Cyclitol metabolism is a central feature of Burkholderia leaf symbionts

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Abstract

The symbioses between plants of the Rubiaceae and Primulaceae families with *Burkholderia* bacteria represent unique and intimate plant-bacterial relationships. Many of these interactions have been identified through PCR-dependent typing methods, but there is little information available about their functional and ecological roles. We assembled seventeen new endophyte genomes representing endophytes from thirteen plant species, including those of two previously unknown associations. Genomes of leaf endophytes belonging to *Burkholderia s.l*. show extensive signs of genome reduction, albeit to varying degrees. Except for one endophyte, none of the bacterial symbionts could be isolated on standard microbiological media. Despite their taxonomic diversity, all endophyte genomes contained gene clusters linked to the production of specialized metabolites, including genes linked to cyclitol sugar analog metabolism and in one instance non-ribosomal peptide synthesis. These genes and gene clusters are unique within *Burkholderia s.l.* and are likely horizontally acquired. We propose that the acquisition of secondary metabolite gene clusters through horizontal gene transfer is a prerequisite for the evolution of a stable association between these endophytes and their hosts.

Introduction

Interactions with microbes play an important part in the evolution and ecological success of plants. For example, mycorrhizal associations are present in a vast majority of land plants, and the association with nitrogen-fixing bacteria provided legumes with an important evolutionary advantage (Brundrett, 1991; van Rhijn and Vanderleyden, 1995; Vessey *et al.*, 2005; Smith and Read, 2008). Nevertheless, microbes may also be harmful for plants as microbial pathogen interactions are responsible for major crop losses (Dangl and Jones, 2001; McCann, 2020). Many plant-microbe interactions only occur temporarily: contacts between microbes and the host are often limited to a sub-population or a specific developmental phase of the host. However, in some associations microbes are transferred from parents to offspring in a process called vertical transmission, resulting in permanent associations with high potential for co-evolution (Gundel *et al.*, 2017). While vertically-transmitted microbes are common in the animal kingdom, they have been more rarely described in plants (Fisher *et al.*, 2017).

A particular case of vertically transmitted microbes in plants are the bacterial leaf endophytes found in three different plant families: the monocot Dioscoreaceae, and the dicot Rubiaceae and Primulaceae. In the genera *Psychotria*, *Pavetta*, *Sericanthe* (Rubiaceae) and *Ardisia* (Primulaceae) this association may manifest in the form of conspicuous leaf nodules that house extracellular symbiotic bacteria (Miller, 1990; Van Oevelen *et al.*, 2002; Lemaire, Robbrecht, *et al.*, 2011; Lemaire, Van Oevelen, *et al.*, 2012; Ku and Hu, 2014). In some of these systems, the symbiont was detected in seeds, indicating that they can be transmitted vertically (Miller I. M., 1987; Sinnesael *et al.*, 2018). Molecular analysis of the leaf nodules revealed that all endophytes are members of the *Burkholderia sensu lato*, more specifically to the newly defined *Caballeronia* genus (Van Oevelen *et al.*, 2002; Ku and Hu, 2014). Similar leaf endophytes, also belonging to the *Burkholderiaceae,* are present in Rubiaceae species that do not form leaf nodules, including some *Psychotria species* (Lemaire, Lachenaud, *et al.*, 2012; Verstraete *et al.*, 2013). To date, only one symbiont of Rubiaceae and Primulaceae has been cultivated: the endophyte of *Fadogia homblei*, which has been identified as *Paraburkholderia caledonica* (Verstraete *et al.*, 2011). Interestingly, members of *P. caledonica* are also commonly isolated from the rhizosphere or soil and have been detected in leaves of some *Vangueria* species (Verstraete *et al.*, 2014).

Speculations about possible functions of these leaf symbioses have long remained unsubstantiated because efforts to isolate leaf nodule bacteria or to culture bacteria-free plants were unsuccessful (Miller, 1990). Recently, sequencing and assembly of leaf symbiont genomes of several *Psychotria*, *Pavetta* or *Ardisia* species allowed new hypotheses about the ecological function of leaf symbiosis. Leaf symbiotic *Candidatus* Burkholderia crenata associated with *Ardisia crenata*, are responsible for the production of FR900359, a cyclic depsipeptide with potent bioactive and insecticidal properties (Fujioka *et al.*, 1988; Carlier *et al.*, 2016). Similarly, analysis of the genome of *Ca.* Burkholderia kirkii (*Ca*. B. kirkii), the leaf symbiont of *Psychotria kirkii*, revealed a prominent role of secondary metabolism (Carlier and Eberl, 2012). In this species, two biosynthetic gene clusters harboured on a plasmid encode two homologs of a 2-*epi*-5-*epi*-valiolone synthase (EEVS). EEVS are generally required for the production of cyclitol sugar analogs, a family of bioactive natural products with diverse targets (Mahmud, 2003, 2009). *Ca*. B. kirkii is likely involved in the synthesis of two cyclitol metabolites: kirkamide, a C_7N aminocyclitol with insecticidal properties, and streptol

glucoside, a derivative of valienol with broad allelopathic activities (Sieber *et al.*, 2015; Georgiou *et al.*, 2021). Similarly, representative genomes of *Candidatus* Burkholderia humilis, *Candidatus* Burkholderia pumila, *Candidatus* Burkholderia verschuerenii, *Candidatus* Burkholderia brachyanthoides, *Candidatus* Burkholderia calva and *Candidatus* Burkholderia schumanniana associated with leaf nodules of various *Psychotria* and *Pavetta* species, encode putative EEVS gene clusters (Pinto-Carbó *et al.*, 2016). The broad conservation of EEVS in otherwise small genomes suggests that C_7 cyclitol compounds are important for leaf symbiosis in these species.

C_7 cyclitols are a group of natural products derived from the pentose phosphate pathway intermediate sedoheptulose-7-phosphate (SH7P) (Mahmud, 2003). Proteins of the sugar phosphate cyclase family are key enzymes in the synthesis of C_7 cyclitols. Enzymes of this family catalyse the cyclization of sugar compounds, an important step in primary and secondary metabolism (Wu *et al.*, 2007). Within this family, three main categories of enzymes use SH7P as a substrate: desmethyl-4-deoxygadusol synthase (DDGS), 2-*epi*-valiolone synthase (EVS) and 2-*epi*-5-*epi*-valiolone synthase (EEVS), of which EEVS is the only known enzyme involved in C_7N aminocyclitol synthesis (Osborn *et al.*, 2017). EEVS were originally only found in bacteria, where they catalyse the first step in the biosynthesis of C_7N aminocyclitol secondary metabolites (Mahmud, 2003; Sieber *et al.*, 2015). More recently, EEVS homologs have been discovered in some Eukaryotes such as fish, reptiles, and birds as well (Osborn *et al.*, 2015, 2017).

A second common feature of the leaf endophytes in Rubiaceae and Primulaceae is their reduced genomes. Leaf nodule *Burkholderia* symbionts of Rubiaceae and Primulaceae typically have smaller genomes than free-living relatives, as well as a lower coding capacity (Pinto-Carbó *et al.*, 2016). This reductive genome evolution is thought to be a result of increased genetic drift sustained in bacteria that are strictly host-associated, which leads to fixation of deleterious and/or neutral mutations and eventually to the loss of genes (Pettersson and Berg, 2007). This process is best documented in obligate insect symbionts such as *Buchnera* and *Serratia,* endosymbionts of aphids, or in *Sodalis*-allied symbionts of several insect groups (Shigenobu *et al.*, 2000; Toh *et al.*, 2006; Manzano-Marín *et al.*, 2018). Some of these symbionts have extremely small genomes and may present an extensive nucleotide bias towards adenosine and thymine (AT-bias) (Moran *et al.*, 2008). The process

of genome reduction has multiple stages: first, recently host-restricted symbionts begin accumulating pseudogenes and insertion elements (McCutcheon and Moran, 2011; Lo *et al.*, 2016; Manzano-Marín and Latorre, 2016). Non-coding and selfish elements eventually get purged from the genomes over subsequent generations, which together with the general deletional bias in bacteria results in a decrease in genome size (Mira *et al.*, 2001). This ultimately leads to symbionts with tiny genomes, retaining only a handful of essential genes necessary for survival or performing their role in the symbiosis. This process has been well documented in the leaf nodule symbionts of *Psychotria*, *Pavetta* and *Ardisia* species, but little is known about the genomes and functions of endophytes in species that do not form leaf nodules, notably Rubiaceae species of the *Vangueria* and *Fadogia* genera.

Here, we performed a comparative study of Rubiaceae and Primulaceae leaf endophytes from leaf nodulating and non-nodulating plant species using genomes assembled from shotgun metagenome sequencing data as well as isolates. We constructed a dataset of 26 leaf symbiont genomes (17 of which from this study) from 22 plant species in 5 genera. All leaf symbionts show signs of genome reduction, in varying degree, and horizontal acquisition of secondary metabolite clusters is a universal phenomenon in these bacteria.

