

Genome Analysis of Spiroplasma Citri Strains From Different Host Plants and Its Leafhopper Vectors

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Research article

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Abstract

Background

Spiroplasma citri comprises a complex of bacteria that cause diseases in citrus, horseradish, carrot, sesame, and also infect a wide array of ornamental and weed species. *S. citri* is transmitted in a persistent propagative manner by the beet leafhopper, *Neoliturus tenellus* in North America and *Circulifer haematoceps* in the Mediterranean region. Leafhopper transmission and the pathogen's wide host range serve as drivers of genetic diversity. This diversity was examined by comparing the genome sequences of seven *S. citri* strains from the United States (BR12, CC2, C5, C189, LB319, BLH-13, and BLH-MB) collected from different hosts and times with other publicly available spiroplasmas.

Results

Phylogenetic analysis using 16S rRNA sequences from 39 spiroplasmas obtained from NCBI database showed that *S. citri* strains, along with *S. kunkelii* and *S. phoeniceum*, two other plant pathogenic spiroplasmas, formed a monophyletic group. To refine genetic relationships among *S. citri* strains, phylogenetic analyses with 863 core orthologous sequences were performed. Strains that clustered together were: CC-12 and C5; C189 and R8-A2; BR12, BLH-MB, BLH13 and LB 319. Strain GII3-3 remained in a separate branch. Sequence rearrangements were observed among *S. citri* strains, predominantly in the center of the chromosome. One to nine plasmids were identified in the seven *S. citri* strains analyzed in this study. Plasmids were most abundant in strains isolated from the beet leafhopper, followed by strains from carrot, Chinese cabbage, horseradish and citrus, respectively. All these *S. citri* strains contained one plasmid with high similarity to plasmid pSci6 from *S. citri* strain GII3-3X which is known to confer insect transmissibility. Additionally, 17 to 25 prophage-like elements were identified in these genomes, which may promote rearrangements and contribute to repetitive regions.

Conclusions

The genome of seven *S. citri* strains were found to contain a single circularized chromosome, ranging from 1.58 Mbp to 1.74 Mbp and 1,597-2,232 protein-coding genes. These strains possessed a plasmid similar to pSci6 from the GII3-3X strain associated with leafhopper transmission. Prophage sequences found in the *S. citri* genomes may contribute to the extension of its host range. These findings increase our understanding of *S. citri* genetic diversity.

Background

Spiroplasmas are wall-less, gram-positive bacteria with mobile helical cells. The bacteria are fastidious, culturable in cell-free media [1], and have a diverse host range [2]. Spiroplasmas are found in many arthropods including bees, flies, mosquitos, scorpion flies, beetles, and ticks [2] and have host relationships that range from commensal, mutualistic and pathogenic [3]. Plant pathogenic spiroplasmas cause economic damage to crops and ornamentals. These pathogens include: *Spiroplasma citri*, causal

agent of citrus stubborn disease (CSD) [4], brittle root of horseradish [5] and carrot purple leaf [6]; *S. kunkelli*, is the causal agent of corn stunt [7]; and *S. phoeniceum* were isolated from periwinkle showing symptoms typical of mycoplasma-like organisms [8]. Plant pathogenic spiroplasmas are transmitted in a persistent propagative manner by leafhoppers. Vectors of *S. citri* are the beet leafhopper (BLH), *Neolaliturus* (syn. *Circulifer) tenellus* (Baker) [9] in North America and *Circulifer haematoceps* (Mulsant et Rey) in the Mediterranean region [10]. *S. kunkelli* is transmitted by *Dalbulus maidis* (DeLong) [7] and *S. phoeniceum* was experimentally transmitted by *Macrosteles fascifrons* (Stål) [8].

Characterization of spiroplasmas have been based on morphological and biological properties. However, because growth, metabolism, and DNA-DNA relatedness studies are time consuming, serological tests (deformation tests and enzyme-linked immunosorbent assays) are used for identification of new spiroplasma groups by the International Subcommittee on the Taxonomy of Mycoplasmatales according to Gasparich *et al* [2, 11]. Recently, long-read high-throughput sequencing technology and whole genome sequencing of bacteria have become cost-effective and offers a precise method to differentiate bacterial species and strains that have highly repetitive regions in its genome [12, 13].

The pathogen's wide host range and vector transmission serve as bottlenecks and drivers of genetic diversity of *S. citri* populations. In this study, whole-genome sequences of seven strains of *S. citri*, collected in different locations, times, and hosts, were analyzed with other *S. citri* strains and other spiroplasmas from plants and arthropods provided insight into the evolution and diversity of *S. citri* and is presented herein.

Results

Genome assembly and annotation

Cultures of six strains of *Spiroplasma citri* were established and sequences reported previously (Table 1) [14, 15] and a new strain, C5, is reported here. Briefly, *S. citri* strains C189 and LB 319 were isolated from the woody crop, citrus. BR12, CC-2, and C5 strains were isolated from the seasonal crops such as horseradish, Chinese cabbage, and carrot, respectively. BLH-13 and BLH-MB strains were isolated from the BLH. The complete genomes of the six strains were acquired using the long-read technology, PacBio [14, 15] and C5 was obtained using Nanopore sequencing technology. Sequences from each strain were assembled into single chromosomal contigs. Contigs that did not associate with the chromosome were designated as putative plasmids (Table 2). The chromosome and plasmid status of each contig were further confirmed by BLASTn analyses against the GenBank database Release 236 (Supplementary Table S1). The circular chromosome for all seven strains ranged from 1,576,550 to 1,742,208 bp, with an average G + C content of 25.4%. Total genome size ranged from 1,611,714 to 1,832,173 bp in strains isolated from plants and 1,968,976 to 2,155,613 bp in strains isolated from the BLH. Annotation of each contig was performed by the NCBI Prokaryotic Genome Annotation Pipeline (PGAP), which predicted 32 tRNA genes, three rRNA genes and protein-coding genes which ranged between 1,597 and 2,232. Extrachromosomal DNAs, characterized as putative plasmids varied in all the strains viz., one or two

plasmids from citrus, two plasmids from horseradish, three plasmids from Chinese cabbage, seven plasmids from carrot, and eight or nine plasmids from the BLH. Putative plasmid sizes ranged from 2,047 bp to 135,023 bp (Supplementary Table S1). Seven of the 32 plasmids identified in these seven strains could not be circularized and further research is needed to determine if they are linear or products of sequencing error or culturing conditions.

Table 1
Spiroplasma citri strains analyzed in this study

Strain	Host	Location	Year of collection	Reference
C189	Citrus	Riverside, California	1960	[15]
LB 319	Citrus	Ducor, California	2007	[15]
BR12	Horseradish	Collinsville, Illinois	1984	[15]
CC-2	Chinese cabbage	Fresno, California	2016	[14]
C5	Carrot	Bakersfield, California	2005	This study
BLH-13	Beet leafhopper	Mettler, California	2010	[15]
BLH-MB	Beet leafhopper	Parlier, California	2011	[15]

Table 2
Genome assembly statistics for *Spiroplasma citri* strains analyzed in this study.

