Xenorhabdus bovienii Strain Diversity Impacts Coevolution and Symbiotic Maintenance with Steinernema spp. Nematode Hosts

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ABSTRACT  Microbial symbionts provide benefits that contribute to the ecology and fitness of host plants and animals. Therefore, the evolutionary success of plants and animals fundamentally depends on long-term maintenance of beneficial associations. Most work investigating coevolution and symbiotic maintenance has focused on species-level associations, and studies are lacking that assess the impact of bacterial strain diversity on symbiotic associations within a coevolutionary framework. Here, we demonstrate that fitness in mutualism varies depending on bacterial strain identity, and this is consistent with variation shaping phylogenetic patterns and maintenance through fitness benefits. Through genome sequencing of nine bacterial symbiont strains and cophylogenetic analysis, we demonstrate diversity among Xenorhabdus bovienii bacteria. Further, we identified cocladogenesis between Steinernema feltiae nematode hosts and their corresponding X. bovienii symbiont strains, indicating potential specificity within the association. To test the specificity, we performed laboratory crosses of nematode hosts with native and nonnative symbiont strains, which revealed that combinations with the native bacterial symbiont and closely related strains performed significantly better than those with more divergent symbionts. Through genomic analyses we also defined potential factors contributing to specificity between nematode hosts and bacterial symbionts. These results suggest that strain-level diversity (e.g., subspecies-level differences) in microbial symbionts can drive variation in the success of host-microbe associations, and this suggests that these differences in symbiotic success could contribute to maintenance of the symbiosis over an evolutionary time scale.

IMPORTANCE  Beneficial symbioses between microbes and plant or animal hosts are ubiquitous, and in these associations, microbial symbionts provide key benefits to their hosts. As such, host success is fundamentally dependent on long-term maintenance of beneficial associations. Prolonged association between partners in evolutionary time is expected to result in interactions in which only specific partners can fully support symbiosis. The contribution of bacterial strain diversity on specificity and coevolution in a beneficial symbiosis remains unclear. In this study, we demonstrate that strain-level differences in fitness benefits occur in beneficial host-microbe interactions, and this variation likely shapes phylogenetic patterns and symbiotic maintenance. This highlights that symbiont contributions to host biology can vary significantly based on very-fine-scale differences among members of a microbial species. Further, this work emphasizes the need for greater phylogenetic resolution when considering the causes and consequences of host-microbe interactions.
between bacterial symbionts and nonnative hosts such that they better engage in symbiosis (15), as well as the influence of coevolution on competition among symbionts (16). However, lacking are studies that experimentally examined the influence of symbiont strain variation on specificity within a coevolutionary context. Such studies are necessary to better understand how symbiont diversity impacts coadaptation, coevolution, and mutualism maintenance. In this study, we assessed the influence of bacterial strain diversity on specificity and coevolution in the association between Xenorhabdus bovienii bacterial symbiont strains and Steinernema spp. nematodes (Nematoda: Panagrolaimomorpha).

The life cycles of Steinernema spp. nematodes and their proto-bacterial symbionts of the genus Xenorhabdus (17) include requisite reproductive stages that occur within an insect host and an environmental nematode stage, the infective juvenile (IJ) (Fig. 1) (18). IJs seek out and invade the insect host, and the nematodes and bacteria kill the insect and reproduce within the cadaver (18, 19). When nutrients are depleted, the nematode progeny form the next generation of IJs (20). Previous studies on a selection of Steinernema-Xenorhabdus pairs have shown that the bacterium can contribute to virulence toward the insect host (21, 22) and support nematode reproduction (19), but it is not known if these bacterial contributions occur with other nematode-bacterium pairs. This interaction is an obligate mutualism in some associations (17), where the nematodes cannot reproduce without the bacterial symbiont (Fig. 1a), and bacteria rely on the nematode host for transmission between insect hosts (Fig. 1b). Xenorhabdus bovienii bacterial strains are broad-host-range symbionts that associate with at least nine Steinernema nematode species from two phylogenetic subclades. Conversely, each of the nematode host species harbors only X. bovienii (23). This suggests that symbiotic maintenance and coevolution may depend on the bacterial sub-species (strain)-level diversity. To assess the impact of bacterial strain diversity within an evolutionary context, we integrated phylogenetic analysis and experimental crossing of symbionts to analyze the coevolutionary relationship and specificity between X. bovienii bacterial strains and their associated nematode hosts.

