Roles of poly-3-hydroxybutyrate (PHB) and glycogen in symbiosis of Sinorhizobium meliloti with Medicago sp.

Chunxia Wang,1 Marsha Saldanha,2,† Xiaoyan Sheng,1 Kristopher J. Shelswell,2‡ Keith T. Walsh,2 Bruno W. S. Sobral1 and Trevor C. Charles2

Virginia Bioinformatics Institute, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA

Department of Biology, University of Waterloo, 200 University Avenue West, Waterloo, ON N2L 3G1, Canada

Correspondence
Chunxia Wang
cwang@vbi.vt.edu

INTRODUCTION

The Gram-negative soil bacterium Sinorhizobium meliloti fixes atmospheric nitrogen in symbiotic association with its host plants, including Medicago truncatula (barrel medic) and Medicago sativa (alfalfa). A successful symbiosis involves a complex series of interactions between the host and bacteria (Brewin, 1991; Long, 1989, 2001; van Rhijn & Vanderleyden, 1995). Initially, plants release flavonoids that attract S. meliloti cells from the surrounding environment to the plant’s roots, and induce the production of Nod factors, which are specific lipochitin oligosaccharides produced by the bacteria. The Nod factors then induce root hair curling and root nodule development. S. meliloti cells invade developing root nodules via extended invaginations of the root hair cell membrane, called infection threads, and root nodule invasion requires the action of additional signal molecules, such as the exopolysaccharides (EPSs) produced by S. meliloti. The infecting bacteria grow and divide as they progress through the infection thread (Gage et al., 1996), which is then degraded and the bacteria are taken into the cells of the developing nodule (Udvardi & Day, 1997). Once released from the infection threads, the bacterial cells differentiate into bacteroids, able to convert atmospheric N2 to ammonium (Schultze & Kondorosi, 1998).

Nitrogen fixation within legume nodules results from a complex metabolic exchange between the bacterium and its plant host. Rhizobia are strict aerobes; therefore dicarboxylates provided by plants are metabolized via the
tricarboxylic acid (TCA) cycle in the bacteroid. Nitrogenase is the enzyme responsible for converting N₂ into NH₃ and its activity is sensitive to oxygen, bringing about the need for anaerobic conditions within the nodule. Low levels of oxygen might be expected to limit the operation of the TCA cycle. It is possible that much of the carbon flow in the bacteroid may be linear, with the substrate diverted to storage pools such as polyhydroxybutyrate (PHB) and glycogen, and some of it may be secreted as amino acids (Lodwig & Poole, 2003). As a result of this complex situation, many of the bacterial metabolic processes that occur in the free-living state are not the same as in the nodule.

PHB and glycogen are major carbon storage compounds in rhizobia. The roles of PHB and glycogen in rhizobia–legume symbiosis are not fully understood (Lodwig & Poole, 2003; Mandon et al., 1998; Marroqui et al., 2001; Trainer & Charles, 2006). For instance, bacteroids of determinate nodules (e.g. bean nodules) often accumulate high levels of PHB, and the accumulation of PHB requires nitrogen fixation (Cermola et al., 2000). However, bacteroids of indeterminate nodules (e.g. alfalfa nodules) do not accumulate PHB (Aneja & Charles, 1999; Hirsch et al., 1983). In the symbiosis between S. meliloti and M. sativa, it has been reported that phb mutants form bacteroids capable of fixing nitrogen as efficiently as the wild-type (Aneja & Charles, 1999; Aneja et al., 2005; Cai et al., 2000; Povolo et al., 1994; Willis & Walker, 1998), but are less competitive than the wild-type (Aneja et al., 2005; Willis & Walker, 1998). Recently, it has been shown that S. meliloti phbC mutants are not only unable to produce PHB but are also deficient in synthesis of the EPS succinoglycan (EPSI) (Aneja et al., 2004). It has been hypothesized that PHB accumulated by the bacteria prior to infection serves to fuel infection and/or bacteroid differentiation (Lodwig et al., 2005).