<i>Spiroplasma citri</i> strain	<i>S. citri</i> C189 ¹	<i>S. citri</i> LB 319 ²	<i>S. citri</i> BR12 ³	<i>S. citri</i> CC-2 ⁴	<i>S. citri</i> C5 ⁵	<i>S. citri</i> BLH-13 ⁶	<i>S. citri</i> BLH-MB ⁷
Chromosome size (bp)	1577041	1734522	1731112	1709192	1618536	1576550	1742208
Combined size of plasmids (bp)	34663	95488	101061	82444	126436	392426	413405
Chromosome + plasmid size (bp)	1611704	1830010	1832173	1791636	1795359	1968976	2155613
No. of plasmids	1	2	2	3	7	8	9
Chromosome GC content (%)	25.6	25.4	25.4	25.6	25.6	25.4	25.4
Total no. genes	1946	2207	2200	2068	2064	2594	2411
Total protein-coding genes	1597	1853	1876	1716	1701	2232	2082
Total rRNA genes	3	3	3	3	3	3	3
Total tRNA genes	32	32	32	32	32	32	32
¹ Accessions: CP047426.1, CP047427.1 [15]							
² Accessions: CP046371.1 - CP046373.1 [15]							
³ Accessions: CP046368.1 - CP046370.1 [15]							
⁴ Accessions: CP042472.1 - CP042475.1 [14]							
⁵ Accessions: CP053304.1 - CP053311.1 (this study)							
⁶ Accessions: CP047428.1 - CP047436.1 [15]							
⁷ Accessions: CP047437.1 - CP047446.1 [15]							

Phylogenomics

Molecular phylogenetic inference of 39 spiroplasmas was performed using 16S rRNA genes in the NCBI database. Analysis of this gene sequence indicated that *S. citri* strains are closely related, but not

identical. The phylogeny inferred from the 16S rRNA gene shows that *S. citri* strains formed a monophyletic group with plant pathogenic *S. kunkelii*, *S. phoeniceum*, and a honeybee pathogen, *S. melliferum* (Fig. 1). To facilitate a high-resolution comparison of *S. citri* strains, core genomes were analyzed for nine *S. citri* genomes available in NCBI. Using the orthoMCL pipeline, a total of 863 orthologous genes were identified as conserved among the *S. citri* strains. The 863 orthologous genes were concatenated, and a maximum-likelihood approach was employed to generate a *S. citri* phylogeny (Fig. 2). Phylogenetic analyses with the core orthologous sequences among the *S. citri* strains showed that CC-2 isolated from Chinese cabbage and C5 strain isolated from carrot are in the same clade. Citrus strains C189 from southern California and R8-A2 from Morocco clustered together. The citrus strain LB 319, BLH-13 and BLH-MB from central California, and BR12 from horseradish in Illinois clustered together. There was clear separation of *S. citri* from *S. kunkelii* (Supplementary Figure S1). The phylogenetic tree resulting from analysis of core orthologous genes established that strains isolated from citrus were very closely related. Strains from the BLH were more closely related to strains isolated from citrus than those isolated from Chinese cabbage and carrot. *S. citri* strain GII3-3X, isolated from *C. haematopceps*, did not group with strains isolated from BLHs from California, but this may be due to the incomplete genome sequence of GII3-3X.

Comparative genomics

The circular chromosome of the seven *S. citri* strains from the U.S. were compared via BLASTn to the R8-A2 strain from citrus in Morocco as the reference sequence. Visualization of these results was performed using the BLAST Ring Image Generator (BRIG). This genome level comparison among *S. citri* strains isolated from different sources showed a high level of homogeneity among each other and the reference genome, R8-A2 (Fig. 3). *S. citri* strains C189, LB 319, and BR-12, which were isolated from citrus and horseradish, appear most similar to R8-A2. A large region of dissimilarity near the middle of the chromosome is notable in the BLH-13 strain, ranging from ~ 600kbp to ~ 800kbp. These differences were not found in the BLH-MB strain, but some variability in this region can be seen in CC-2 and C5.

Dot matrix pairwise sequence comparisons revealed a highly repetitive region at ~ 1,200 kbp (Supplementary Figure S2). The repetitive region is marked in Fig. 3 as an area of higher dissimilarity in the chromosome among the *S. citri* strains analyzed in this study.

Pairwise whole genome comparisons were performed with *S. citri* strains BLH-13, LB 319, and CC-2 which were selected to represent the biological diversity in this study. This comparison revealed high genome similarity, higher numbers of shared genes, and limited genome re-arrangement as observed in the center region (Fig. 4A). In contrast, genome comparison among different species of plant pathogenic spiroplasmas were examined using LB 319 from citrus, *S. phoeniceum* P40 from periwinkle, and *S. kunkelii* CR2-3X from corn. Here, *S. citri*, *S. kunkelii*, and *S. phoeniceum* showed significant differences in gene content, low level of genome similarity, and extensive genome rearrangements. *S. kunkelii* and *S. phoeniceum* also exhibited fewer regions of genome similarity and extensive genomic rearrangements (Fig. 4B).

Homologous genes were also identified among LB 319, BLH-13, and CC-2 (Fig. 5A). These *S. citri* strains shared 990 core homologous gene clusters, with 42 and 43 homologous gene clusters specific to each of these strains. Among different plant pathogenic *Spiroplasma* spp., LB 319, *S. phoeniceum* P40, and *S. kunkelii* CR2-3X, shared 755 core homologous gene clusters (Fig. 5B). There were 201 to 424 homologous gene clusters specific to *S. phoeniceum* P40 and *S. kunkelii* CR23x, respectively. LB 319 shared 120 homologous gene clusters with *S. phoeniceum*, while sharing only 37 homologous isolated from *S. kunkelii*. Additionally, *S. phoeniceum* and *S. kunkelii* shared 271 homologous gene clusters that were absent from LB-319.

Functional assignment of *S. citri* LB 319 protein-coding sequences

Due to similarity of the chromosome of the seven *S. citri* strains studied, LB 319 was selected for further characterization. LB 319 had 1,750 annotated protein coding sequences (CDS) and the functional classification of these protein coding sequences assigned only 553 CDS (32%) in different clusters of orthologous groups (COGs). The most abundant functional category was DNA replication, recombination and repair, followed by translation. These categories mainly consist of gDNA polymerases, nucleotide repair, DNA topoisomerases, ribosomal proteins and tRNA synthetases genes. Other important functional categories include translation (COG category K), nucleotide metabolism and transport (COG category F) and transcription (COG category O) (Fig. 6). The low number of assigned COGs suggests that a large proportion of them may be fragments of unrecognized pseudogenes.

Plasmid variability between *S. citri* strains

Plasmids are known bacterial virulence factors, but also play important roles in establishing host range [16–19]. Although a high level of similarity was found in the chromosome of *S. citri* strains, more diversity was found in the number of putative plasmids associated with these strains (Fig. 7A). For the sake of this study these putative plasmids are referred to as plasmids since the DNA in 25 of 32 plasmid-like contigs were circularized. Eight and nine plasmids were found in *S. citri* strains isolated from the BLH. Strains isolated from carrot and Chinese cabbage contained seven and three plasmids, respectively. *S. citri* strains isolated from citrus and horseradish possessed one to two plasmids. *S. citri* adhesion-related proteins (ScARPs), which are expected to be involved in *S. citri* adhesion to insect cells [20, 21], were predicted in several plasmids by NCBI's Prokaryotic Genome Annotation Pipeline (PGAP). These ScARPs were present in one plasmid in BR12 and CC-2, two plasmids in C5 and BLH-MB, and three plasmids in BLH-13. These plasmids are highly similar to pSci2 and pSci5 from *S. citri* strain GII3-3X and pBJS-O from *S. citri* strain BR3-3X [22, 23] (Supplementary Table S1). Interestingly, no full-length ScARPs were predicted in C189 or LB 319 plasmids. *S. citri* strain C189, isolated from citrus in 1960, retained only one plasmid, pScp-C189-1. BLAST results revealed that this plasmid was highly similar to plasmid pSci6, identified in *S. citri* strain GII3-3X [22]. All strains analyzed in this study contained at least one plasmid with very high similarity to pSci6. (Fig. 7B). BLH-MB possessed two plasmids which resembled pSci6.