FIG 1 X. bovienii bacterium-Steinernema spp. nematode-Galleria mellonella insect interactions. (a) Schematic diagram of the nematode (gray)-bacterium (green) life cycle. All the events shown within the box occur within the insect host. (b) Image of interactions, provided to show the actual scale. The photograph shows an infective juvenile nematode that is newly emerged from a G. mellonella cadaver. The inset depicts a micrograph of bacteria within the nematode receptacle. Bar, 10 μm.

RESULTS

Genetic diversity of X. bovienii strains. Genetic variation among possible partner pairs is a prerequisite for specificity in bacterium-host associations. To begin to understand the extent of genetic variation among X. bovienii strains, we conducted genomic comparisons of nine bacterial strains identified as X. bovienii through 16S rRNA sequencing (see Table S1 in the supplemental material), isolated from six different nematode host species (24, 25). We sequenced and annotated the genomes, and the conserved homologs were compared for average nucleotide identity (ANI). All X. bovienii strains had ANIs greater than 96% (see Table S2 in the supplemental material), further supporting that they belong to a single species according to current standard criteria in microbial systematics (26).

To discern conservation and variation in gene content in the nine X. bovienii strains, we conducted gene content analyses using the MaGe platform (27, 28). We found that approximately 55% of the genome content was shared by all strains, and approximately 94% was shared with at least one other strain, with a range of <1% to 9% of genes being unique to an individual strain (see Table S3 in the supplemental material). Since these unique genes may represent specificity determinants, we analyzed their possible functions suggested by their annotation (see Table S3). Within each strain, the most highly represented gene category was that of unknown function. Additionally, unique genes in some strains were predicted to encode membrane or secreted proteins (e.g., putative toxins) that might be expected to interact with nematode or insect hosts (see Table S3). Other genes identified in this analysis included those of predicted metabolic or cellular function and mobile genetic elements (see Table S3). Although examination of the flexible gene content of the X. bovienii strains awaits a more detailed analysis, in total these data indicated a broad spectrum of genetic diversity, and therefore differences in functional potential among X. bovienii bacterial strains. These results strengthen the idea that specificity and coevolution among partner pairs may be occurring between Steinernema spp. hosts and their native X. bovienii partners.

Cophylogenetic analysis. Specificity between partner pairs is expected to arise through coevolution occurring during long-term maintenance of symbioses. Therefore, to focus our attention on those partner pairs most likely to exhibit specificity, we used phylogenetic analyses to assess the potential for coevolution, as evidenced by cocladogenesis (identical topologies) between symbiont and host phylogenetic trees. A previous phylogenetic study using a multilocus approach revealed instances of codiversification (similar but not identical tree topologies) in some but not all X. bovienii-Steinernema spp. associations, suggesting that finescale specificity between hosts and symbionts may occur (24). To generate more refined phylogenetic inferences, we used conserved homologs from whole bacterial genome content to construct the bacterial phylogeny. Cophylogenetic analyses (Fig. 2) revealed congruences between the X. bovienii phylogeny (see Fig. S1a in the supplemental material) and the Steinernema host phylogeny (see Fig. S1b). Specifically, the cophylogeny provided robust support for cocladogenesis between the group of S. feltiae and S. punta-catenaeus bacterial symbiont strains, which was supported by statistical evidence. For the nine X. bovienii strain genomes, there are 2,027,025 possible rooted trees. Of these, only 14,175 (0.7% of the total) contained a monophyletic clade consisting of the four bac-
phylogeny indicates that not all pairings are strictly maintained. Switching within some but not all parts of the nematode-bacteria associates with a nematode of another clade, indicating that the bacterial monophyletic clade is unlikely to have occurred by random chance. This statistical permutation test provided strong evidence that the *S. feltiae* and *S. punctauvese* nematode isolates and their bacterial symbiont strains share an evolutionary history, and it is likely that specificity is occurring between these partner pairs. In contrast, among other nematode isolates and bacterial strains, host switching has occurred, including one bacterial strain, Xb-Si, which associates with a nematode of another clade, *S. intermedium*. Host switching within some but not all parts of the nematode-bacteria phylogeny indicates that not all pairings are strictly maintained. Therefore, there are likely divergent maintenance pressures that impact the different nematode-bacterium pairings.