Material and Methods

Sample collection and DNA extraction

Leaves of Rubiaceae and Primulaceae species were freshly collected from different locations in South Africa or requested from the living collection of botanical gardens (Table S1). Attempts to isolate the endophytes were made for all fresh samples collected in South Africa (Table S1). Leaf tissue was surface sterilized using 70% ethanol, followed by manual grinding of the tissue in 0.4% NaCl. Supernatants were plated on 10% tryptic soy agar medium (TSA, Sigma) and R2A medium (Oxoid) and incubated at room temperature for 3 days or longer until colonies appeared. Single colonies were picked and passaged twice on TSA medium. Isolates were identified by PCR and partial sequencing of the 16S rRNA gene using the pA/pH primer pair (5'-AGAGTTTGATCCTGGCTCAG and 5'-AAGGAGGTGATCCAGCCGCA) (Edwards *et al.*, 1989). PCR products were sequenced using the Sanger method at Eurofins Genomics (Ebersberg, Germany). DNA was extracted from whole leaf samples as follows. Whole leaves were ground in liquid nitrogen using a mortar and pestle. Total DNA was extracted using the

protocol of Inglis et al. (Inglis *et al.*, 2018). Total DNA from a *Fadogia homblei* isolate was extracted following Wilson (Wilson, 2001). Sequencing library preparation and 2x150 paired-end metagenome sequencing was performed by the Oxford Wellcome Centre for Human Genetics or by Novogene Europe (Cambridge, UK) using the Illumina NovaSeq 6000. Sequencing reads were classified using Kraken v2.1.2 against a custom database comprising complete prokaryotic and plastid genome sequences deposited NCBI RefSeq (accessed 4/4/2021), and visualised using KronaTools v2.7.1 (Ondov *et al.*, 2011; Wood *et al.*, 2019).

Isolation of bacteria

Fresh leaf tissue was first washed in running tap water and surface-sterilized for 5 min in a 1.4% solution of sodium hypochlorite followed by 5 min in 70% ethanol. Leaves from a single plant were processed separately to prevent cross-contamination. Tissue was rinsed in sterile distilled water twice and ground using a sterile mortar and pestle in aseptic conditions. Macerates were resuspended in 1 -5 mL of sterile 0.4% NaCl and serial dilutions were spread onto R2A agar (Reasoner and Geldreich, 1985) and 10% tryptic soy agar (10% TSA; 10% tryptic soy broth, Oxoid, Thermo Scientific, 18 g L−1 agar) and incubated at 28°C for a week. Colonies were picked as they appeared, streaked out on TSA and incubated at room temperature. Strains were passaged three times on TSA prior to preservation at −80°C in tryptic soy broth supplemented with 20% glycerol.

Bacterial genome assembly

Sequencing reads were trimmed and filtered using fastp v0.21.0 with default settings, retaining reads with a minimum Phred score of 15 and less than 40% of bases failing the quality threshold (Chen *et al.*, 2018). Overlapping paired-end reads were merged using NGmerge v0.3 with default settings (Gaspar, 2018). Reads derived from isolates were assembled using Skesa v2.4.0 using default settings (Souvorov *et al.*, 2018). Assembly statistics were compiled using Quast v5.1.0 (Gurevich *et al.*, 2013). For sequencing reads derived from new leaf samples, metagenome assemblies were created using metaSPAdes v3.15 on default settings but including the merged reads (Nurk *et al.*, 2017). Metagenomes were binned using Autometa v1.0.2, using a minimal contig length of 500 bp, taxonomy filtering (-m) and maximum-likelihood recruitment (using the -r option)(Miller *et al.*, 2019). Genome bins identified as *Caballeronia*, *Paraburkholderia*, or *Burkholderia* by Autometa

were further assembled by mapping the original reads to these bins using smalt v0.7.6 (Ponsting and Ning, 2010). Mapped reads were extracted using samtools v1.9 (Li *et al.*, 2009) and reassembled using SPAdes v3.15 (Bankevich *et al.*, 2012) in default settings but using the --careful option, and binned again using Autometa. Contigs likely derived from eukaryotic contamination were removed after identification by blastn searches (e-value < $1e^{-6}$) against the NCBI nucleotide database (accessed January 2021) (Camacho *et al.*, 2009). Per-contig coverage information was calculated using samtools and contigs with less than 10% or more than 500% of the average coverage were manually investigated, and sequences likely derived from other bacterial or eukaryotic genomes were removed. The metagenome assembly approach was validated using the *Fadogia homblei* PRU 128010 dataset (Table S1) to compare the *Paraburkholderia caledonica* metagenome-assembled genome (MAG) to the genome sequence of strain *Paraburkholderia caledonica* R-82532 isolated from the same source material. MAG sequences of *F. homblei* endophytes contained 100% of the sequences of the R-82532 isolate genome, with only a small excess of contaminating sequences before manual filtering (MAG size = 8.90 Mb vs 8.71 Mb for the R-82532 assembly, with 100% average nucleotide identity on shared sequences).

To provide a more homogenous dataset for comparative genomics, Illumina read data for six previously published Rubiaceae symbionts, and the symbionts of *Ardisia crenata* and *Fadogia homblei* were re-assembled as above but using the published draft genomes as trusted contigs for both metaSPAdes and SPAdes assemblies (Table S2). The resulting assemblies were compared to the published assemblies using dotplots created by MUMmer v3.1 (Marçais *et al.*, 2018). Genome assemblies of the symbionts of *Psychotria kirkii* (Carlier and Eberl, 2012; Carlier *et al.*, 2013) and *Psychotria punctata* (Pinto-Carbó *et al.*, 2016) were downloaded from Genbank (Table S2). To assess whether the (re-)assembled genomes or MAGs represent new species, genomes were analysed using TYGS (Type Strain Genome Server) (Meier-Kolthoff and Göker, 2019), and NCBI Blastn-based Average Nucleotide Identities (ANI) values calculated using the JSpecies web server, accessed Sept. 2021 (Richter *et al.*, 2016) and the pyANI python package v0.2 (https://github.com/widdowquinn/pyani).

Genome annotation and pseudogene prediction

Assembled genomes were annotated using the online RASTtk pipeline (Brettin *et al.*, 2015), using GenemarkS as gene predictor, and locus tags were added using the Artemis software

v18.1.0 (Carver *et al.*, 2012). Prediction of pseudogenes was performed using an updated version of the pseudogene prediction pipeline previously used for leaf symbionts (Carlier *et al.*, 2013). Briefly, orthologs of predicted proteins sequences of each genome in a dataset of published *Burkholderia* genomes (Table S3) were determined using Orthofinder v2.5.2 (Emms and Kelly, 2019) with default settings. The nucleotide sequences of each gene, including 200bp flanking regions (the query), were aligned to the highest scoring amino acid sequence in each orthogroup (the target) using TFASTY v3.6 (Pearson, 2000). Genes were considered as pseudogenes if the alignment spanned over 50% of the query sequence and the query nucleotide sequence contained a frameshift, or a nonsense mutation resulting in an uninterrupted alignment shorter than 80% of the target sequence. Moreover, ORFs were classified as non-functional if at least one of the following criteria was true: amino acid sequence shorter than 50 residues which did not cluster in an orthogroup, and sequence without any significant blastx hit against the reference database (e-value cut off = 0.001); proteins without predicted orthologs in the *Burkholderia* dataset, but which showed a blastx hit against the reference set in an alternative reading frame; and finally proteins without any hit in the *Burkholderia* genome database or in the NCBI nr database. Blastx and blastp searches were performed using DIAMOND v2 (Buchfink *et al.*, 2021). For the genomes of the symbionts of *P. kirkii* and *P. punctata* the original gene and pseudogene predictions were used. Insertion elements in both newly assembled and re-assembled genomes were predicted using ISEscan v1.7.2.3 with default settings (Xie and Tang, 2017).

Phylogenetic analysis

16S rRNA sequences were extracted from the endophyte (meta)genomes using Barrnap v0.9 (https://github.com/tseemann/barrnap). For genomes where no complete 16S rRNA could be detected, reads were mapped to the 16S rRNA gene of the closest relative with a complete 16S rRNA sequence. These reads were assembled using default SPAdes (Prjibelski *et al.*, 2020) using the --careful option. Near complete (>95%) 16S rRNA sequences could be extracted using these methods, except for the hypothetical endophyte of *Pavetta revoluta.* The 16S rRNA sequences were identified using the EzBiocloud 16S rRNA identification service (https://www.ezbiocloud.net/identify). Phylogenetic analysis of the leaf endophytes and *Burkholderia s.l.* genomes was performed using the UBCG pipeline v3.0 (Na *et al.*, 2018). The pipeline was run using the default settings, except for the gap-cutoff (-f 80). The resulting

superalignment of 92 core genes was used for maximum-likelihood phylogenetic analysis using RAxML v8.2.12, using the GTRGAMMA evolution model, and performing 100 bootstrap replications (Stamatakis, 2014). Plastid reference alignments were created using Realphy v1.12 using standard settings and the *Coffea arabica* chloroplast genome (NCBI accession NC_008535.1) as reference (Bertels *et al.*, 2014). Published chloroplast genomes of *Ardisia mamillata* (NCBI accession MN136062), *Psychotria kirkii* (NCBI accession KY378696), *Pavetta abyssinica* (NCBI accession KY378673), *Pavetta schumanniana* (NCBI Accession MN851271), and *Vangueria infausta* (NCBI accession MN851269) were also included in the alignment. Phylogenetic trees were constructed using PhyML v3.3.3 with automatic model selection, and 1000 bootstrap replicates (Guindon *et al.*, 2010). For plant species with uncertain taxonomic identification, seven plant markers were extracted by blastn searches against the metagenome: ITS, nad4, rbcL and rpl16 of *Pavetta abyssinica* (NCBI accessions MK607930.1, KY492180.1, Z68863.1, and KY378673.1), matK from *Pavetta indica* (NCBI accession KJ815920.1), petD from *Pavetta bidentata* (NCBI accession JN054223.1), and trnTF from *Pavetta sansibarica* (NCBI accession KM592134.1).