Prophage prevalence in *S. citri* strains

The PHASTER (PHAge Search Tool – Enhanced Release) web server was used to identify and annotate putative prophage regions within the *S. citri* genomes. Seventeen to 25 prophage-like elements were identified in the *S. citri* genomes (Supplementary Figure S3). Plasmid pScpLB319-2 in LB 319 and pScpC5-3 in C5 contained prophage sequences (Supplementary Figure S3 B,E). Two plasmids in BLH-13 (pSciBLH13-1 and pSciBLH13-6) and three plasmids in BLH-MB (pSciBLHMB-1, pSciBLHMB-7, and pSciBLHMB-8) possessed prophage sequences (Supplementary Figure S3 F,G). No prophage sequences were predicted in plasmids from C189, BR12, or CC-2. A large proportion of these prophage sequences were homologous to plectrovirus SpV1 [24] and SVTS2 [25]. While multiple plectrovirus SpV1 sequences were found to be distributed throughout the chromosome, a concentrated area of SVTS2 sequences was found at approximately 1.2Mbp. This region of the chromosome was found to have highly repetitive sequences in all *S. citri* genomes in this study as shown by dot-matrix pairwise sequence comparisons (Fig. 3, Supplementary Figure S2). Further characterization of the prophage regions in the chromosome and plasmid will be examined in the future.

Discussion

Prior to advances in long-read sequencing, the best assembly of *S. citri* was strain GII3-3X, which contained 39 chromosomal contigs [22]. The first sequence of *S. citri* containing a single chromosomal contig was reported from Morocco in 2017, *S. citri* R8-A2^T [26]. Complete genomes, with single chromosomal contigs, of six more strains of *S. citri* isolated in the United States were reported in 2020 [14, 15] and a seventh strain, C5, isolated from carrot, is reported in this study. Chromosome sizes of these genomes were similar in size to that of the Moroccan strain (~ 1.6Mbp), although most of the U.S. strains were slightly larger in size. Additionally, the number of predicted protein coding regions was higher in U.S. strains compared to R8-A2^T genome. One set of rRNA genes and 32 tRNA genes were predicted in U.S. strains, which is consistent with the R8-A2^T strain [26].

A high level of homology and synteny was observed between the *S. citri* strains in this study, with some dissimilar regions and genomic rearrangements appearing in the center region of the chromosome. However, comparison with the most closely related species, *S. phoeniceum* and *S. kunkelii*, showed that the chromosomal organization is largely rearranged and exhibits much lower levels of sequence similarity. *S. phoeniceum* is associated with lethal yellows in periwinkle [27], while *S. kunkelii* causes corn stunt disease of *Zea mays* L. [28]. Large rearrangements were also observed when comparing *S. citri* to *S. melliferum*, a honeybee pathogen [29]. When comparing gene content, *S. citri* strains shared approximately 80% of the homologous gene clusters observed, with about 3% of gene clusters being unique to each strain. However, *S. citri* strain LB 319 shared approximately 64% of gene clusters with *S. phoeniceum* and *S. kunkelii*, while about 23% of gene clusters were unique to *S. citri*. These differences may be caused by differential gene loss, phage-mediated horizontal gene acquisition and by ecological and biological diversification [29, 30]. Moreover, some of this variation may be due to variation in prophage sequences [31], which are viral or phage genomic DNA sequences integrated into a bacterial genome. *S. citri* is highly susceptible to viral invasion, due to its lack of a cell wall [32]. Between seventeen

and twenty-five areas of the genome were predicted to contain prophage insertions in the *S. citri* genomes studied which contributed to the variations in chromosome size. The majority of these sequences in *S. citri* are homologous to SpV1, a plectrovirus, located throughout the genome [31] and supported results from the PHASTER analysis. SpV1 viral sequences have been associated with major variations of the *S. citri* genome [33]. These viral sequences, integrated into the *Spiroplasma* chromosome, can have a large effect on genome stability. A model for the evolution of the *Spiroplasma* genome has been linked to viral invasion, which could account for intraspecific genome size variation, low conservation in chromosomal organization, and a gain of lineage-specific genes [30]. The rearrangements and genome instability are apparent in pairwise comparisons of *S. citri* strains, and even more so when compared to their closest relatives, *S. phoeniceum* and *S. kunkelii*. Viral invasions likely promoted these rearrangements in plant pathogenic bacteria and could attribute to their adaptation to different hosts. In contrast to SpV1, phage sequences homologous to SVTS2 were present in one specific region in all the *S. citri* strains studied. Integration of SVTS2 viral sequences into the chromosome of *S. citri* has been associated with the resistance of *S. citri* to spiroplasma virus SVTS2 [34]. This may be why SVTS2 sequences are not prevalent throughout the genome and the region containing SVTS2 sequences appears to be consistent across strains.

Every *S. citri* strain studied had a unique pattern of extrachromosomal DNA and the presence or absence, position (free or integrated), and number of these sequences is a significant source of variation among strains [35]. After several years of maintenance in plants, *S. citri* strain BR3-G showed chromosomal rearrangements compared to strain BR3-T, which was transmitted from plant to plant by the BLH [33]. Strain BR3-G was found to be non-transmissible by the BLH which was correlated to a large deletion of a SpV1-related transposase gene [33]. Prolonged cultivation of bacteria has been reported to cause free plasmid DNA to be integrated into the chromosome through recombination events [36–38]. Strains isolated from BLH examined in this study contained two or three plasmids with predicted prophage sequences. The strains isolated from plants exhibited one or no plasmids with predicted prophage sequences. The plasmids that contain viral sequences were homologous to those in the chromosome of *S. citri* strain R8-A2. It is plausible that after transmission by the BLH to plants, plasmids containing viral sequences could be incorporated by recombination with chromosomal plectroviral sequences. This would result in fewer plasmids in perennial plants compared to annual plants, which was observed in this study.

Plasmids of phytoplasmas and spiroplasmas are known to be involved in insect transmissibility [39–42]. All the newly sequenced *S. citri* strains contained at least one plasmid with high homology to plasmid pSci6, identified in *S. citri* strain G13-3X [22]. pSci6 plasmid encodes P32 protein, associated with insect transmissibility, and this plasmid confers insect transmissibility into non-transmissible strains of *S. citri* [43, 44]. Several other genes have been assigned putative functions in this plasmid. This included *soj-parA*, which is involved in DNA partitioning, and *traG* and *mob*, which are associated with DNA transfer and are suggested to be involved in a type IV secretory pathway [22]. A coding region was also identified in plasmid pScp-C189-1, which has homology to a plasmid replication-relaxation (relaxase) family protein. Plasmids in *S. citri* have been suggested to be horizontally transferred between cells by conjugation [22]. Several important genes are at the core of plasmid conjugation, including type IV

coupling proteins and relaxases [45]. The *traG* and *mob* genes found in pSci6 correspond to VirB4/D4 components of the type IV secretion pathway, which allows for the translocation of DNA through cytoplasmic membranes [46]. Walled bacteria require many components in their conjugation system; however, these components may not be necessary in *S. citri*, a wall-less bacterium. In addition to *traG* and *mob*, Saillard *et al.* suggested that pSci6 should contain a relaxase, but this family of proteins was not reported [22]. The replication-relaxation (relaxase) family protein is essential for plasmid replication and plasmid DNA relaxation, part of conjugative DNA transfer in bacteria [47–49]. A BLAST search of the coding sequences in pScp-C189-1 revealed homology to a replication-relaxation family protein. This further supports previous studies that reported genetic exchanges by a conjugation-like process in *S. citri* [50]. The fact that this plasmid is present in all our sequenced *S. citri* strains suggests it may play an important role in insect transmission and extension of the host range of this pathogen.