**Experimental testing of mutualistic interactions.** As an experimental test of specificity and coevolution, we examined the ability of nematode-bacteria pairs to engage in mutualism through experimental coinjections of three *S. feltiae* nematode isolates and nine *X. bovienii* bacterial strains (see Fig. S2 in the supplemental material). Nematodes and bacteria were reared separately, mixed, and coinjected into *Galleria mellonella* (Lepidoptera: Pyralidae) larvae. The progression of the life cycle (Fig. 1a; see also Fig. S2) was then monitored for virulence (percent mortality of the coinfected insects), productive infection (percentage of insect cadavers that produced progeny), progeny number (average number of progeny per productive infection), progeny infective potential (ability of the progeny IJs to seek, invade, and kill insect hosts), and bacterial carriage (average CFU per IJ). To assess these traits within a phylogenetic framework, we used linear regression to compare the measurements to bacterial and nematode phylogenetic distances and Bayesian tree distances (i.e., branch lengths from the consensus Bayesian tree between the native pair and the tested bacterial strain or its host). This analysis enabled the comparison of the experimental data to the strongest phylogenetic trend within the bacterial strains to link performance in mutualism with evolutionary history. Certain nematode-bacterium combinations displayed a large amount of trial-to-trial variability, possibly due to seasonal fluctuations or the use of outbred insect and nematode lines. Due to the lack of an inbred insect line, we controlled for differences among insect hosts by limiting insect size variation and randomizing insects among treatments. To address genetic differences between biological replicates and to control for seasonal fluctuations, data were normalized relative to the native combination within each experiment. While variation remained high in some cases, trends (e.g., slopes of the linear regression lines) were similar across trials.

With respect to virulence, some combinations showed significant differences when compared by log-rank analysis, measuring the overall trends within a survival curve (see Table S4 in the supplemental material). However, linear regression analysis did not show significant correlations between the phylogenetic framework and individual measurements of virulence, such as LT₅₀ values (e.g., the time at which half the insects had died), which suggests that the differences do not reflect coevolution (see Table S5 in the supplemental material). As expected, *S. feltiae* FL and *S. feltiae* FR nematodes alone killed fewer insects than nematode-bacterium combinations, indicating *X. bovienii* bacteria contribute to virulence (see Table S4) (*P* < 0.05). Similarly, *S. feltiae* MD nematodes were significantly more virulent by log-rank test when associated with six of the bacterial strains (see Table S4) (*P* < 0.05), though there was no significant difference when data for these nematodes were combined with the three other strains (see Table S4). This suggests that *S. feltiae* MD is less reliant than the other nematodes on its bacterial symbiont for virulence. By 7 days postinjection, there were no significant differences among the nematode-bacterium combinations in the percentages of insects they killed (see Table S4). Therefore, minor differences in virulence among the nematode-bacterium combinations likely do not significantly impact the mutualism.