Glycogen is synthesized in bacteria through the action of glycogen synthase on ADP-glucose (Ugalde et al., 2003), resulting in the formation of α-1,4-linked glucan. A common genetic organization of the glycogen metabolism genes is found in the closely related Agrobacterium tumefaciens, Rhizobium tropici, Rhizobium leguminosarum and Mesorhizobium loti, within the glgPBCApgm operon (Lepek et al., 2002). Through analysis of a glgA mutant of R. tropici, it has been shown that there may be a link between glycogen synthase deficiency, decreased EPS, and increased symbiotic performance during symbiosis with Phaseolus vulgaris (Marroqui et al., 2001). However, the reason for the increased symbiotic efficiency of the glgA mutant is uncertain (Lodwig & Poole, 2003). In M. loti and R. leguminosarum bv. phaseoli, glgA mutations were reported to have no effect on symbiosis (Lodwig et al., 2005). There are two predicted glycogen-synthase-encoding genes in S. meliloti (Galibert et al., 2001). The glgA1 gene is located within the glgPBCApgm operon on the chromosome, while the glgA2 gene is located on megaplasmid pSymB (Finan et al., 2001; Galibert et al., 2001). Under growth-limiting conditions, free-living rhizobial cells produce glycogen simultaneously with PHB (Tsien & Schmidt, 1977; Zevenhuizen, 1981). This suggests that glycogen metabolism may fulfil a similar role to PHB, and the carbon flux between the two compounds is relatively plastic and appears subject to common control (Povolo & Casella, 2000; Encarnacion et al., 2002; Dunn et al., 2002). In S. meliloti, it has been reported that under oxygen-limiting conditions free-living cells can use intracellular glycogen to generate ATP while maintaining their PHB content (Povolo & Casella, 2000). However, the relationship between these two compounds in the bacteroid is unclear. To better understand the roles these carbon storage compounds play in the symbiotic process and in the overall metabolism of S. meliloti, in both the free-living and bacteroid states, we constructed strains containing different combinations of mutations affecting PHB and glycogen biosynthesis. The symbiotic performance of the mutants was then evaluated on M. truncatula and M. sativa.

**METHODS**

**Bacterial strains, plasmids and growth conditions.** Strains and plasmids used in this work are shown in Table 1. S. meliloti strains were grown in TY medium (Beringer, 1974), MOPS (Mendrygal & Gonzalez, 2000) or YMB (g l⁻¹: K₂HPO₄, 0.5; MgSO₄.7H₂O, 0.2; NaCl, 0.1; mannitol, 10; yeast extract, 0.4) (Tombolini et al., 1995) at 30°C. Escherichia coli strains were grown at 37°C in Luria–Bertani medium (Miller, 1972). Antibiotics were used at the following concentrations: 100 μg ampicillin ml⁻¹, 20 μg kanamycin ml⁻¹, 25 μg chloramphenicol ml⁻¹, 50 μg rifampicin ml⁻¹, 50 μg spectinomycin ml⁻¹ and 50 μg streptomycin ml⁻¹. M9 minimal medium with various carbon sources, each at a final concentration of 15 mM, was prepared as described previously (Charles & Finan, 1991; Charles et al., 1997). Sucrose was added to the medium at 5% (w/v) when required. Media were solidified by the addition of 1.5% (w/v) agar. Liquid cultures were shaken at 220 r.p.m.

**Genetics and molecular biology techniques.** Bacterial conjugations and φM12 transductions were carried out as described previously (Charles & Finan, 1990, 1991). DNA manipulations were performed using standard methods (Ausubel et al., 1997). Oligonucleotide primers were purchased from Sigma-Aldrich. DNA amplification by PCR using Pfu DNA polymerase (Promega) was performed using an Eppendorf Mastercycler gradient (Brinkmann Instruments).