Conclusion

Six *Spiroplasma citri* strains were previously sequenced [14, 15] and a seventh strain, C5, was *de novo* assembled in this study. Collectively, these data greatly expanded the availability of *S. citri* genomes and allowed performance of extensive comparative genomic studies that provide insights into this organism's genetic diversity and evolution. An extremely high level of homogeneity was observed in the chromosomal contigs across *S. citri* strains. Variation in plasmid number may play an important role in insect transmission and extension of *S. citri* host range. Moreover, differences in genome size and stability appear to result from variations in number and site of plectroviral sequences inserted into the genome. These features likely contribute to *S. citri* adaptation to different hosts and transmissibility by leafhopper vectors. Further studies will be necessary to validate the roles of plasmids and viral insertion sequences in *S. citri* strains isolated from various hosts.

Methods

Strain isolation and DNA preparation

Cultures of *S. citri* strains CC-2, C189, BR-12, LB 319, BLH-13, and BLH-MB were isolated and DNA extracted in a previous study [14, 15]. *S. citri* strain C5 was collected in 2005 from carrot growing in NW Bakersfield, California. Briefly, *S. citri* was isolated and grown in LD8 medium [51]. Later the cultures were triple cloned and stored at -80 °C until further use. Cultures were re-established and total genomic DNA was extracted by CTAB [52] or by DNeasy Blood and Tissue Extraction kit (Qiagen). Collection details of *S. citri* in this study are listed in Table 1.

Whole-genome shotgun sequencing

S. citri strain C5 was sequenced on the Oxford Nanopore (Oxford, United Kingdom) MinION platform [53]. The library was prepared with Oxford Nanopore (Oxford, United Kingdom) Rapid Barcoding Kit-SQK-RBK004 according to the manufacturer's specifications. Data was collected using MinION Release 19.10.1. Bases were called using Guppy v.3.4.5 and the adapter screening and quality filtering of raw

sequencing data were performed using Fastp v 0.20.0 [54]. Remaining *S. citri* strains' genomes were sequenced previously on PacBio (Menlo Park, CA, USA) RS II platform [14, 15].

De novo sequencing assembly

Sequences from *S. citri* strains CC-2, C189, BR-12, LB 319, BLH-13, and BLH-MB were reported previously [14, 15]. Briefly, raw reads were filtered, subreads were established by PacBio, and assembled into contigs using Canu 1.8 [55]. For *S. citri* strain C5, contigs were assembled using Canu 1.8. An additional polishing step was performed by medaka v 1.0.3 (Oxford Nanopore Technologies) and frame-shift-corrected by DIAMOND v 0.9.28 [56] and MEGAN v 6.18.4 [57], following the pipeline described by Arumugam *et al.* [58]. Approximately ~ 500 bp segments from each end of a contig were used for BLASTn search to check the contig singularity. Appropriate reads connecting both ends were used for enclosure. The chromosome and plasmid status of each contig were further confirmed by BLASTn analyses against the GenBank database. The genome sequence data was deposited in the NCBI database (accession numbers shown in Table 2). Annotation of each contig was performed by the NCBI Prokaryotic Genome Annotation Pipeline (PGAP) [59].

Phylogenetic analyses

The 16S rRNA sequences of thirty-nine *Spiroplasma* species were obtained from the NCBI database. Sequence alignments were carried out with the PRANK alignment tool [60]. Maximum-likelihood approach was used to reconstruct the phylogenetic tree using RAxML software [61]. Bootstrapping was performed with 1,000 replicates. The resulting phylogeny was visualized with FigTree [62].

Orthologous genes of *S. citri* isolates were predicted using the OrthoMCL v. 2.0 pipeline [63]. All-versus-all BLASTN (E value $< 10^{-5}$, alignment coverage $> 50\%$) comparison of all gene sequences for each species was performed and orthologous genes were clustered by OrthoMCL v. 2.0. Multiple sequence alignments was done with PRANK v. 170427 [64]. The sequence alignments were concatenated by FASconCAT v. 1.1, yielding a gene super-matrix [65]. Maximum-likelihood approach was used to reconstruct the phylogenetic tree using RAxML v. 8.2 software with 1,000 bootstrap replicates [61]. The resulting phylogeny was visualized using FigTree v. 1.4.3 [62].

Bioinformatics analysis

Large genome comparison of eight *S. citri* sequences was computed and visualized with the use of BLAST Ring Image Generator (BRIG) v 0.95 [66]. Pairwise genome alignment was achieved by the Lastz v. 1.04 program [67]. The results were visualized using AliTV v. 1.0 [68]. Shared and genome-specific genes were identified between the *S. citri* strains isolated from different sources and among *S. citri* LB 319, *S. kunkelii* CR2-3X and *S. phoeniceum* P40. The sequence similarity search step in the OrthoMCL analysis was conducted at the nucleotide level [63]. Functional annotation of COG was done using eggNOG-mapper [69]. Prophage sequences were predicted using PHASTER online server [70].

Abbreviations

PGAP

Prokaryotic Genome Annotation Pipeline

CSD

citrus stubborn disease

CC

Chinese cabbage

LB

Liberty Bell

BR

brittle root

BLH

beet leafhopper

BRIG

BLAST Ring Image Generator

COG

cluster of orthologs groups

ScARPs

S. citri adhesion-related proteins

PHASTER

PHAge Search Tool – Enhanced Release

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

The data described in this study can be freely and openly accessed from the NCBI database. All sequence data has been deposited in GenBank under the accession numbers CP042472-CP042475, CP0426368-CP046373, CP047426-CP047446, and CP053304-CP053311. The versions described in this paper are the first versions. PacBio sequencing reads for BioProject PRJNA558054 have been deposited in the NCBI Sequence Read Archive (SRA) under accession number SRR9903453 for CC-2. PacBio sequencing reads for BioProject PRJNA591027 have been deposited in the NCBI SRA under accession numbers SRR10843927 for C189; SRR10507068 for LB 319; SRR10507067 for BR12; SRR10507065 for BLH-13; and SRR10507066 for BLH-MB. Nanopore sequencing reads for BioProject PRJNA625113 have been deposited in the NCBI SRA under accession number SRR11536473 for C5. *S. citri* cultures for BLH-13,

BLH-MB, BR12, LB 319, and CC-2 have been deposited in ATCC no. SD-7532-7535 and SD-7278, respectively. However, ATCC Biorepository Service Agreement 2019-BRS-00049 maintains confidentiality of information regarding these cultures. C189 and C5 cultures are available from the corresponding author.