With regard to nematode progeny characteristics, significant differences were identified among different nematode-bacterium pairings relative to bacterial phylogenetic distance or to divergence from the native symbiont. Injections of nematodes alone resulted in no production of progeny, supporting that bacterial symbionts contribute to *S. feltiae* nematode reproduction (data not shown). Both the ability to produce progeny (productive infection percentage and progeny number) and the infective potentials of those progeny correlated with the bacterial phylogenetic distance; as bacterial strain divergence increased, the success of the interaction decreased (with one exception, the number of *S. feltiae* MD progeny) (Fig. 3a to c; see also Table S5 in the supplemental material). Although bacterial carriage in nematode progeny also

**FIG 2** Cophylogeny of nematode species hosts and bacterial symbiont strains. Numbers indicate bootstrap values, and thicker lines indicate posterior probabilities greater than 0.9. All posterior probabilities were greater than 0.8. Shaded boxes indicate clades of nematodes with their respective symbionts: *X. bovienii* nematode hosts (gray), *S. feltiae* and *S. punctauvese* nematodes (green), and the distantly related nematode *S. intermedium* (yellow).
showed a negative trend with respect to phylogenetic distance (Fig. 3d), this was not significant (see Table S5). Productive infection percentage, progeny number, and progeny infective potential were also strongly correlated with nematode host phylogenetic distance (Fig. 3e to g; see also Table S5), indicating that bacteria from hosts more closely related to the *S. feltiae* nematodes are better able to engage in symbiosis than bacteria from more distantly related hosts.

Because the infective potential of the nematode progeny is integral to subsequent nematode reproduction and therefore evolutionary success, we examined potential causes of defects in nematode progeny infective potential. However, we found no significant correlation between bacterial phylogenetic distance and progeny IJ longevity (see Fig. S3a in the supplemental material) or IJ development, as assessed by morphology (see Fig. S3b and c), indicating these parameters do not affect progeny infective potential.
Nematode and bacterial strain fitness. Experimental testing suggests that interactions between the nematode host and bacterial strains closely related to its native symbiont are more efficacious than those with divergent symbionts. We evaluated this trend by using linear regression analysis of nematode reproductive fitness (i.e., total number of progeny, the product of the productive infection percentage and progeny number) relative to bacterial (Fig. 4a; see also Table S5 in the supplemental material) and nematode (see Table S5) phylogenetic distances. There was a significant negative relationship for each nematode isolate (see Table S5), demonstrating that nematode fitness is highest with closely related strains (those that fall within the same clade) and lowest with strains from different clades (Fig. 4c). This indicates that closely related strains (those that fall within the same clade as the native symbiont) may be functionally redundant in hosts, which in turn suggests that *S. feltiae* and *S. puntauvense* nematode isolates require the same goods and services from their symbiont.

The data show a clear trend that strains within the same phylogenetic clade as the native symbiont provide greater benefits than those from different clades (Fig. 4c). This indicates that closely related strains (those that fall within the same clade as the native symbiont) may be functionally redundant in hosts, which in turn suggests that *S. feltiae* and *S. puntauvense* nematode isolates require the same goods and services from their symbiont. In contrast, more distantly related strains were defective in various parameters of mutualistic support of nematode fitness (e.g., Xb-Sj has a greater defect in progeny infective potential than Xb-So, which has a greater defect in productive infection percentage), suggesting that not all *X. bovienii* bacterial strains are functionally redundant within nematode hosts (Fig. 3 and 4c).

The observed negative trends might be caused by bimodal or distributed variations in strain contributions to fitness. Distributed variation is supported by the fact that negative trends remained similar (e.g., negative slope of the same magnitude) when only the symbionts outside the native clade were considered (data not shown). To examine this further, the effects of the native clade data points on the linear negative trends relative to bacterial phylogenetic distance (Fig. 3; see also Table S5 in the supplemental material) were analyzed by computing Cook’s distance (29). Linear regressions for each trend containing all 5 strains outside the native clade and one data point representing the average of all symbionts from the native clade were constructed and used for the analyses. In all trends tested but one, the Cook’s distance of the point representing the native symbiont was less than 1, indicating that this data point was not influential on the overall trend (see Table S6 in the supplemental material). Therefore, the observed trends depend on the various results from all bacterial strains, not just a gross difference between bacteria that fall within the clade versus those outside the clade. The one trend that was dependent on inclusion of the native symbiont clade in the analyzed data was bacterial carriage by *S. feltiae* MD. However, the high variability of the data underlying this particular trend likely caused dramatic impacts on regression curves when individual data points were removed.