Core-genome phylogenies of symbiont genomes were constructed by individually aligning the protein sequences of all single-copy core genes using MUSCLE v3.8.1551, back-translating to their nucleotide sequence using T-Coffee v13.45 (Di Tommaso *et al.*, 2011), and concatenating all nucleotide alignments into one superalignment using the AlignIO module of Biopython 1.78 (Cock *et al.*, 2009). Maximum-likelihood phylogenetic analysis was performed using RAxML, using the GTRGAMMA evolution model, 100 bootstrap replicates, and using partitioning to allow the model parameters to differ between individual genes. Phylogenetic trees were visualised and edited using iTOL (Letunic and Bork, 2019).

Comparative genomics

Ortholog prediction between leaf symbiont genomes and a selection of reference genomes of the *Burkholderia, Paraburkholderia* and *Caballeronia* genera (BPC-set; selected using NCBI datasets tool (https://www.ncbi.nlm.nih.gov/datasets/genomes); Table S3) was performed using Orthofinder v2.5.2 using default settings (Emms and Kelly, 2019).For the leaf endophytes, predicted pseudogenes were excluded from the analysis. The core genome of a certain group was defined as the number of orthogroups containing genes of all genomes in the group. Core genome overlap was visualised in Venn diagrams using InteractiVenn

(Heberle *et al.*, 2015). Non-essential core genes were identified by blastp searches against the database of essential genes (DEG)(Zhang, 2004), identifying as putative essential genes ORFs with significant matches in the database (e-value < $1e^{-6}$). Standardised functional annotation was performed using eggNOG-mapper v2.1.2 (Huerta-Cepas *et al.*, 2019; Cantalapiedra *et al.*, 2021). Enrichment of protein families in leaf symbiont genomes was determined by comparing the proportion of members of leaf symbionts and the BPC-set in orthogroups. Enriched KEGG pathways were identified by comparing the average per-genome counts of genes in every pathway between leaf symbiont genomes and genomes from the BPC-set. Presence of motility and secretion system clusters was investigated using the TXSScan models implemented in MacSyFinder (Abby *et al.*, 2014, 2016). Homologues of the *Ca.* B. kirkii UZHbot1 putative 2-*epi*-5-*epi*-valiolone synthase (EEVS) were identified by blastp searches against the proteomes of the leaf symbiont genomes (e-value cut-off: $1e^{-6}$). Putative EEVS genes were searched against the SwissProt database, and functional assignment was done by transferring the information from the closest match within the sugar phosphate cyclase superfamily (Schneider *et al.*, 2004; Osborn *et al.*, 2017). Contigs containing these genes were identified and extracted using Artemis, and aligned using Mauve (Lòpez-Fernàndez *et al.*, 2015). Gene phylogenies were constructed by creating protein alignments using MUSCLE followed by phylogenetic tree construction using FastTree v2.1.9 (Price *et al.*, 2009), including the protein sequences of three closely related proteins in other species, determined by blastp searches against the RefSeq protein database (accessed July 2021). The data generated in this study have been deposited in the European Nucleotide Archive (ENA) at EMBL-EBI under accession number PRJEB52430 (https://www.ebi.ac.uk/ena.browser/view/PREJB52430).

GC-MS analysis of kirkamide

Extracts were derivatised with N-methyl-N-(trimethyl-silyl)-trifluoroacetamide (MSTFA, Merck Ltd) according to the method of Pinto-Carbó *et al.* (2016). Three replicates of the plant extracts were derivatised from a concentration of 1 mg/ml in 2 ml double distilled water as follows: The extracts were filtered through 0.22 µm syringe fitted filters and 100 µl transferred to 2.0 ml screw top glass vials with 200 µl inserts and dried overnight under a nitrogen stream. The residues were dissolved in 50 µl MSTFA, vortexed for two minutes, left at 70 °C for one hour and then 50 µl pyridine was added as the solute. The derivatised samples were analysed on a

Shimadzu GC-MS-QP2010 (Shimadzu Corporation, Japan) with ionization energy set at 70 eV. The compounds were separated using a Rtx – 5MS column (29.3 m x 250 µm x 0.25 µm i.d.; 0.25 µm df) with helium as the carrier gas. Splitless injections of 1 µl were performed, with the column flow set to linear velocity. Sampling time was set to 2 min, with the solvent cut-off time set to 3.5 min. The injector and interface temperatures were set at 250°C. The GC oven temperature program was set to an initial 40°C and held for 1 min, thereafter it was increased to 330°C at a rate of 7°C min^{-1} which was held for 10 min, bringing the total run time to 52 min. The MS ion source and interface temperatures were set to 250°C. The detector voltage was set to 0.1 kV, relative to the instrument tuning results. The mass-to-charge ratio (m/z) detection was set to start at 7 min (ensuring complete solvent elimination) and ranged from 45 to 650 m/z with a scan speed of 2 500 aum s^{-1}. Pyridine was used as a blank at the start of the analysis to observe any instrumental errors.

UPLC-QToF-MS analysis of streptol and streptol glucoside

The presence of underivatised streptol and streptol glucoside in the plant extracts was analysed using a Waters Synapt G2 high-definition mass spectrometry (HDMS) system (Waters Inc., Milford, Massachusetts, USA). The apparatus consists of a Waters Acquity UPLC connected to a quadropole-time-of-flight (QToF) instrument. The method of Georgiou et al. (2021) was followed for the detection of streptol and streptol glcoside in negative mode $[M-H]^-$. The samples were analysed using a Luna Omega 1.6 µm C_{18} 100 A, 100 x 2.1 mm (Phenomenex, Separations) column and a solvent system that consisted of MeCN:H_2O (A, 8:2, 0.1 % NH_4OAc) and MeCN:H_2O (B, 2:8, 0.1 % NH_4OAc). The gradient was set to start at 95 % of B and to decrease to 50 % of B in 7 min, for the next 2 min the gradient was kept at 50 % of B, the gradient was then gradually decreased from 50 % to 5 % of B for the next 3 min and was followed by a column wash for the next 2 min giving a total run time of 12 min. The column temperature was 40 °C, injection volume 7 µl and the flow rate 0.3 ml min^{-1}. Mass to charge ratios (*m/z*) were recorded between 50 and 1 200 Da. High energy collision induced dissociation (CID) was used for tandem MS fragmentation. The collision energy for the ramping was set to increase from 10 V to 20 V in order to get a range of data. The full scan MS data was recorded from the QTOF-MS and XICs (extracted ion chromatograms) were used for processing the data to single out the ions of interest. In some instances targeted MS/MS spectra were employed for the detection of streptol. Presence of streptol was determined by

the presence of spectral features with ion fragments at 85, 108, 111, 121 and 175 *m/z* and a monoisotopic mass of 175.06119 (± 5 ppm). Presence of streptol-glucoside was determined by the presence of spectral features with ion fragments at 112, 139, 175 and 337 *m/z* and a monoisotopic mass of 337.1140 (± 5 ppm).

Results

Detection and identification of leaf endophytes

To gain insight into potential association of various Primulaceae and Rubiaceae species with *Burkholderia s.l.* endosymbionts, we collected samples from 16 Rubiaceae (1 *Fadogia* sp., 5 *Pavetta* spp., 2 *Psychotria* spp., and 8 *Vangueria* spp.) and 3 Primulaceae (3 *Ardisia* spp.) species (Table S1). We extracted DNA from entire leaves and submitted the samples to shotgun sequencing without pre-processing of the samples to remove host or organellar DNA. We found evidence for endophytic *Burkholderia* in 14 out of 19 species investigated (Table S1). In these samples, the proportion of sequencing reads identified as *Burkholderiaceae* ranged from 5% to 57% of the total, except for the *Pavetta revoluta* sample (0.4%) and 1 of 2 *Vangueria infausta* samples (0.9%). Analysis of 16S rRNA sequences revealed 100% pairwise identity over 1529 bp suggesting that the same endophyte species was present in both *V. infausta* samples. In *Pavetta revoluta*, the closest relative of the leaf endophyte based on 16S rRNA sequence similarity was *Caballeronia calidae* (98.89% identity over 808 bp; Table S1). Of the nine species with significant amounts of *Burkholderia* s.l. reads and for which isolation attempts were made (Table S1), only the endophyte of *Fadogia homblei* could be cultured (isolate R-82532). Leaf samples of four species (*Psychotria capensis*, *Psychotria zombamontana*, *Pavetta ternifolia*, and *Pavetta capensis*) contained low amounts of bacterial DNA (<2% of reads), and likely do not have stable symbiotic endophyte associations. Seven percent of the reads obtained from the *Pavetta indica* sample were classified as bacterial, but with a diverse range of taxa present indicating possible contamination with surface bacteria (Figure S1). Plastid phylogenies indicated that samples attributed to *Pavetta capensis* and *Pavetta indica* did not cluster with other *Pavetta* species (Figure S2). Analysis of genetic markers revealed that our *Pavetta indica* sample was likely a misidentified *Ixora* species. Analysis of *Pavetta capensis* marker genes revealed the

specimen is likely part of the Apocynaceae plant family, with a 100% identity match against the *rbcL* sequence of *Pleiocarpa mutica.* These samples were not taken into account in further analyses.