Competing interests

The authors declare that they have no competing interests.

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Author contributions

RKY, GV, FO and DP conceptualized the study and acquired the *S. citri* cultures. Funds for this research were from grants to RKY and GV. DP, YM, and VS cultured the pathogens and purified the DNA. FO supervised the PacBio submissions. AE and TD cultured, purified DNA, and provided raw sequence data for *S. citri* strain C5, JC provided technical assistance for genome assembly and bioinformatics, SH provided some technical assistance. RR and ST conducted data curation and analysis. RR, ST and RY wrote the manuscript and DP, SH, JC, GC, and GV edited the manuscript. All authors read and approved the final manuscript.

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Figures

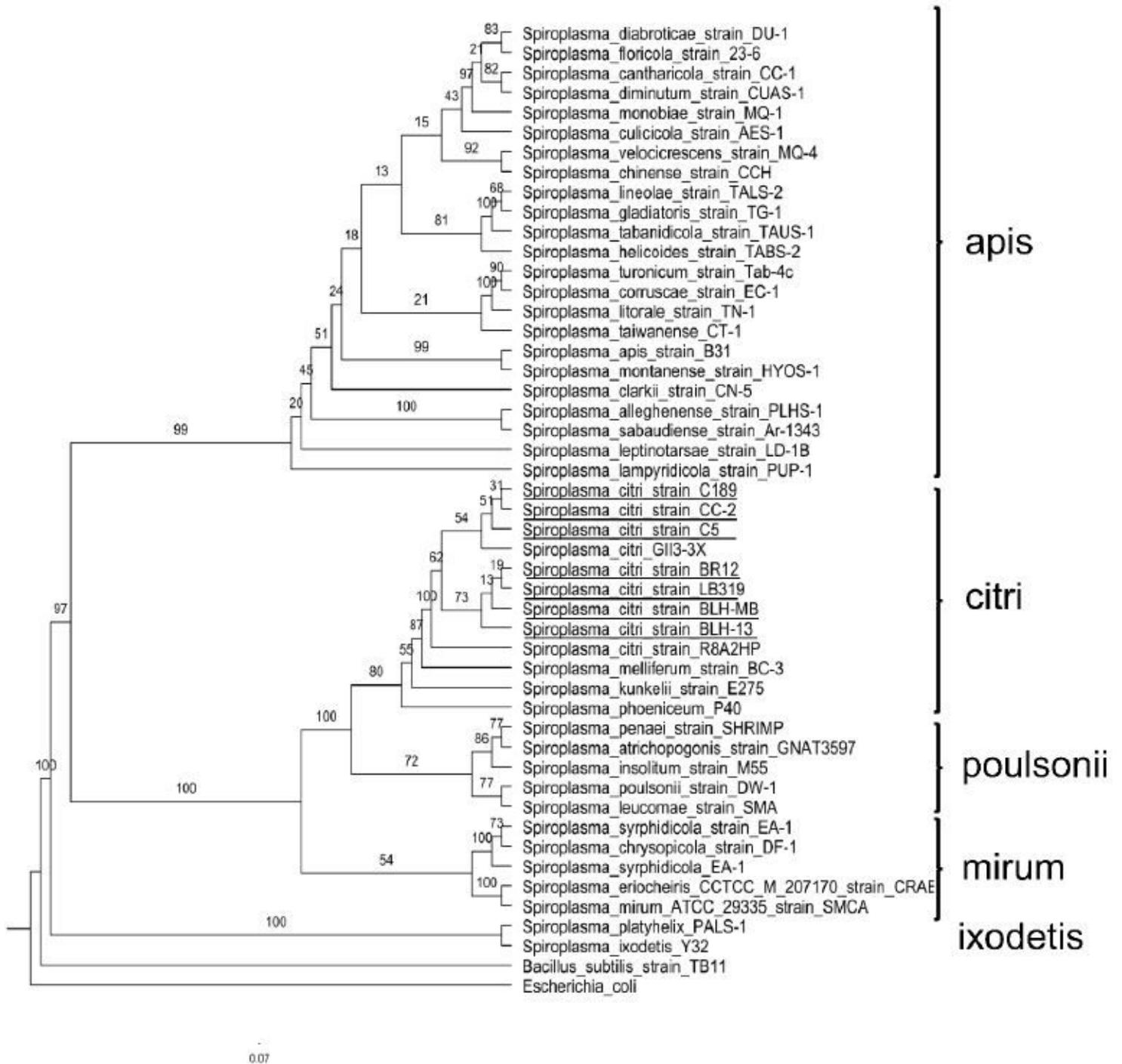


Figure 1

Maximum-likelihood 16S rRNA phylogenetic analysis of *Spiroplasma* species. A maximum-likelihood approach was used to generate the phylogeny with 1,000 bootstrap replicates. Bootstrap values are indicated at each node. The resulting phylogeny was visualized using FigTree v. 1.4.3 [62]. *S. citri* strains analyzed in this report are underlined.