### X. bovienii bacterial genes contributing to specificity

Fitness benefit differences among the bacterial strains are unexpected in light of their close phylogenetic relationship; one explanation for the observed fitness advantages of *X. bovienii* within the *S. feltiae* and *S. puntauvense* clade symbionts is variation in shared bacterial genes which could alter functionality and/or cause incompatibility between hosts and symbionts. Such genes are expected to be under positive selection across all bacterial symbionts or within a specific group, such as the *S. feltiae* and *S. puntauvense* clade. However, due to the close similarities of the bacterial strains, we were unable to reliably detect positive selection through *dN/dS* analysis (analysis of the ratio of nonsynonymous to synonymous evolutionary changes).

Another explanation is that *S. feltiae* and *S. puntauvense* symbionts as a group uniquely encode or lack genes that impact fitness. The increased fitness of these symbionts relative to other strains may be due to the presence of genes that are absent in other bacterial strains that increase their ability to support symbiotic interactions or the absence of genes that are present in other bacterial strains that have deleterious effects on the nematode host. To assess which genes follow this pattern, we identified genes based on sequence identity and clustering, that were significantly overrepresented or underrepresented in the symbionts of *S. feltiae*
and *S. punctauwense* compared to the other *X. bovienii* strains (see Fig. S4 in the supplemental material). Among the identified families, the most common were of unknown function, representing 80% of overrepresented genes and 54% of underrepresented families. Families of mobile genetic elements were the second most abundant, comprising 4% of overrepresented genes and 38% of underrepresented genes. Other families were those predicted to be involved in primary and secondary metabolism, toxins, and toxin/antitoxin systems. Genes involved in metabolism are potentially important in the symbiosis due to their possible nutritional role. Among the overrepresented metabolic genes (see Fig. S4) were two (azlC and azlD) predicted to encode components of a branched-chain amino acid transporter and one predicted to encode an associated transcriptional regulator (*rhaR*). Genes from these three families, as well as another of unknown function (listed in the metabolism group), are clustered together in a putative operon that is only present in the *S. feltiae* and *S. punctauwense* symbionts. Toxins may also be involved in symbiosis specificity due to their potential role in defensive symbiosis. Additionally, toxin/antitoxin modules have been implicated in ensuring symbiont transmission through regulation of symbiosis genes (30). However, elucidation of the roles of these gene families awaits further functional analyses.

The presence or absence of specific genes within the *S. feltiae* and *S. punctauwense* clade symbionts likely reflects the coevolution of these symbionts and their specific hosts. It is possible that the symbionts within the clade have gained or lost certain genes due to the requirements of the nematode host. However, it is also possible that the nematode host has evolved in response to bacterial products (e.g., now the host requires nutrients because the bacterium could produce them). In either case, the partners are a coevolved unit.

**DISCUSSION**

The observed negative correlation between symbiotic success and the phylogenetic framework supports two overarching ideas. First, the correlation suggests that in the *S. feltiae*-*X. bovienii* symbiosis, specificity is due to coadaptation between symbionts and hosts, with the bacterial symbiont and/or the host having coevolved to fill the needs of the other partner. Additionally, the fact that the observed fitness trends are inversely correlated with nematode host phylogenetic distance, in some cases more strongly than with bacterial phylogenetic distance (see Table S5 in the supplemental material), provides compelling evidence that the nematode host with which a symbiont associates is a contributing factor to the correlation. This idea is further supported by our finding that the bacterial strain that associates with the most phylogenetically distant nematode host, *Xb-Si*, is unable to coevolve in any aspect of mutualism with *S. feltiae*, even though it is not the most distantly related bacterium from the native symbiont (Fig. 4c). *Xb-Sj* is the most distantly related symbiont, but it is able to engage in symbiotic interactions (Fig. 3 and 4c).