Analysis of the 16S rRNA sequences extracted from metagenome-assembled genomes (MAGs) identified all leaf endophytes as *Burkholderia s.l.* (Table S1). Phylogenetic analysis shows that all endophytes of *Psychotria, Pavetta*, and *Ardisia* cluster within the genus *Caballeronia*, while the endophytes of *Vangueria* and *Fadogia* belong to the *Paraburkholderia* genus (Figure 1A). All endophytes of *Ardisia* are closely related to each other and form a clade with *Caballeronia udeis* and *Caballeronia sordidicola*. Based on the commonly used ANI (95-96%) cut-off (Richter and Rossello-Mora, 2009), these endophytes are separate species from *C. udeis* and *C. sordidicola* (ANI <94%; 16S rRNA sequence identity <98.4). The endophytes of *Ardisia crenata* and *Ardisia virens* are very closely related and belong to the same species: *Ca.* Burkholderia crenata (ANI >99%; 16S rRNA sequence identity 99.8%) (Table S4). Similarly, the endophytes of *Ardisia cornudentata* and *Ardisia mamillata* belong to the same species (ANI = 95.56%), which we tentatively named *Ca.* Caballeronia ardisicola (species epithet from *Ardisia*, the genus of the host species, and the Latin suffix - *cola* (from L. n. *incola*), dweller, see species description in Supplementary Information). Endophytes of *Psychotria* and *Pavetta* are scattered across the *Caballeronia* phylogeny, but all are taxonomically distinct from free-living species (Figure 1A; ANI <93% with closest non-endophyte relatives). Each of these endophytes also represents a distinct bacterial species with pairwise Average Nucleotide Identity (ANI) values below the commonly accepted species threshold of 95-96%, including the endophyte of *Pavetta hochstetteri* which we tentatively named *Candidatus* Caballeronia hochstetteri (Table S4 and Supplementary information). Although their MAGs share 95.65% ANI (a borderline value for species delineation), *Ca.* B. schumanniana (endophyte of *Pavetta schumanniana*) and *Ca.* B. kirkii have been previously described as distinct species on the basis of 16S rRNA gene sequence similarity (Verstraete *et al.*, 2011) (Table S4). The endophytes of *Vangueria* and *Fadogia* form three distinct lineages of *Paraburkholderia*. The endophytes of *Vangueria dryadum* and *Vangueria macrocalyx* are nearly identical (ANI >99.9%; identical 16S rRNA), but do not belong to any known *Paraburkholderia* species (ANI <83% with closest relative *Paraburkholderia* species). We tentatively assigned these bacteria to a new species which we

named *Ca. Paraburkholderia dryadicola* (from a Dryad, borrowed from the species epithet of one of the host species, and Latin suffix – *cola*, see species description in Supplementary Information). Similarly, the endophytes of *V. infausta*, *V. esculenta*, *V. madagascariensis*, *V. randii*, and *V. soutpansbergensis* cluster together with *Paraburkholderia phenoliruptrix* (Figure 1A). While the endophyte of *Vangueria soutpansbergensis* forms a separate species (named here *Ca. Paraburkholderia soutpansbergensis;* ANI <95% with *P. phenoliruptrix*) the other endophytes fall within the species boundaries of *P. phenoliruptrix*. (ANI 95-96% between these endophytes and *P. phenoliruptrix*). Lastly, the endophytes of *Fadogia homblei* and *Vangueria pygmaea* showed identical 16S rRNA sequences, and clustered with *Paraburkholderia caledonica*, *P. strydomiana*, and *P. dilworthii* (Figure 1A). Similarly high ANI values (>97.5%) and 16S rRNA sequence similarity (>99.7%) ambiguously fall within the species boundaries of both *P. caledonica* and *P. strydomiana*. Because endophytes of *F. homblei* were previously classified as *P. caledonica* (Verstraete *et al.*, 2011, 2014), we propose classifying the endophytes of *F. homblei* and *V. pygmaea* as members of *P. caledonica*, and consider *P. strydomiana* a later heterotypic synonym of *P. caledonica*.

Phylogenetic analysis based on the core genomes of endophytes indicates a general lack of congruence with the host plant phylogeny (Figure S3). Endophytes of *Ardisia* are monophyletic within the *Caballeronia* genus and follow the host phylogeny. In contrast, endophytes of *Pavetta* are not monophyletic and are nested within the *Psychotria* endophytes. Similarly, the *Fadogia homblei* endophyte clusters with endophytes of *Vangueria.*

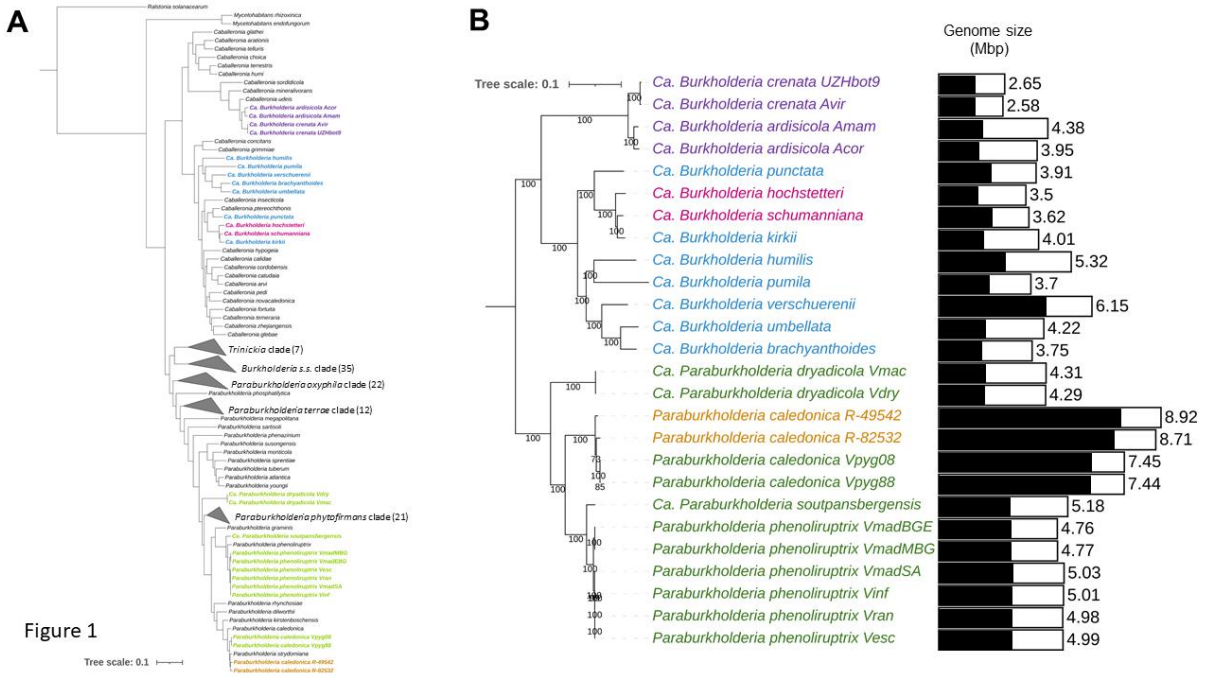

Figure 1

Figure 1: Phylogeny of *Burkholderia, Caballeronia,* and *Paraburkholderia*, including the leaf endophytes. (A) UBCG phylogeny of the *Burkholderia* s.l. based on 92 conserved genes. Bootstrap support values based on 100 replications are displayed on the branches. Branches with <50% support were collapsed. *Ralstonia solanacearum* was used as outgroup to root the tree. Coloured samples in boldface represent the leaf endophytes from Rubiaceae and Primulaceae **(B)** Core genome phylogeny of leaf endophytes based on alignment of 423 single-copy core genes. Bootstrap support values based on 100 replicates are shown on the branches. Samples are colour-coded based on the host genus: Purple – *Ardisia*; Blue – *Psychotria*; Pink – *Pavetta*; Green – *Vangueria*; Orange – *Fadogia*; Black bars represent the coding capacity of the genome (the proportion of the genome coding for functional proteins).

Leaf endophyte genomes show signs of genome reduction.

We could assemble nearly complete bacterial genomes for all samples where we detected *Burkholderia* endophytes, except for those of the *Pavetta revoluta* and one *Vangueria infausta* sample with too few bacterial reads. Binning analysis grouped endophyte sequences in a single bin per sample, with high completeness and purity (Table 1). Most assemblies ranged between 3.5 and 5 Mbp in size, with 2 outliers: 2.58 Mbp for *Ca.* B. crenata Avir (the endophyte of *Ardisia virens*), and 8.92 Mbp for *P. caledonica* R-49542 (endophyte of *Fadogia homblei*)(Table 1). The G+C-content of all MAGs fell in the range of 59-64 percent G+C content, which is within the range of free-living *Paraburkholderia* and *Caballeronia* genomes (Vandamme *et al.*, 2017). All MAGs showed signs of ongoing genome reduction. Because of rampant null or frameshift mutations, a large proportion of predicted CDS code for non-functional proteins. As a result, coding capacity is low for all endophyte

MAGs varying between 83% in *P. caledonica* R-49542 (Figure 1B, Figure S4) and 40% in *Ca.* C. ardisicola Acor, the endophyte of *Ardisia cornudentata* (Figure 1B, Figure S5). In addition, insertion sequence (IS) elements make up a large amount of the MAGs: 1.97% of the assembly size on average, but up to almost 10% in some symbionts of *Psychotria* (Table 1). Reassembly of previously investigated endophytes of *Psychotria* and *Pavetta* yielded assemblies of similar size to the original assemblies, except for Ca. *Burkholderia schumanniana* UZHbot8 (endophyte of *Pavetta schumanniana*). The original genome assembly size was estimated at 2.4 Mbp, while our reassembly counted 3.62 Mbp. A dot plot between both assemblies indicated that the size discrepancy is not solely due to differential resolution of repeated elements (Figure S6). Thus, our new assembly includes 1.2 Mbp of genome sequence that was missed in the original assembly.