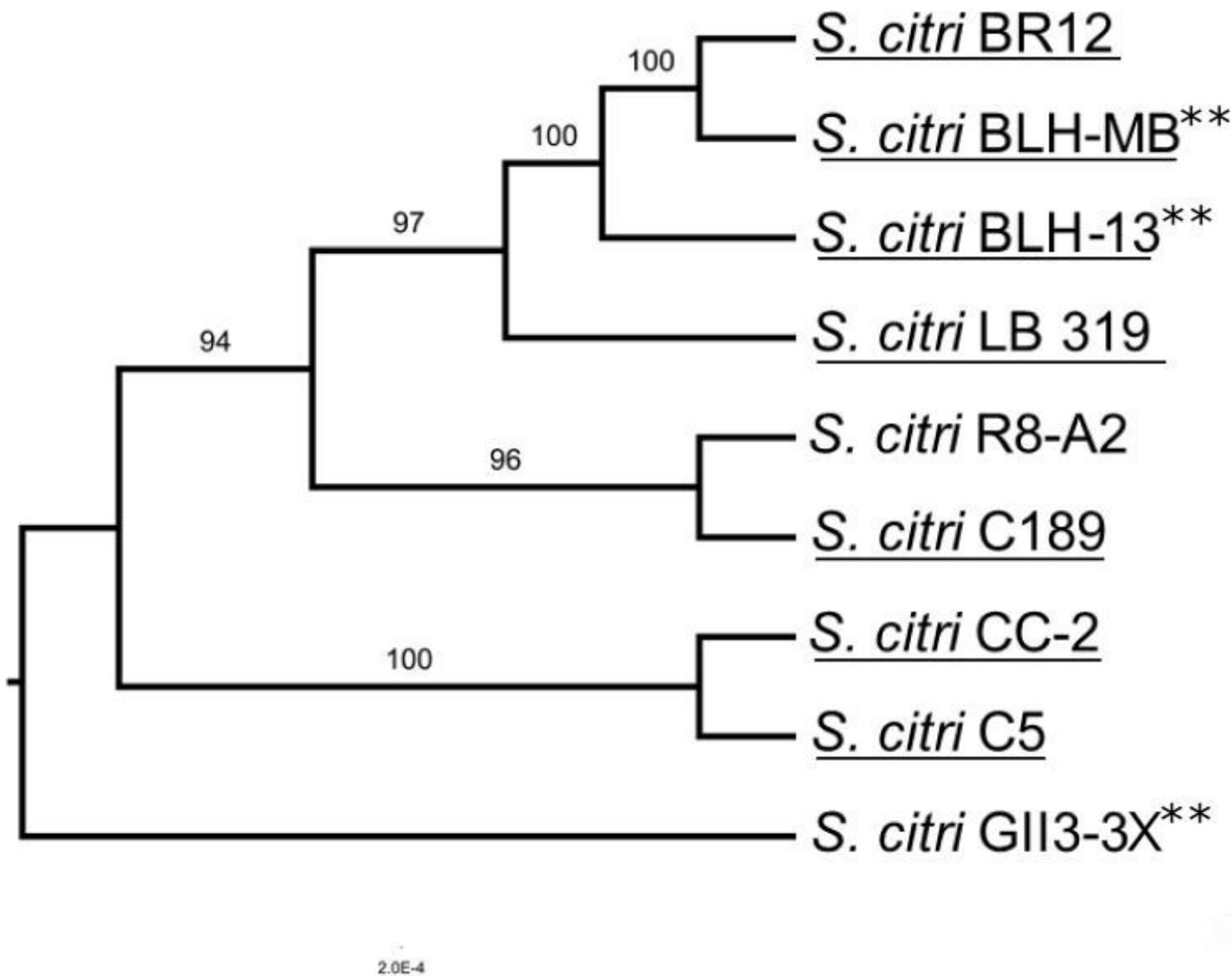


Figure 2

Phylogenetic analysis of *Spiroplasma citri* strains. Maximum-likelihood phylogeny of *Spiroplasma* based on core orthologous genes. In total, 863 orthologous genes were concatenated, and a maximum-likelihood approach was used to generate the phylogeny with 1,000 bootstrap replicates. Bootstrap values are indicated at each node. The resulting phylogeny was visualized using FigTree v. 1.4.3 [62]. *S. citri* strains analyzed in this report are underlined. Strains isolated from beet leafhopper have been marked with asterisks (**).

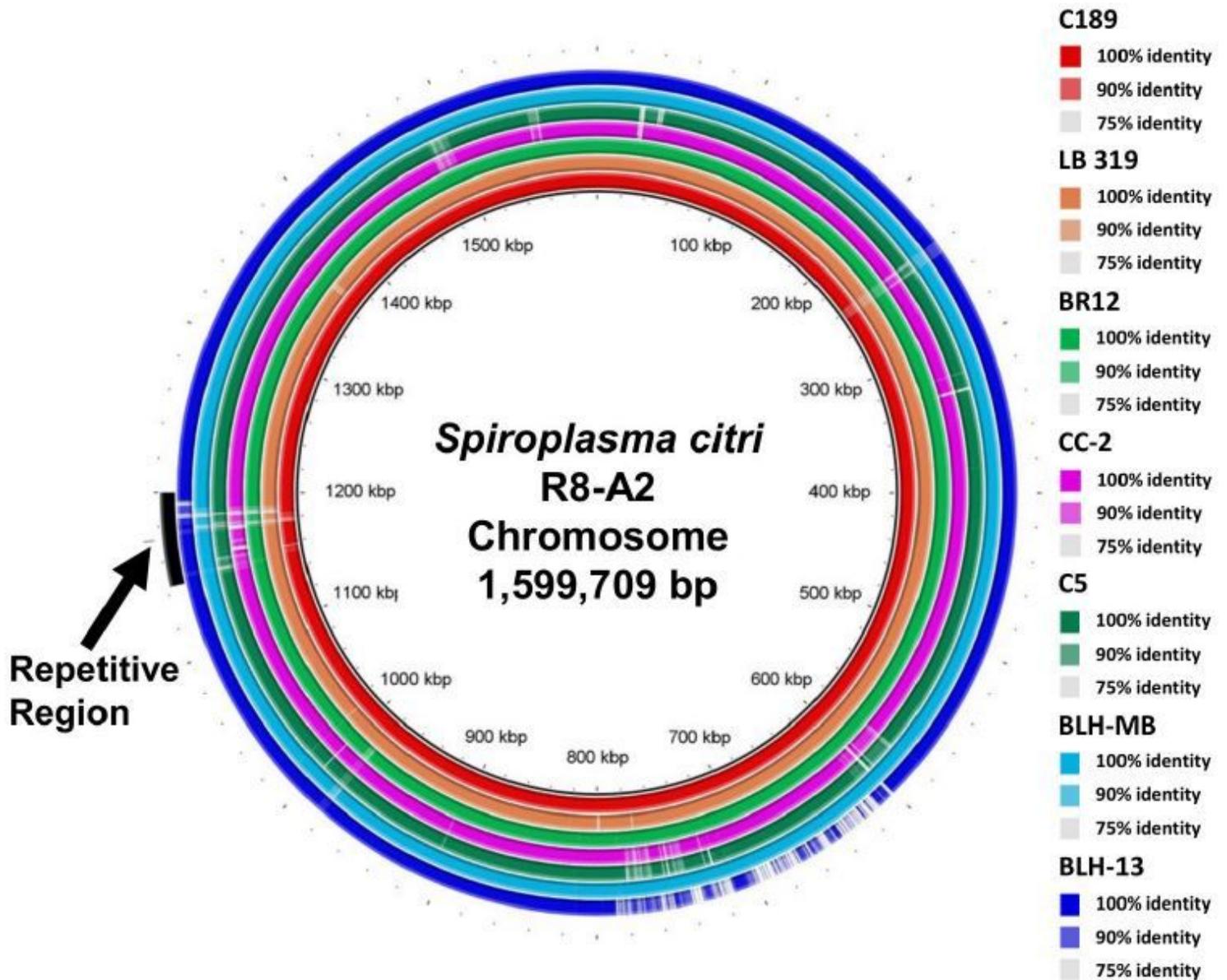


Figure 3

BLASTn results of *Spiroplasma citri* chromosomes. Whole genome comparison of eight *S. citri* strains visualized by BLAST Ring Image Generator (BRIG) [66]. *S. citri* strain R8-A2 was used as a reference. Each of the illustrated rings refers to one *S. citri* strain's chromosome, according to the listed coloration. White regions represent dissimilarity from the reference genome. A highly repetitive region, marked in this image, was revealed during dot matrix pairwise sequence comparisons (Supplementary Figure S2).