The second fundamental concept supported by our experimental data is that animal hosts can receive significantly different fitness benefits when associating with divergent bacterial symbiont strains, and such variations could contribute to the evolution of specificity within a symbiotic relationship. Coevolution and coadaptation may be caused by nematode adaptation to unique provisions of particular bacterial strains or by bacterial strain adaptation to fulfilling the specialized needs of a nematode host. In either case, the nematode-bacterium pairings are coevolved units; their life histories are intertwined, and the fitness of each depends on their combined success. The two overarching ideas supported by our data are likely true for other symbioses. Indeed, recent studies have revealed that strain-level symbiont variability impacts the success of the squid–*Vibrio* (14) and legume–*Rhizobium* (12, 13) symbioses, although these studies did not assess the impact of variability with relation to coevolution.

Our data are based on experimental laboratory crosses, but the findings are likely to be ecologically relevant, as mixed infections with multiple nematode hosts and symbionts can occur (31). In fact, nematode isolates of three of the host species relevant to our study (*S. feltiae*, *S. kraussei*, and *S. intermediate*) have been isolated in close proximity (32), although the isolates used here were not. Because mixed infections can lead to nonnative crosses of nematode hosts and bacterial symbionts, variations in benefits could play a significant role in driving maintenance of partner pairs. Greater benefits of some associations relative to others could provide positive feedback for the evolutionary maintenance of the mutualism (i.e., increased evolutionary success) and therefore a selective pressure that results in the observed phylogenetic patterns (Fig. 5). This is consistent with the theory of partner fidelity feedback, where linkages in host and symbiont fitness provide positive reinforcement that stabilizes the mutualism (2). A partner fidelity feedback mechanism is further supported by the fact that *S. feltiae* nematodes and *X. bovienii* bacteria cannot separately complete their life cycles (Fig. 1b and data not shown). Our data extend current theory by demonstrating that bacterial strain diversity can drive partner fidelity feedback for maintenance of mutual relationships.

Diversity in the goods and services that are integral to symbiotic function are likely responsible for variations in symbiotic success. One mutualistic role that bacterial symbionts can perform is defense, where the symbiont provides protection for the host against specific pathogens, competitors, or predators. For example, this type of function can be conferred by secondary symbionts of aphids, where the bacterial symbiont contributes to protection against a parasitoid wasp predator of the aphid host. In some of these associations, protection is conferred by a phage-carried toxin, but this mechanism is not conserved among all secondary symbionts (33). Similarly, specialized toxins or secondary metabolites produced by some but not all *X. bovienii* may contribute to nematode host defense against organisms within the insect host, as is true for *X. nematophilus* (34, 35). In the absence of the defensive compound, the nematode host may be killed before establishing a new infection or suffer from population losses that result in fewer progeny. Alternatively, since some classes of *Xenorhabdus* toxins are insecticidal (36), variations in symbiont-encoded toxins could influence the efficiency of insect host killing, as well as the insect host range of the nematode. Finally, symbiont-derived toxins may have nematicidal effects to which the native nematode host is resistant. In a nonnative pairing, such a nematicidal activity obviously would have a detrimental impact.

Many of the genes identified as unique (see Table S3 in the supplemental material) or enriched (see Fig. S4 in the supplemental material) within the *X. bovienii* bacterial strains could encode defensive factors. For example, unique and enriched genes including those encoding exported proteins of unknown function, nonribosomal peptide synthetases (NRPS), polyketide synthetases (PKS), and a predicted Shiga toxin. NRPS-PKS gene clusters are of particular interest, as they synthesize small molecules (secondary metabolites) that have a variety of biological activities, such as
antimicrobial (37–39), hemolytic (39), and immunosuppressive (40) effects, which could serve as defensive factors. Indeed, a fungal endosymbiotic NRPS gene cluster provides plants protection from insect feeding (41). Also of interest is the putative Shiga toxin that, among the tested X. bovienii strains, is uniquely encoded by Xb-Si. Shiga toxins affect lipid bilayers and have cytotoxic activities that allow bacterial pathogens to cause disease within eukaryotic hosts (42). Such a toxin could be involved in pathogenesis toward the insect host or in defense. Indeed, the presence of this toxin may be responsible for the inability of Xb-Si to support symbiosis with S. feltiae nematodes (Fig. 4c), as it could have a cytotoxic effect in the S. feltiae nematodes.