Burkholderia leaf endophytes in Rubiaceae and Primulaceae shared a core genome of 607 genes (Figure S7). Even within specific phylogenetic lineages the core genomes were small: 774 genes in endophytes belonging to the *Caballeronia* symbionts of *Psychotria* and *Pavetta*, 1001 genes in endophytes of *Caballeronia* symbionts of *Ardisia*, and 1199 in *Paraburkholderia* endophytes of *Fadogia* and *Vangueria*. This corresponds to 29.5%, 52.4%, and 28.4% of the average functional proteome for each species cluster, respectively. Only 28 proteins of the total core genome did not show significant similarity with proteins from the database of essential genes (Table S5). Eleven of these proteins have unknown functions and five are membrane-related. Fifteen genes of the endophyte core genome did not have orthologs in >95% of related *Burkholderia*, *Caballeronia*, and *Paraburkholderia* genomes (Table S6). No COG category was specifically enriched in this set of proteins.

Because secretion of protein effectors is often a feature of endophytic bacteria (Brader *et al.*, 2017), we searched for genes encoding various secretion machineries in the genomes of *Burkholderia* endophytes. Flagellar genes, as well as Type III, IV or VI secretion system were not conserved in all leaf endophytes (Figure S8). The most eroded symbionts of *Psychotria*, *Pavetta,* and *Ardisia* lack almost all types of secretion systems, and most also lack a functional flagellar apparatus. Type V secretion systems are present in *Ca.* Caballeronia ardisicola Acor, *Ca.* B. pumila UZHbot3 (endophyte of *Psychotria pumila*), and *Ca.* B. humilis UZHbot5 (endophyte of *Psychotria humilis*). The genomes of *Paraburkholderia* symbionts of *Vangueria* and *Fadogia* were generally richer in secretions systems, but only T1SS and T2SS

466 are conserved. A Type V secretion system is present in all *Paraburkholderia* endophytes
467 except *Ca.* Paraburkholderia dryadicola Vdry and Vmac (endophytes of *V. dryadum* and *V.*
468 *macrocalyx*, respectively). The flagellar apparatus is missing in both *Ca.* P. dryadicola MAGs,
469 in *Ca.* P. soutpansbergensis Vsou, and in *P. phenoliruptrix* Vesc (the endophyte of *V.*
470 *esculenta*), and is incomplete in some other *P. phenoliruptrix* endophytes. Lastly, only the
471 genomes of *Paraburkholderia caledonica* endophytes R-49542 and R-82532 encode a
472 complete set of core Type VI secretion system proteins.

473 *Genes related to cyclitol metabolism are enriched in leaf endophytes*

474 We wondered if specific metabolic pathways might be enriched in genomes of leaf
475 symbionts, despite rampant reductive evolution. We assigned KEGG pathway membership
476 for each predicted functional CDS (thus excluding predicted pseudogenes) in leaf symbiont
477 genomes or MAGs as well as a set of free-living representative *Paraburkholderia* or
478 *Caballeronia* species. The number of genes assigned to a majority of the KEGG pathways
479 (256 pathways in total) was significantly smaller in endophyte genomes compared to their
480 free-living relatives. A small portion (86 pathways) did not differ between leaf symbionts and
481 free-living representatives. Genes belonging to a single pathway were significantly enriched
482 in leaf endophytes: acarbose and validamycin biosynthesis (KEGG pathway map00525).
483 Acarbose and validamycin are aminocyclitols synthesized via 2-*epi*-5-*epi*-valiolone synthase
484 (EEVS). EEVS catalyses the first committed step of C_7N aminocyclitol synthesis (Mahmud,
485 2003, 2009), and likely plays a role in the production of kirkamide, a natural C_7N
486 aminocyclitol present in leaves of *Psychotria kirkii* and other nodulated Rubiaceae, as well as
487 streptol and streptol glucoside, 2 cyclitols with herbicidal activities (Pinto-Carbó *et al.*, 2016).
488 Indeed, of 10 *Ca.* Burkholderia kirkii UZHbot1 genes assigned to KEGG pathway map00525, 8
489 genes were previously hypothesised to play a direct role in the synthesis of C_7N
490 aminocyclitol or derived compounds (Pinto-Carbó *et al.*, 2016). Similarly, 7 out of 11
491 orthogroups most enriched in leaf endophytes contained a gene putatively involved in
492 cyclitol synthesis in *Ca*. Burkholderia kirkii UZHbot1 (Table S7)(Carlier and Eberl, 2012; Sieber
493 *et al.,* 2015). To gain a better understanding of the distribution of cyclitol biosynthetic
494 clusters in leaf endophytes, we searched for homologs of the two 2-*epi*-5-*epi*-valiolone
495 synthase (EEVS) genes of *Ca.* Burkholderia kirkii UZHbot1 (locus tags BKIR_C149_4878 and
496 BKIR_C48_3593) in the other leaf endophyte genomes. We detected putative EEVS

homologs in all but the two genomes of *Ca.* B. crenata. For *Ca.* B. crenata UZHbot9 we have previously shown the genome encodes a non-ribosomal peptide synthase likely responsible for the synthesis of the depsipeptide FR900359 (Fujioka *et al.*, 1988; Carlier *et al.*, 2016; Crüsemann *et al.*, 2018), and these genes were also detected in *Ca.* B. crenata Avir. Because EEVSs are phylogenetically related to 3-dehydroquinate synthases (DHQS), we aligned the putative EEVS sequences retrieved from leaf endophytes to EEVS and DHQS sequences in the Swissprot database. All putative EEVS sequences retrieved from leaf endophytic *Burkholderia* were phylogenetically related to *bona fide* EEVS proteins, but not to dehydroquinate synthase (DHQS) and other sedoheptulose 7-phosphate cyclases. EEVS are otherwise rare in *Burkholderia* s. l., with putative EEVSs present in only 11 out of 5674 publicly available *Burkhoderiaceae* genomes (excluding leaf symbiotic bacteria) in the NCBI RefSeq database as of June 2022 (Figure S9).

Evolution of cyclitol metabolism in leaf endophytic Burkholderia

Phylogenetic analysis of the endophyte EEVS protein sequences showed the presence of two main clades of *Burkholderia* EEVS homologs, as well as a divergent homolog in the genome of *Ca.* C. ardisicola Acor, and a second divergent homolog in *Ca.* P. dryadicola Vdry and Vmac (Figure 2A). The gene context of these EEVS genes in the different clades reveals that the two main EEVS clades correspond to the two conserved gene clusters previously hypothesized to play a role in kirkamide and streptol glucoside biosynthesis in *Ca.* Burkholderia kirkii (Carlier *et al.*, 2013). The gene order of these clusters is very similar in every genome, with a similar genomic context in closely related genomes (Tables 2 & 3 and Figure S10). These gene clusters are generally flanked by multiple mobile elements, consistent with acquisition via horizontal gene transfer (Table S9). Furthermore, the EEVS phylogeny did not follow the species phylogeny, indicating that HGT or gene conversion occurred (Figure 2A and Figure 2B). For clarity, we named the two main putative cyclitol biosynthetic gene clusters S-cluster (for streptol) and K-cluster (for kirkamide) based on previous biosynthetic hypotheses from *in silico* analysis of the putative cyclitol gene clusters of *Ca.* B. kirkii (Figure 2A) (Pinto-Carbó *et al.*, 2016). Both K and S-clusters encode a core set of proteins linked to sugar analog biosynthesis: a ROK family protein and a HAD family hydrolase, and both contain aminotransferases (although from different protein families). Two EEVS genes contain nonsense mutations and are likely not functional: the S-cluster EEVS

of *Ca.* Burkholderia humilis UZHbot5, and the K-cluster EEVS of *Ca.* Burkholderia brachyanthoides UZHbot7. The MAG of *Ca.* B. humilis UZHbot5 still contains an apparently functional K-cluster EEVS, while the pseudogenized EEVS of *Ca.* B. brachyanthoides UZHbot7 is the only homolog in the MAG. Interestingly, genes of the K-cluster appear to be exclusive to *Psychotria* and *Pavetta* symbionts, while the S-cluster is more widespread, including in the MAGs of *Vangueria* endophytes. Accordingly, we detected kirkamide in leaf extracts of *Psychotria kirkii*, but in none of the *Fadogia* or *Vangueria* species we tested (see supplementary information). We also detected signals that were consistent with streptol/valienol and streptol glucoside by UPLC-QToF-MS in all samples. However, these signals occurred in a noisy part of the chromatogram, and we cannot confidently conclude if these *m/z* features come from a single streptol derivative or from several compounds.

The MAG of *Ca.* P. soutpansbergensis Vsou and genomes of *P. caledonica* R-49542 and R-82532 encoded EEVS homologs of the K-cluster, but the full complement of the genes of the K-cluster is missing (Table 3 and Figure S10). In both cases the EEVS gene is flanked by IS elements (Table S9). Accordingly, we did not detect kirkamide in leaf samples from either *Fadogia homblei* or *V. soutpansbergensis* in our chemical analyses. The MAGs of *Ca.* P. dryadicola Vmac and Vdry encodes an EEVS that clusters outside of the K- and S-EEVS clusters. Genes with putative functions similar to those of the K-cluster are located in the vicinity of the EEVS in the MAGs of both *Ca.* P. dryadicola strains: oxidoreductases, an aminotransferase, and an N-acetyltransferase (Table S8). Similarly, *Ca.* C. ardisicola Acor contains a second divergent EEVS, in addition to the S-cluster EEVS. This EEVS belongs to a larger gene cluster coding for similar functions also found in the other EEVS-clusters, but contains at least one frameshift mutation and no longer codes for a functional enzyme (Table S8). Lastly, *Ca.* B. verschuerenii UZHbot4 contains a second, recently diverged EEVS paralog of the K-cluster. This EEVS is part of a small cluster of genes, with putative functions divergent from those found in the other EEVS-clusters and likely does not play a role in kirkamide synthesis (Table S8).