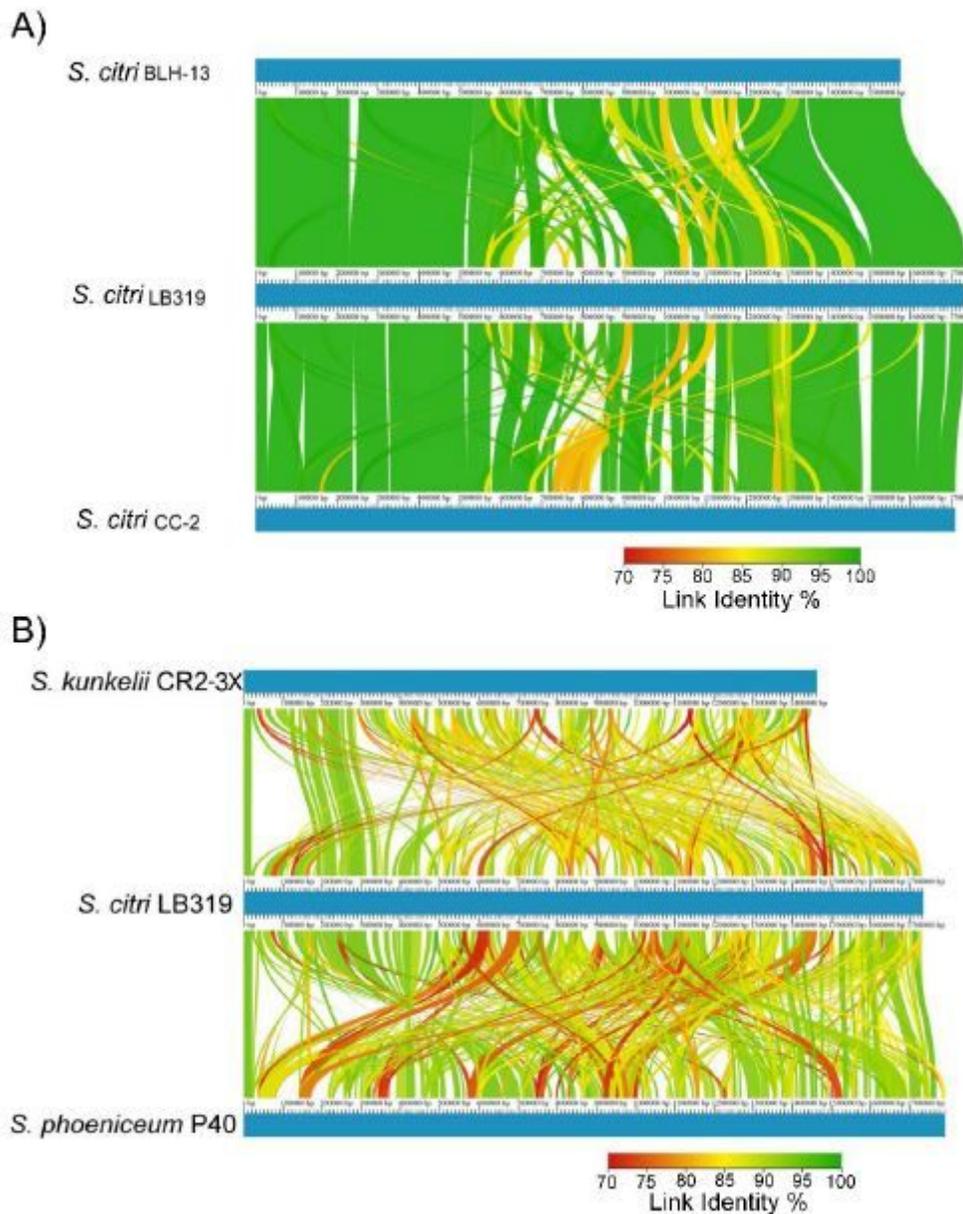


Figure 4

Genome-wide comparison of pathogenic Spiroplasma species. Linear chromosomal maps were built using AliTV v. 1.0 visualization software [68], based on whole-genome alignments with Lastz v. 1.0.4 aligner [67]. Both panels depict pairwise comparisons, expressed as percentage of nucleotide similarity, that connect different homologous genomic regions. Chromosomes are completely finished and pictured in blue. (A) *S. citri* strains BLH-13 isolated from the beet leafhopper (BLH), LB 319 isolated from citrus and CC-2 isolated from Chinese cabbage. (B) *S. citri* LB 319, *S. phoeniceum* P40 and *S. kunkelii* CR2-3X.

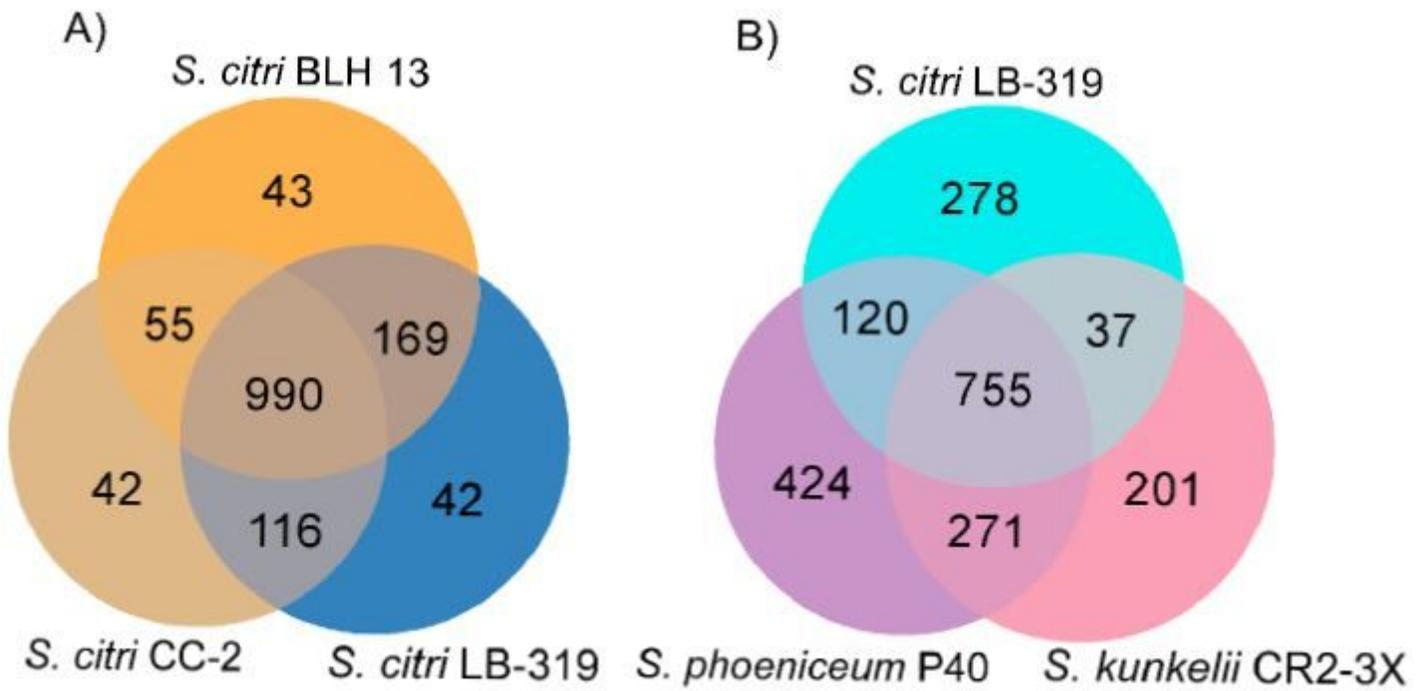


Figure 5

Numbers of shared and genome-specific homologous gene clusters. The Venn diagrams show the number of shared and genome-specific homologous gene clusters among the genomes compared. (A) Comparison among *Spiroplasma citri* BLH13, CC-2, and LB 319. (B) Comparison among *S. citri* LB 319, *S. phoeniceum* P40, and *S. kunkelii* CR2-3X.