**Construction of in-frame deletion of glgA1.** The location of glgA1 in a cluster of other glycogen pathway genes directly upstream of the gpm gene required that we construct a non-polar mutant of glgA1. Oligonucleotide primers 5′-GATCGACAAGCTGGGAATGT-3′ and 5′-CACCCTGATATCCGACTG-3′ were designed to amplify a 2.0 kb glgA1-flanking region. After PCR using Pfu polymerase, the blunt-end amplification product was ligated into the HinClI site of pUC7, and the resulting construct was designated pMS007. The cloaked fragment was confirmed by DNA sequence analysis. Digestion of pMS007 with PstI followed by plasmid self-ligation resulted in the elimination of a 379 bp internal region of glgA1. This deletion construct was designated pMS008. The deletion fragment was subcloned into pk19mobsac using EcoRI, to make pMS010. Gene replacement in Rm1021 was carried out by first introducing pMS010 by triparental mating, selecting for Sm³Nmr single-crossover cointegrants. Subsequent selection for double-crossover events was carried out on TY agar containing 5%
**Table 1.** Bacterial strains and plasmids used in this study

<table>
<thead>
<tr>
<th>Strain or plasmid</th>
<th>Genotype or relevant characteristics*</th>
<th>Source or reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>S. meliloti</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rm1021</td>
<td>Derived from wild-type SU47, Sm&lt;sup&gt;+&lt;/sup&gt;</td>
<td>Meade et al. (1982)</td>
</tr>
<tr>
<td>Rm5000</td>
<td>SU47, Rif&lt;sup&gt;+&lt;/sup&gt;</td>
<td>Finan et al. (1984)</td>
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<tr>
<td>Rm11105</td>
<td>Rm1021 pMS007</td>
<td>Charles et al. (1997)</td>
</tr>
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<td>Rm11477</td>
<td>Rm5000 glgA2::ΩSpSm</td>
<td>This study</td>
</tr>
<tr>
<td>Rm11478</td>
<td>Rm1021 glgA2::ΩSpSm</td>
<td>This study</td>
</tr>
<tr>
<td>Rm11479</td>
<td>Rm1021 glgA1ΔPsiI</td>
<td>This study</td>
</tr>
<tr>
<td>Rm11480</td>
<td>Rm1021 pMS007, glgA1ΔPsiI</td>
<td>This study</td>
</tr>
<tr>
<td>Rm11481</td>
<td>Rm1021 pKS029, glgA2::ΩSpSm</td>
<td>This study</td>
</tr>
<tr>
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<td>Rm1021 glgA1ΔPsiI, glgA2::ΩSpSm</td>
<td>This study</td>
</tr>
<tr>
<td>Rm11483</td>
<td>Rm1021 glgA1ΔPsiI, glgA2::ΩSpSm, pKS031</td>
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<td><strong>E. coli</strong></td>
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<tr>
<td>DH5α</td>
<td>F&lt;sup&gt;−&lt;/sup&gt; endA1 hsdR17 (r&lt;sup&gt;−&lt;/sup&gt; m&lt;sup&gt;−&lt;/sup&gt;) supE44 thi-1 recA1 gyrA96 relA1 Δ(argF–lacZYA)U169 δ800lacZAM15, λ&lt;sup&gt;−&lt;/sup&gt;</td>
<td>Hanahan (1983)</td>
</tr>
<tr>
<td>MT616</td>
<td>MT607 (pRK600), mobilizer, Cm&lt;sup&gt;+&lt;/sup&gt;</td>
<td>Finan et al. (1986)</td>
</tr>
<tr>
<td><strong>Plasmids</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pGEM-T Easy</td>
<td>Amp&lt;sup&gt;+&lt;/sup&gt;, for cloning PCR products</td>
<td>Promega</td>
</tr>
<tr>
<td>pK19mobsac</td>
<td>Suicide vector, Nm/Km&lt;sup&gt;+&lt;/sup&gt;</td>
<td>Schafer et al. (1994)</td>
</tr>
<tr>
<td>pUC7</td>
<td>ColE1 cloning vector, Amp&lt;sup&gt;+&lt;/sup&gt;</td>
<td>Vieira &amp; Messing (1982)</td>
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<td>glgA2 in pGEM-T Easy</td>
<td>This study</td>
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<td>pKS031</td>
<td>glgA2::ΩSpSm&lt;sup&gt;+&lt;/sup&gt; in pGEM-T Easy</td>
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<td>pMS001</td>
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<td>glgA1ΔPsiI in HinclI site of pUC7</td>
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<tr>
<td>pMS010</td>
<td>glgA1ΔPsiI in EcoRI site of pK19mobsacB</td>
<td>This study</td>
</tr>
</tbody>
</table>