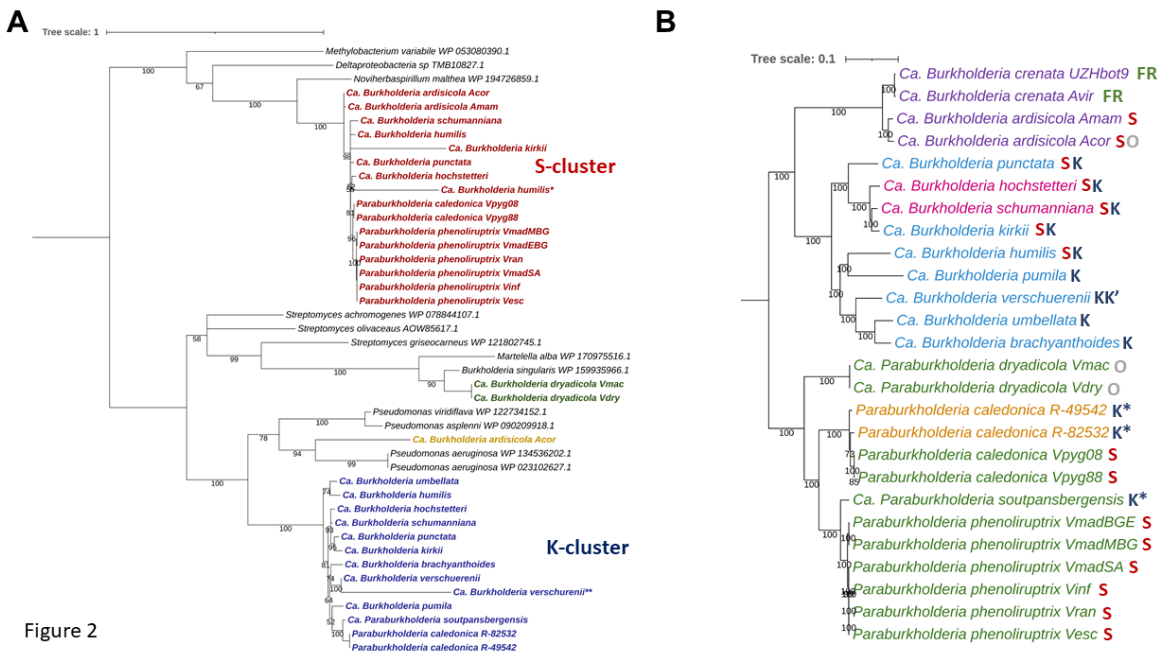

Figure 2

Figure 2: EEVS protein phylogeny and distribution in leaf endophytes. (A) EEVS protein phylogeny of detected EEVS-genes and their closest relatives. Local support values based on the Shimodaira-Hasegawa test are shown on the branches, and branches with support <50% are collapsed. Coloured samples in boldface are the EEVS homologs found in different leaf endophytes. Colours represent different clusters of similar EEVS genes. K- and S-cluster are named after their putative products (K for Kirkamide, and S for Streptol glucoside). NCBI accession numbers of the close relatives are given next to their species name. The tree is rooted using related 3-dehydroquinate synthase genes (not shown). *The EEVS gene in *Ca*. Burkholderia humilis UZHbot5 contains an internal stop codon, creating two EEVS-like pseudogenes. The largest of both was used for the phylogeny. **This EEVS gene of *Ca.* Burkholderia verschuerenii UZHbot4 is found outside of the K-cluster. Blue and red labels correspond to EEVS sequences belonging to the K and S clusters, respectively. Orange and green labels correspond to EEVS sequences found clustering outside of the K and S clusters, the colour corresponding to the corresponding taxa as in Figure 1. **(B)** Distribution of specialised metabolism in the leaf endophytes. The phylogenetic tree corresponds to the species phylogeny as in Figure 1A. Samples are colour-coded based on the host species: Purple – *Ardisia*; Blue – *Psychotria*; Pink – *Pavetta*; Green – *Vangueria*; Orange – *Fadogia*. Codes next to the species represent presence of specialised metabolite clusters; FR – FR900359 depsipeptide; K – Kirkamide EEVS-cluster; S – Streptol glucoside EEVS-cluster; O – Other EEVS-cluster. K' – Secondary EEVS cluster with EEVS similar to the K-cluster. K* - Only the K-cluster EEVS is present, not the accessory genes.

Discussion

Different evolutionary origins of leaf symbioses in different plant genera

In this work, we investigated the evolution of associations between *Burkholderia s. l.* bacteria and plants of the Rubiaceae and Primulaceae families, and attempted to identify key characteristics of these associations. To this end, we re-analyzed publicly available genome data from previous research, and sequenced and assembled the genomes of an additional 17 leaf endophytes. In addition to leaf endophytes which had been previously

582 detected (Lemaire, Smets, *et al.*, 2011; Verstraete *et al.*, 2011, 2013; Ku and Hu, 2014), we
583 document here the presence of *Burkholderia s.l.* symbionts in *Pavetta hochstetteri* and
584 *Vangueria esculenta*, and possibly *Pavetta revoluta*. In contrast to previous findings
585 (Lemaire, Lachenaud, *et al.*, 2012), we could not detect evidence of leaf endophytes in
586 *Psychotria capensis*, but did confirm the absence of leaf endophytes in *Psychotria*
587 *zombamontana*. Phylogenetic placement of hosts and endophytes are consistent with
588 previous data, except for the placement of *Vangueria macrocalyx* and its endophyte
589 (Lemaire, Lachenaud, *et al.*, 2012; Verstraete *et al.*, 2013). Both chloroplast sequences of *V.*
590 *macrocalyx* and *V. dryadum* and the MAGs of their endophytes were nearly identical while
591 previous research showed a clear phylogenetic difference both between the host species
592 and their endophytes (Verstraete *et al.*, 2013). Blastn analysis of plant genetic markers (ITS,
593 petB, rpl16, trnTF) of both species against the NCBI nr database showed higher identities to
594 markers from *Vangueria dryadum* than to those of *Vangueria macrocalyx*. However, since
595 comparison of the vouchered *V. macrocalyx* specimen to other vouchered *Vangueria*
596 *dryadum* and *V. macrocalyx* by expert botanists clearly separated both species, we decided
597 to consider both species distinct.

598 Previous studies showed that Rubiaceae and Primulaceae species with heritable leaf
599 symbionts are monophyletic within their respective genera (Lemaire, Vandamme, *et al.*,
600 2011; Verstraete *et al.*, 2013). Thus, while the transition to a symbiotic state arose
601 separately in multiple plant genera, it likely evolved only once in each plant genus. The only
602 exception is the *Psychotria* genus, where it likely arose twice: once in species forming leaf
603 nodules, and once in species without leaf nodules (Lemaire, Lachenaud, *et al.*, 2012). The
604 repeated emergence of leaf symbiosis is reflected on the microbial side as well. A
605 parsimonious interpretation of whole genome phylogenetic analyses indicates that
606 *Burkholderia* endophytes evolved independently at least 8 times, most probably from
607 ancestors with an environmental lifestyle (Figure 1A). *Caballeronia* endophytes of *Ardisia*
608 seem to have emerged once, with most closely related species commonly isolated from soil
609 (Lim *et al.*, 2003; Vandamme *et al.*, 2013; Uroz and Oger, 2017). As previously reported,
610 symbionts of *Psychotria* and *Pavetta* cluster in 3 distinct phylogenetic groups within the
611 *Caballeronia* genus. Finally, symbionts of *Vangueria* and *Fadogia* belong to 5 distinct clades
612 within the genus *Paraburkholderia*. Apart from *Ca.* P. dryadicola that is without closely

related isolates, endophytic *Paraburkholderia* species also cluster together with species commonly isolated from soil (Verstraete *et al.*, 2014; Beukes *et al.*, 2019). High host-specificity is a hallmark of the *Psychotria*, *Pavetta*, and *Ardisia* leaf symbiosis, but this characteristic is not shared in *Vangueria* and *Fadogia*. Based on genome similarity, we identified at least three phylogenetically divergent endophyte species that can infect multiple hosts: *P. caledonica*, *P. phenoliruptrix*, and *Ca.* P. dryadicola. It is also possible that these plants are in the early stages of endophyte capture, where the plant is open to acquire endophytes from the soil, as previously hypothesized for *F. homblei* (Verstraete *et al.*, 2013). Endophytes might later evolve to become host-restricted and vertically transmitted, leading to diversification from their close relatives and forming new species. This could, for example, already be the case for *Ca.* P. soutpansbergensis, which is related to *P. phenoliruptrix* but shows a more divergent genome (ANI <95%). Overall, these results highlight the general plasticity of bacteria in the *Burkholderia s.l.*, as well as the probable frequent occurrence of host-switching or horizontal transmission within leaf symbiotic associations.