Another basis for many symbiotic relationships is the mutually beneficial exchange of nutrients between host and symbiont, and integration of nutritional requirements could influence coadaptation. It has been proposed that Xenorhabdus bacteria provide nutritional support to the nematode host, and lack of this support leads to a decreased ability to produce progeny (19, 43). Consistent with this, S. feltiae nematodes are unable to reproduce within the insect host without their bacterial symbionts (data not shown), possibly due to a lack of specific nutrients. Further corroborating this idea, we observed that among the S. feltiae/S. puntauense symbionts there was an overrepresentation of genes predicted to encode branched-chain amino acid transporter systems, which could contribute to nutritional support of nematode reproduction or infective potential. Branched-chain amino acid transport influences Rhizobium nodulation on plants, with various phenotypes depending on the plant host (44). Thus, variability in symbiont amino acid transport capability, coupled with variation in nematode host requirements for certain amino acids, could help explain some fitness differences.

There is increasing recognition that beneficial microbes have profoundly impacted the origin and evolution of animals (4), and studies have implicated symbiosis in host speciation through reproductive isolation (8). These phenomena depend on symbioses being maintained throughout the evolutionary history of the host organism. We found that this maintenance is shaped by bacterial strain diversity, and our analyses have highlighted that the contributions of symbionts to host biology can vary significantly based on differences among members of a microbial species. Furthermore, our findings suggest that in addition to current studies of microbiota that identify microbes by the species or phylum level, a comprehensive understanding of the causes and consequences of host-microbe interactions will require the use of greater phylogenetic resolution and classification through evolutionary and functional characterizations.

MATERIALS AND METHODS

Bacterial strains and nematode isolates. Bacterial strains were obtained by sonication of nematode hosts after surface sterilization. Strain identity was confirmed by analysis of 16S rRNA from whole-genome sequences (25, 43) and average nucleotide identity (26). Bacterial strains were stored in lysozyme broth (LB) supplemented with 20% glycerol frozen at −80°C. Bacterial cultures were grown at 30°C in LB that had not been exposed to light, with aeration, or on LB agar with 0.1% pyruvate (45). S. feltiae nematode isolates used were obtained from the laboratories of Patricia Stock or Byron Adams (via Adler Dillman) and were verified through sequencing of the 12S and 28S genes (24). Nematodes were propagated through Galleria mellonella larvae (46). Axenic IJs were produced in vitro as previously described (47, 48). Nematodes were stored at 25°C in 250-ml tissue culture flasks (BD Falcon, Franklin Lakes, NJ) at a density of 5 to 10 IJ/µl and a volume of less than 60 ml.

Genes and genome sequencing and assembly. Nematode 12S and 28S rRNA genes were sequenced as previously described (49), and sequences were submitted to NCBI. Bacterial genomes were sequenced using Illumina paired-end libraries (mean insert length, 300 bp) and quality trimmed using DynamicTrim.pl v.1.10 in the solexQC package. Dynamic trimming was performed according to TrimmAl's, v1.2rev59 (50) default settings. After excluding reads of <20 bp and lacking barcode sequences, genomes were assembled with Velvet v.1.1.06 (51, 52) using automatic determination of sequencing coverage and a series of kmer values. Draft genomes were annotated using MaGe (27, 28) and submitted to EMBL. 16S rRNA sequences from draft genomes were assessed using BLASTn (http://blast.ncbi.nlm.nih.gov) and were submitted to GenBank.