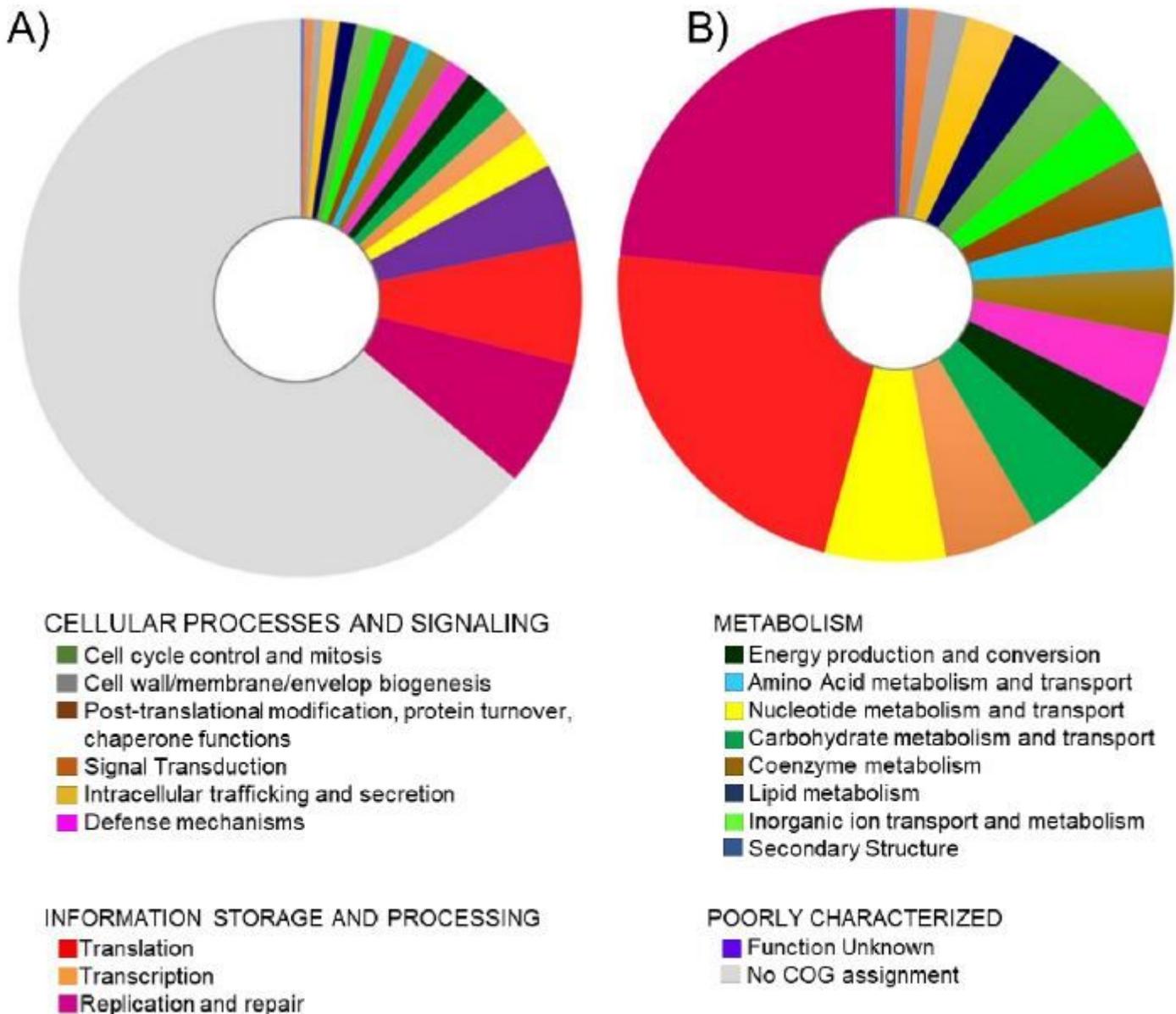


Figure 6

Functional classification of protein-coding genes in *S. citri* LB 319. The functional categorization of each protein-coding gene was classified according to the COG assignments. The pie graph indicates the COG distribution statistics. Each color represents a COG functional description. A) All annotated protein-coding genes in the *S. citri* LB 319 genome. B) Protein-coding genes that could be assigned functional category.

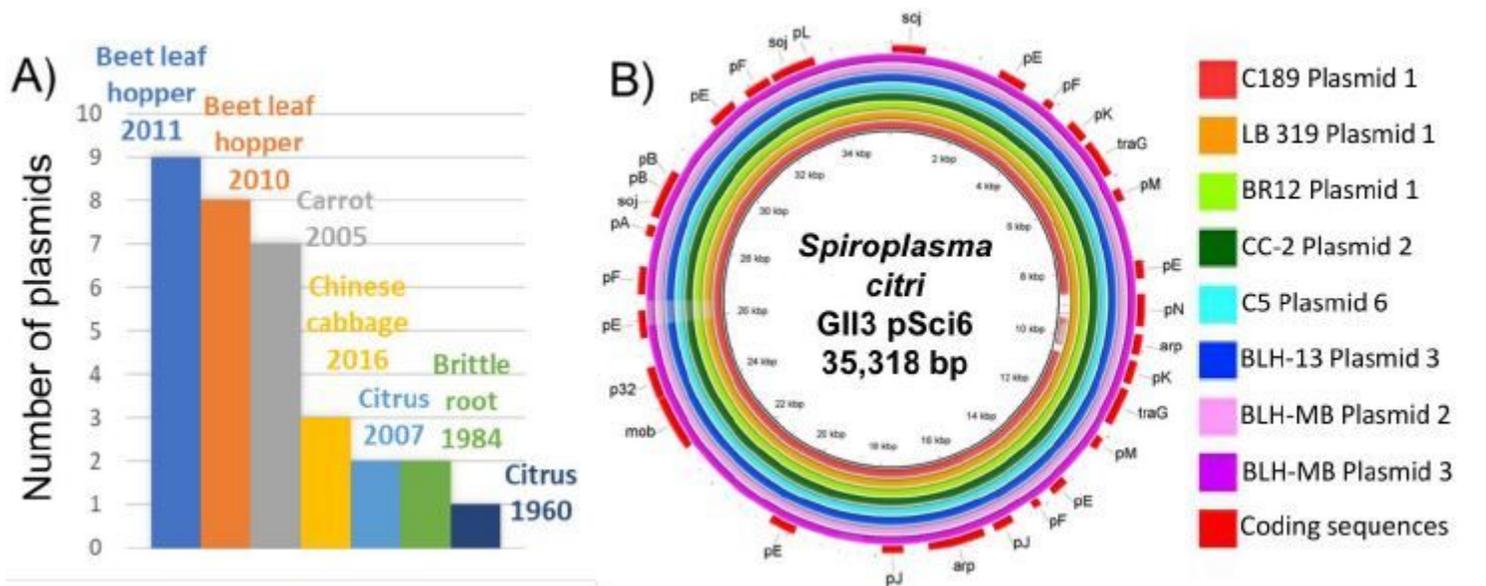


Figure 7

Analysis of *Spiroplasma citri* plasmids. A) Number of plasmids from each of the *S. citri* strains analyzed in this study. Each bar represents one strain and is labeled with the host that strain was collected from and the year collected. B) BLASTn results of conserved *S. citri* plasmid. Whole genome comparison of conserved *S. citri* plasmid visualized by BLAST Ring Image Generator (BRIG) [66]. Plasmid pSci6, identified in *S. citri* strain GII3-3X [22], was used as a reference. Each of the illustrated rings refers to *S. citri* plasmids identified in the seven other strains analyzed in this study that were closely related to pSci6. Lighter regions represent dissimilarity from the reference plasmid. Outermost ring denotes coding sequences and is labeled with gene names. pA-pN represent hypothetical proteins, as named in GenBank accession AJ969074 [22].

Supplementary Files

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