Genome reduction is a common trait of leaf endophytes

Bacterial genomes contain a wealth of information yet few leaf endophyte genomes are available. In this study we provide an additional thirteen leaf endophyte genome assemblies among which the first genomes of endophytes from *Vangueria* and *Fadogia*. Aside from the genomes of *P. caledonica* endophytes, all leaf endophyte genomes were small, mostly between 3.5 and 5 Mbp. This is well below the average 6.85 Mbp of the *Burkholderiaceae* family (Carlier *et al.*, 2016; Pinto-Carbó *et al.*, 2016). In addition to their small sizes, the genomes of *Psychotria*, *Pavetta*, and *Ardisia* endophytes show signs of advanced genome reduction. Only 41-70% of these genomes code for functional proteins, compared to an average of about 90% for free-living bacteria (Land *et al.*, 2015). Most of these genomes also contain a high proportion of mobile sequences, up to 9% of the total assembly. Together, this indicates ongoing reductive genome evolution, a process often observed in obligate endosymbiotic bacteria (Moran and Plague, 2004; Bennett and Moran, 2015). Interestingly, the MAGs of *Vangueria* and *Fadogia* endophytes, which are not contained in leaf nodules, also show signs of genome erosion: most MAGs of *P. phenoliruptrix* endophytes are at or below 5 Mbp in size, with over half of their proteome predicted as non-functional. The genomes of 2 *Ca.* P. dryadicola strains even approach the level of genome reduction found in

most *Psychotria* symbionts. The intermediate genome reduction in endophytes of *Vangueria* and *Fadogia* could be explained by the relatively recent origin of the symbiosis, although leaf symbiosis in *Fadogia* has been estimated to be older than in *Vangueria* (7.6 Mya vs. 3.7 Mya) (Verstraete *et al.*, 2017). Other factors likely contribute to the extent or pace of genome reduction in the endophytes, such as mode of transmission and transmission bottlenecks. The larger genome size and fewer pseudogenes compared to most other leaf endophytes may explain why we could isolate *P. caledonica* endophytes from *F. homblei*, but not other endophytes. We could not identify essential genes or pathways that were consistently missing in the genomes or MAGs of *Burkholderia* endophytes. It is therefore possible that other endophytic bacteria may be culturable using more complex or tailored culture conditions.

Secondary metabolism as key factor in the evolution of leaf symbiosis

Although leaf symbionts share a similar habitat and all belong to the *Burkholderia s. l.*, their core genome is surprisingly small and consists almost entirely (95%) of genes that are considered essential for cellular life. This poor conservation of accessory functions perhaps reflects the large diversity and possible redundancy of functions encoded in the genomes of *Burkholderia s.l.* that associate with plants. Interestingly, the capacity for production of secondary metabolites is a key common trait of *Burkholderia* leaf endophytes. We previously showed that *Ca.* B. crenata produces FR900359, a cyclic depsipeptide isolated from *A. crenata* leaves (Carlier *et al.*, 2016). This non-ribosomal peptide possesses unique pharmacological properties and may contribute to the protection of the host plant against insects (Carlier *et al.*, 2016; Crüsemann *et al.*, 2018). However, our data suggests that the production of cyclitols is widespread in leaf endophytic *Burkholderia*. Indeed, with the exception of *Ca*. B. crenata cited above, we found evidence for the presence of cyclitol biosynthetic pathways in all genomes of leaf endophytic *Burkholderia*. We have previously reported the presence of two gene clusters containing a 2-*epi*-5-*epi*-valiolone synthase (EEVS) in MAGs of *Psychotria* and *Pavetta* symbionts (Pinto-Carbó *et al.*, 2016). These gene clusters are likely responsible for the production of 2 distinct cyclitols: kirkamide, a C_7N aminocyclitol with insecticidal properties which has been detected in several *Psychotria* plants; and streptol-glucoside, a plant-growth inhibitor likewise detected in *Psychotria kirkii* (Sieber *et al.*, 2015; Pinto-Carbó *et al.*, 2016; Hsiao *et al.*, 2019). EEVS from leaf symbionts

belong to four phylogenetic clusters, including the two EEVS genes previously detected in *Psychotria* and *Pavetta* symbionts (Pinto-Carbó *et al.*, 2016). Similar to these previously analysed leaf endophyte genomes, the EEVS gene clusters in the newly sequenced genomes are flanked by IS-elements, and their phylogeny is incongruent with the species phylogeny. This indicates that these genes and clusters are likely acquired via horizontal gene transfer. This hypothesis is strengthened by the fact that the closest homologs of the genes in the EEVS clusters are found in genera as diverse as *Pseudomonas*, *Streptomyces*, and *Noviherbaspirillum*, but are rare in the genomes of *Burkholderia s.l.* The presence of the two main EEVS gene clusters (K-cluster and S-cluster) is not strictly linked to the symbiont or host taxonomy. For example, the EEVS of the K-cluster (hypothesised to produce kirkamide) is present in all sequenced symbionts of *Psychotria* and *Pavetta* but also in the endophytes of *F. homblei* and *V. soutpansbergensis*. However, in the latter two, accessory genes of the K-cluster are absent. It is possible that this EEVS interacts with gene products of other secondary metabolite clusters (Osborn *et al.*, 2017). We also noticed that some endophyte MAGs contain multiple EEVS genes or gene clusters. This could provide functional redundancy, protecting against the rampant genome erosion. For example, two genes of the S-cluster *Ca*. C. hochstetteri PhocE (endophyte of *Pavetta hochstetteri*) are likely pseudogenes, while the K-cluster gene is still complete. On the other hand, in *Ca.* Burkholderia humilis UZHbot5 (endophyte of *Psychotria humilis*) seven out of ten genes of the S-cluster (including the EEVS) are either missing or non-functional, and the K-cluster is heavily reduced with only four functional genes out of eight (including the EEVS). As one functional EEVS copy remains, it is possible that genes located elsewhere in the genome provide these functions, as kirkamide has previously been detected in extracts of *P. humilis* (Pinto-Carbó *et al.*, 2016). Alternatively, this symbiosis may have reached a “point of no return” where host and symbiont have become dependent on each other and non-performing symbionts can become fixed in the population (Bennett and Moran, 2015).

The presence of gene clusters coding for specialised secondary metabolites in all leaf symbionts could indicate that secondary metabolite production is either a prerequisite for or a consequence of an endophytic lifestyle. The fact that *P. caledonica* leaf symbionts have EEVS genes of different origin favours the hypothesis that the acquisition of secondary metabolism precedes an endophytic lifestyle. In this case, the ancestor of both endophytes

may have acquired differing EEVS genes or EEVS gene clusters through HGT followed by infection of the respective host plants. The lack of EEVS homolog in *Ca.* B. crenata Avir and Acre indicates that production of cyclitols is not essential for leaf symbiosis. Interestingly, MAGs of the sister species *Ca.* C. ardisicola Amam and Acor encode an EEVS and the full S-cluster complement. Since there is strong phylogenetic evidence of co-speciation in the *Burkholderia*/*Ardisia* association (Lemaire, Smets, *et al.*, 2011; Ku and Hu, 2014), the common ancestor of *Ca*. C. ardisicola and *Ca.* B. crenata possibly possessed both cyclitols and *frs* pathways, and one of these pathways was lost in the lineages leading to contemporary *Ca*. B. crenata and *Ca*. C. ardisicola. Alternatively, the genome of the common ancestor of *Ardisia*-associated *Burkholderia* may have encoded cyclitol S-cluster and later acquisition of the *frs* gene cluster in the Ca. B. crenata lineage alleviated the requirement of EEVS-related metabolism. The model of horizontal acquisition of secondary functions supports the model of endophyte evolution described by Lemaire *et al* (Lemaire, Vandamme, *et al.*, 2011). Different environmental strains which acquired genes for secondary metabolite production could colonise different host plants in the early open phase of symbiosis. The different phylogenetic endophyte clades observed in the *Burkholderia s.l.* phylogeny could each represent distinct acquisitions of secondary metabolite gene clusters by divergent free-living bacteria followed by colonisation of different host plants. Many *Burkholderia* species associate with eukaryotic hosts, including plants (Eberl and Vandamme, 2016), and many of these associations may be transient in nature. However, useful traits such as synthesis of protective metabolites may help stabilise these relationships, resulting in long-term associations such as leaf symbiosis.

Author contributions:

AC, MM, and BD designed the research. MM identified and collected wild plant specimens from the Pretoria region (South Africa). BD, MB, SS, and AC performed the laboratory experiments and analyses. GM analysed metabolomics data. PV analysed data and made taxonomic assignments. BD, MM and AC wrote the manuscript with input from all authors.

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Notes

The authors declare no conflict of interest.

Tables

Table 1: Genome statistics of newly assembled and re-assembled leaf endophyte genomes. Coding capacity refers to the proportion of the genome that codes for functional proteins.