FIG 5 Contributions of increased benefits in maintenance of symbiosis. The illustration shows how increased benefits of the native pairing could serve to reinforce partner fidelity within a symbiotic relationship and therefore contribute to symbiotic maintenance. The different colors represent divergent nematode species or bacterial strains.
Phylogenetic analysis. For bacterial phylogenetic analysis, MaGe was used to identify homologs (genes with conserved synteny with ≥30% nucleotide identity over ≥80% of the length) present in the X. bovienii and X. nematophila genomes, yielding 2,166 gene sets. Technical replicates were averaged and plotted versus the phylogenetic distance of the bacterial symbiont or nematode host of the bacterial symbiont, the Bayesian tree distance from the native combination. The data were also compared to ANI and maximum likelihood tree distances with similar topology in the bacterial monophyletic group (68). The number of trees with a given split was the product of the number of rooted families or domains that were over- or underrepresented in a particular clade. A cutoff of P < 0.05 was used to determine significance.

(ii) Overrepresented and underrepresented gene sets. Protein sequences were downloaded from MaGe and annotated using HMMer models for KEGG (http://nar.oxfordjournals.org/cgi/pmidlookup?view=long&pmid=24214961) and Pfam (67). Sequences were clustered de novo, based on amino acid sequence identity (25% sequence identity and 50% coverage), using the protinorthov5 program available via the BioMed Central website. Fisher’s exact test, implemented within the python package scipy (http://www.scipy.org), was used to identify gene families or domains that were over- or underrepresented in a particular clade. A cutoff of P < 0.05 was used to determine significance.

Statistics. Phylogenology was statistically measured by a permutation test. The total number of possible X. bovienii trees was compared to the number of possible trees that contained the monophyletic group of S. fel-tiae and S. puntauvense symbionts and to the number of possible trees with identical topology in the bacterial monophyletic group (68). The number of trees with a given split was the product of the number of rooted trees for each half.

Statistical analyses for experimental testing were performed using R (69) or Prism (GraphPad). For virulence assays, a log rank test and LTT calculation were done. In the log rank analysis, all data points from the three experimental replicates were combined. Each experimental block was also analyzed separately, and trends remained the same. For experimental testing of mutualistic interactions, linear regression analyses were done to determine R² values and the P values for trends. The data were normalized to the native combination (all values were divided by the value of the natural combination). Technical replicates were averaged and plotted versus the phylogenetic distance of the bacterial symbiont or nematode host of the bacterial symbiont, the Bayesian tree distance from the native combination. The data were also compared to ANI and maximum likelihood tree distances with similar results. Cook’s distance for each trend was computed using a linear regression constructed based on all symbionts outside the native clade (i.e., Xb-Si, Xb-Sj, Xb-Sk-BU, Xb-Sk-CA, and Xb-So) plus one data point of the average of the native clade (i.e., Xb-Sf-FL, Xb-Sf-GR, Xb-Sf-MD, and Xb-Sp). A Cook’s distance of > 1 was considered influential.

Nucleotide sequence accession numbers. Draft nematode and bacterial genome sequences were annotated and submitted to EMBL, and 16S rRNA sequences from draft genomes were assessed using BLASTn. The sequences were submitted to GenBank; the corresponding accession numbers are provided in Table S1 in the supplemental material.

SUPPLEMENTAL MATERIAL
Supplemental material for this article may be found at http://mbio.asm.org/lookup/suppl?doi:10.1128/mBio.00076-15/-/DCSupplemental.

Table S1, DOCX file, 0.1 MB.

Figure S1, PDF file, 0.3 MB.

Figure S2, PDF file, 0.7 MB.

Figure S3, PDF file, 0.04 MB.

Figure S4, PDF file, 2.5 MB.

Table S1, DOCX file, 0.1 MB.

Table S2, DOCX file, 0.1 MB.
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