens or exposed to prolonged artificial sugar diets. Such diets completely eliminated Wolbachia from the fecal droplets but never from the gut tissues, suggesting that a fungal diet may be essential for maintaining these bacteria in the gut lumen (see Fig. S1 in the supplemental material).

NifH protein production and colocalization with Rhizobiales in the hindgut. Using degenerate primers, we identified multiple sequences of the nifH bacterial gene for nitrogenase reductase, with colony Ae342 having three such sequences (pairwise identities of 89.9%), nine other colony samples having one nifH sequence, and colony Ae505 having zero. A maximum-likelihood tree using these and closely related sequences showed that 10/12 sequences are closely related to nifH sequences originating from other Rhizobiales bacteria and that 2/12 sequences (18c8_Ae342 and QC8_Ae342) are equally related to nifH sequences originating from both Rhizobiales and non-Rhizobiales bacteria (see Fig. S8 in the supplemental material). Using microdissections and nifH-specific PCR, we found in two separate experiments that nifH sequence signals were abundant in the hindgut but weak and irregular in the Malpighian tubules and fat body cells (Fig. 3A) and that keeping workers on a sterile sucrose solution without fungus garden food for up to 15 days maintained nifH genes only in the hindguts (Fig. 3A).

To investigate whether some nifH sequences are transcribed into active NifH proteins we performed immunofluorescence (IF) confocal microscopy with a specific anti-NifH antibody. This showed that NifH proteins were present only toward the cuticular boundaries of the ileum and rectum, where DAPI staining revealed that these NifH protein signals were localized.
in or immediately next to bacterial DAPI signals (Fig. 3B). TEM confirmed that only *Rhizobiales* bacteria were localized close to the cuticle of the hindgut lumen (Fig. 3C) and that these bacteria are surrounded by a matrix that might facilitate both biofilm formation and attachment to the cuticle of the rectum and ileum (Fig. 3D and E). *Rhizobiales* were most abundant in the ileum (Fig. 3E), and PAS staining of hindgut sections showed consistent red staining corresponding to abundant polysaccharides in
the matrix where the \textit{Rhizobiales} bacteria occurred (Fig. 3F and G).

**DISCUSSION**

**Simple gut microbiota, uniform diets, and intriguing actinomycetes.** Our results matched the expectation that the gut microbiota of fungus-ingesting \textit{Acromyrmex} leaf-cutting ants should be dominated by relatively few OTUs. A bacterial gut community dominated by few OTUs (what we refer to as “simple” here) has also been found in other eusocial insects with relatively uniform diets, such as honeybees and bumblebees feeding on pollen and nectar (5, 28, 51) and cephalotine ants, which are mostly honeydew-collecting functional herbivores (6). Our results add yet another functionally herbivorous ant genus to the known \textit{Rhizobiales} hosts (6, 14) but also provide novel specifications about the location and function of these gut bacteria. In particular, no other study has combined FISH, TEM, and anti-NifH IF to localize these major endosymbionts of herbivorous ants (6, 14), showing that they are compartmentalized, aided by what appears to be biofilm formation, and colocalized with bacterial NifH proteins.
whose expression is usually tightly regulated by oxygen and nitrogen levels (52).

When comparing prevalences of dominant gut bacteria in field and lab samples from the same Panamanian field site, we generally found a good correspondence (see Fig. S5 in the supplemental material), except that RhiAcro1 and EntAcro1 were sparse in the three A. echinatior field colonies (see Fig. S5 and Table 5AB in the supplemental material). This may be related to the habitats of A. echinatior (open, partly sunlit areas) and A. octospinosus (forest) being clearly distinct and to A. echinatior having somewhat higher fungal protease activity in their field fungus gardens than A. octospinosus (53). The natural forage of A. echinatior colonies may thus be less nitrogen poor than the leaf fragments cut by A. octospinosus workers, but lab colonies of both species received the same bramble leaves (Rubus sp.), a type of forage that likely resembles natural A. octospinosus forage more than natural A. echinatior forage. Wolbachia prevalences are known to differ between lab and field colonies of Panamanian A. octospinosus, as they significantly increase in prevalence when colonies are moved indoors, possibly due to relaxed resource constraints (44).

Our results on fungus-growing leaf-cutting ants complement recent gut microbiota studies in fungus-growing termites. These Macrotermitinae independently evolved farming of another basidiomycete lineage, Termiomyces, but retained the termite habit of predigesting wood fragments and leaf litter during a first gut passage before depositing primary feces as the substrate in which the fungal symbiont grows (54, 55). This broad diet of foraging workers explains their complex gut microbiota (23, 56), but a resident Macrotermes queen was shown to have a simple gut community dominated by a single genus (Bacillus, >98% joint prevalence), consistent with consuming only fungal food provided by the nursing workers (23). It thus appears that substrate ingestion rather than substrate handling may be decisive for the variability of bacterial gut communities of fungus-farming eusocial insects.