Endophyte	Host species	Type	Assembly size (Mb)	Num. of contigs	N50 (bp)	GC content (%)	Average coverage	Num. of Functional genes	Coding Capacity (%)	Proportion of IS elements(%)	Genome completeness (%)	Genome purity (%)
***Ca.* Caballeronia ardisicola Acor**	*Ardisia cornudentata*	New assembly	3,95	332	19528	59,23	62x	2026	40,30	0,83	99,28	98,57
***Ca.* Burkholderia crenata UZHbot9**	*Ardisia crenata*	Re-assembly	2,65	607	6399	59,02	66x	1670	54,73	2,63	95,68	97,08
***Ca.* Caballeronia ardisicola Amam**	*Ardisia mamillata*	New assembly	4,38	333	19687	59,47	13x	2297	40,95	1,10	96,40	97,10
***Ca.* Burkholderia crenata Avir**	*Ardisia virens*	New assembly	2,58	605	6517	59,05	13x	1648	56,13	1,64	94,96	99,25
***Paraburkholderia caledonica* R-49542**	*Fadogia homblei*	Assembly from isolate	8,92	148	145314	61,59	148x	7695	82,83	1,32	100	100
***Paraburkholderia caledonica* R-82532**	*Fadogia homblei*	Assembly from isolate	8,71	123	239289	61,53	168x	7353	81,03	1,05	100	100
***Ca.* Caballeronia hochstetteri PhocE**	*Pavetta hochstetteri*	New assembly	3,50	324	18152	62,51	305x	1823	44,53	1,09	99,28	98,57
***Ca.* Burkholderia schumanniana UZHbot8**	*Pavetta schumanniana*	Re-assembly	3,62	412	14848	63,47	132x	2453	59,95	1,22	100	97,89
***Ca.* Burkholderia brachyanthoides UZHbot7**	*Psychotria brachyanthoides*	Re-assembly	3,75	648	8356	61,00	121x	2109	46,54	3,98	98,56	98,56
***Ca.* Burkholderia humilis UZHbot5**	*Psychotria humilis*	Re-assembly	5,32	238	103328	59,60	60x	3264	50,04	1,19	99,28	99,28
***Ca.* Burkholderia kirkii UZHbot1**	*Psychotria kirkii*	Reference	4,01	203	44916	62,91	196x*	2069	45,80	8,81	99,28	98,57
***Ca.* Burkholderia pumila UZHbot3**	*Psychotria pumila*	Re-assembly	3,70	463	12628	59,13	110x	2192	45,41	4,15	95,68	98,52
***Ca.* Burkholderia kirkii UZHbot2**	*Psychotria punctata*	Reference	3,91	48	100248	64,00	-	2539	54,61	9,17	99,28	98,57

***Ca.* Burkholderia calva UZHbot6**	*Psychotria umbellata*	Re-assembly	4,22	333	28025	61,30	131x	2306	44,37	1,63	98,56	97,86
***Ca.* Burkholderia verschuerenii UZHbot4**	*Psychotria verschuerenii*	Re-assembly	6,15	401	27267	62,07	39x	4839	70,21	0,99	97,84	98,55
***Ca*. Paraburkholderia dryadicola Vdry**	*Vangueria dryadum*	New assembly	4,29	153	50748	61,26	67x	2229	43,21	0,82	100	99,29
***Paraburkholderia phenoliruptrix* Vesc**	*Vangueria esculenta*	New assembly	4,99	180	50333	63,54	160x	3329	59,78	1,09	100	98,58
***Paraburkholderia phenoliruptrix* Vinf**	*Vangueria infausta*	New assembly	5,00	181	49920	63,51	147x	3320	59,29	1,17	100	98,58
***Ca*. Paraburkholderia dryadicola Vmac**	*Vangueria macrocalyx*	New assembly	4,31	150	54987	61,30	186x	2243	43,06	0,87	100	99,29
***Paraburkholderia phenoliruptrix* VmadMBG**	*Vangueria madagascariensis*	New assembly	4,77	247	34361	63,48	79x	3214	61,09	1,15	100	97,20
***Paraburkholderia phenoliruptrix* VmadEBG**	*Vangueria madagascariensis*	New assembly	4,76	242	34985	63,48	107x	3212	60,97	1,12	100	97,20
***Paraburkholderia phenoliruptrix* VmadSA**	*Vangueria madagascariensis*	New assembly	5,03	194	50250	63,49	133x	3291	59,22	0,97	100	99,29
***Paraburkholderia caledonica* Vpyg88**	*Vangueria pygmaea*	New assembly	7,44	92	232014	61,89	35x	6194	82,23	1,00	100	97,20
***Paraburkholderia caledonica* Vpyg08**	*Vangueria pygmaea*	New assembly	7,45	106	232088	61,90	43x	6193	82,33	1,07	100	97,20
***Paraburkholderia phenoliruptrix* Vran**	*Vangueria randii*	New assembly	4,98	205	50270	63,33	84x	3294	59,47	1,47	100	98,58
***Ca.* Paraburkholderia soutpansbergensis Vsou**	*Vangueria soutpansbergensis*	New assembly	5,18	51	337347	63,12	101x	3259	55,24	0,86	99,28	99,28

Table 2: EEVS S-cluster organisation in endophyte genomes. Genomes of the same host with the same cluster layout are merged. X: Gene present; -: Gene absent; **Ψ**: Gene predicted to be pseudogene; *: genes present on a different contig than the EEVS gene; +: m/z features consistent with streptol or streptol-glucoside detected in leaf extracts of host species; n.t.: not tested. Abbreviations: EEVS – 2-*epi*-5-*epi*-valiolone synthase. All genes of the cluster were found in the same orientation, with the same order. The gene order is preserved in the table, using the of *Ca.* B. kirkii UZHbot1 accessions as reference.

	ROK family protein	**EEVS**	**Sugar-nucleotide binding protein**	**Trehalose-6-phosphate synthase**	**Aspartate aminotransferase family protein**	**Alcohol dehydrogenase**	**HAD family hydrolase**	**MFS transporter**	**NTP-transferase**	**NUDIX hydrolase**	**Streptol and streptol-glucoside**
Reference accessions	CCD39391	CCD39393	CCD39394	CCD39395	KND54529	CCD39396	CCD39397	CCD39398	CCD39400	CCD39401	
***Ca.* Caballeronia ardisicola Acor**	X	X	X	X	X	X	X	X	X	X	n.t.
***Ca.* Caballeronia ardisicola Amam**	X	X	X	X	X	X	X	X	X	X	n.t.
***Ca.* Caballeronia hochstetteri PhocE**	X	X	X	**Ψ**	**Ψ**	X	X	X	X	X	n.t.
***Ca.* Burkholderia humilis UZHbot5**	X	**Ψ**	X	**Ψ**	X	-	-	-	-	**Ψ**	n.t.
***Ca.* Burkholderia kirkii UZHbot1**	X	X	X	X	-	X	X	X	**Ψ**	X	+
***Ca.* Burkholderia kirkii UZHbot2**	X	X	X	X	X	X	X	X	X	-	n.t.
***Ca.* Burkholderia schumanniana UZHbot8**	X	X	X	X	X	X	-	**Ψ***	X*	X*	n.t.
Paraburkholderia phenoliruptrix Vesc	X	X	X	X	X	X	X	X	X	**Ψ**	n.t.
Paraburkholderia phenoliruptrix Vinf	X	X	X	X	X	X	**Ψ**	X	X	**Ψ**	n.t.
Paraburkholderia phenoliruptrix VmadSA	X	X	X	X	X	X	X	X	X	**Ψ**	+
Paraburkholderia phenoliruptrix VmadMBG/VmadBGE	X	X	X	X	X	X	**Ψ**	X	X	**Ψ**	n.t.
***Paraburkholderia caledonica* Vpyg08/Vpyg88**	X	X	X	X	X	X	X	X	X	X	+
Paraburkholderia phenoliruptrix Vran	X	X	X	X	X	X	X	X	X	X	n.t.

Table 3: EEVS K-cluster organisation in endophyte genomes. Genomes of the same host with the same cluster layout are merged. X: Gene present; -: Gene absent; **Ψ**: Gene predicted to be pseudogene; *: protein overlaps with contig end, other genes of the cluster not found on other contigs; +: Kirkamide detected in leaf extracts of host species; n.t.: not tested; ‡ Data from Pinto-Carbo et al. 2016; Abbreviations: EEVS – 2-*epi*-5-*epi*-valiolone synthase. All genes of the cluster were found in the same orientation, with the same order. The gene order is preserved in the table, using the of *Ca.* B. kirkii UZHbot1 accessions as reference.

	GNAT family N-acetyltransferase	**Cupin Domain Containing protein**	**HAD family hydrolase**	**Gfo/Idh/MocA family oxidoreductase**	**6-phospho-beta-glucosidase**	**DegT/DnrJ/EryC1/StrS family aminotransferase**	**ROK family protein**	**EEVS**	**Kirkamide**
Reference accessions	CCD36711	CCD36712	CCD36713	CCD36714	CCD36715	CCD36716	CCD6717	CCD36718	
***Paraburkholderia caledonica* R-49542/R-82532**	-	-	-	-	-	-	-	X	-
***Ca.* Burkholderia brachyanthoides UZHbot7**	-	-	-	-	-	-	X/Ψ *	**Ψ**	-‡
***Ca.* Caballeronia hochstetteri PhocE**	X	X	X	X	X	X	X	X	n.t.
***Ca.* Burkholderia humilis UZHbot5**	-	X	**Ψ**	X	X	**Ψ**	X	X	+‡
***Ca*. Burkholderia kirkii UZHbot1**	X	X	X	X	X	X	X	X	+
***Ca*. Burkholderia pumila UZHbot3**	-	X	X	X	X	X	X	X	+‡
***Ca*. Burkholderia kirkii UZHbot2**	X	X	X	X	X	X	X	X	+‡
***Ca*. Burkholderia schumanniana UZHbot8**	X	X	X	X	X	X	X	X	-‡
***Ca*. Burkholderia calva UZHbot6**	X	X	X	X	X	X	X	X	-‡
***Ca*. Burkholderia verschuerenii UZHbot4**	X	X	X	X	X	X	X	X	+‡
***Ca.* Paraburkholderia soutpansbergensis Vsou**	-	-	-	-	-	-	-	X	n.t.

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