Low prevalences of cuticular Pseudonocardia bacteria were found in the worker guts of A. volans and A. octospinosus (ActAcro1, 0.71% of the reads in Av520 and 0.38% of the reads in AoDani). Panamanian Acromyrmex species differ in their typical abundance of cuticular Pseudonocardia actinomycetes, with A. volans workers having very high coverage on their body (also in foragers), A. octospinosus workers having intermediate coverage, and A. echinatior workers having the lowest coverage (reference 57 and personal observations), similar to our frequencies of detection of these bacteria in the guts (see Table S4 in the supplemental material). Further work will be needed to investigate whether the occasional presence of ActAcro1 (99% similar to Ps1 and 97% similar to Ps2 [33]) in the guts of Acromyrmex species has adaptive significance or is merely due to cuticular bacteria being ingested during allogrooming.

Spatial distributions of bacterial species within the Acromyrmex gut. RhiAcro1 was restricted to the hindgut, while WolAcro1 and the Entomoplasmatales species were not (Fig. 2) (44). The latter two usually occur intracellularly, which apparently necessitates an extra plasma membrane of ant origin to live in the host cytoplasm (Fig. 2I, J, and L). Such extra plasma membranes have also been found in close relatives of Entomoplasmatales living in human reproductive organs (58) and have been hypothesized to protect bacteria against host immune defenses, a function that may also be relevant in Wolbachia (59, 60). The significant tendency toward mutual exclusion between EntAcro1 and EntAcro2 suggests that similar symbionts may compete for the same niche space in the host and that complex additional interactions between the four dominant gut bacteria may exist, as WolAcro1 had a negative effect on EntAcro1 and RhiAcro1 but a positive effect on EntAcro2. However, these correlations should be tested in larger scale and more in-depth studies to confirm mutual exclusiveness or reinforcement.

To our knowledge, the localization of insect-associated Rhizobiales has been investigated in only two previous studies and only at the overall organ level: one on Tetraponera ants (21) and one on Odontotaenius beetles (12). Our TEM and PAS analyses show that Acromyrmex Rhizobiales have the characteristic rod-shaped morphology of this genus (61) and are embedded in hindgut biofilms with a polysaccharide matrix, as it has been demonstrated that the PAS reagent specifically stains polysaccharides (62). This may help these RhiAcro1 cultures to adhere to the hindgut lining and to maintain robustness when tetracycline reduces or terminates cell divisions. The ability of proteobacteria to synthesize extracellular polysaccharides for biofilm production has previously been demonstrated in host tissues of other insects (63) and on abiotic surfaces, usually mediated by a polar adhesive that is commonly found in Alphaproteobacteria (64).

Putative functions of Rhizobiales, Entomoplasmatales, and Wolbachia in Acromyrmex. RhiAcro1 and WolAcro1 appear to be obligatorily associated with Panamanian Acromyrmex as symbionts, because they were present in all samples investigated (Fig. 1; see Table S4 in the supplemental material) and were impossible to remove when feeding ants sugar solutions with tetracycline (see Fig. S1 in the supplemental material). This is consistent with earlier studies showing that Wolbachia can survive for a month or more without proliferating (65), since a bacteriostatic antibiotic drug like tetracycline inhibits the growth but does not destroy the bacterial cells. Close relatives of RhiAcro1 have been found in several other, mostly functionally herbivorous, ant species (6, 14, 66, 67), but Mollicutes (Entomoplasmatales), like EntAcro1 (Mesoplasma) and EntAcro2 (Entomoplasmatales), have mostly been found associated with predatory ants such as Formica, generalists such as Polyrhachis, and especially army ants, most notably in the subfamily Aenictinae, which are specialized predators of other ants and termites (68–70). In general, Entomoplasmatales are mostly intracellular pathogens and are not known to be part of biofilms, and a fairly close Mycoplasma relative is known to be sensitive to tetracycline (71), consistent with the rapid demise of EntAcro1 and EntAcro2 in our feeding experiments.

The possible function of the two Entomoplasmatales species remains enigmatic. Finding these bacteria intracellularly and in high cumulative abundances (see Table S4 in the supplemental material) in healthy ant colonies would appear to be incompatible with these bacteria having a direct pathological impact on their host fitness. This interpretation is consistent with no bacterial symbionts of ants having been shown so far to be virulent in the pathogenic sense, and multiple mutualistic functions having been suggested (6, 14, 70). The prevalence of Entomoplasmatales in several predatory ants (including army ants) and fungus-growing ants (they are also dominant in other higher attine ant species in Panama [P. Sapountzis et al., unpublished data]) suggests that their function might be somehow related to the processing of chitin, the main component of the cuticles of insect prey and fungal cell walls ingested by leaf-cutting ants, in spite of the insects pro-
Biosis.

A. octospinosus, suggesting that it may be a mutualist with an as-yet-unknown function (44), also because no clear reproductive manipulations by Wolbachia infections (male killing, feminization, or cytoplasmic incompatibility) have so far been demonstrated in ants (73, 74). All four OTUs that cumulatively make up more than 97% of the Acromyrmex gut microbiota may thus be mutualists, but much further work will be needed to specify the metabolic networks of these bacteria and to evaluate their benefits to the fungus-farming symbiosis.

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