*Abbreviations for antibiotic resistance phenotypes: Amp, ampicillin; Sp, spectinomycin; Sm, streptomycin; Rif, rifampicin; Km, chloramphenicol; Nm, neomycin; Km, kanamycin.

Sucrose, followed by screening for Nm sensitivity. Presence of the deletion was confirmed by PCR, and the corresponding strain was designated Rm11479.

**Construction of insertion in glgA2.** In contrast to glgA1, the glgA2 gene is not predicted to be in an operon with any other genes. Oligonucleotide primers 5′-GTGCAATCAACAGTTCGTC-3′ and 5′-CCCCGACCTTCTGGTTTGG-3′ were designed to amplify a 1.5 kb glgA2-flanking region. After PCR using Taq polymerase, the resulting fragment was cloned into pGEM-T Easy vector to make pKS029. The insert was confirmed by DNA sequence analysis. A unique BamHI site was identified within the glgA2 coding region 759 bp downstream from the translation start codon, and the ΩSpSm interposon (Prentki & Krisch, 1984) was ligated into this site to make pKS031. The insert fragment was then subcloned into pK19mobsac using EcoRI to make pMS001. Gene replacement in Rm5000 was carried out by first introducing pMS001 by triparental mating, selecting for Rif<sup>+</sup>SpSm<sup>+</sup> single-crossover cointegrants. Selection for double-crossover events was carried out on TY agar containing Sm, Sp and 5% sucrose. Presence of the insertion was confirmed by Southern blotting (data not shown), and the corresponding strain was designated Rm11477. The mutation was transferred to the Rm1021 background by transduction of Sm<sup>+</sup> to make strain Rm11478.

**Biochemical assays.** Glycogen was extracted from cells and determined by anthrone, according to the procedure of Chun & Yin (1998). Cell number was determined by serial dilution and plating on TY medium. PHB assays were performed using the spectrophotometric technique (Law & Slepecky, 1961) as modified by Peoples & Sinkey (1989). Cells were harvested from *S. meliloti* cultures grown to saturation in YMB medium (50 ml). Following a saline wash and resuspension of cells in 50 ml saline, PHB was extracted from a 2 ml fraction of culture and assayed. The remaining 48 ml of culture was used for dry weight determination after incubation of the wet pellet at 37°C until no further decrease in weight was noted. Purified PHB was purchased from Sigma for use as a concentration standard. The EPS content was determined as previously described (Marroqui et al., 2001) from cultures grown in MOPS, YMB or TY for 5 days at 30°C. Phosphoglucomutase (PGM) activity was assayed according to the procedure of Buchanan et al. (2005) from bacteria in mid-exponential phase (OD<sub>600</sub> 0.4) grown in TY medium.

**Symbiotic assays.** TY-grown bacterial cells in the late-exponential phase were collected by centrifugation, washed twice in 10 mM MgSO<sub>4</sub>, and resuspended in 10 mM MgSO<sub>4</sub>. *Medicago truncatula* Jemalong (line A17) seeds were obtained from Dr S. Long (Stanford University). Prior to germination, seeds were scarified by treatment with concentrated H<sub>2</sub>SO<sub>4</sub> for 5 min, rinsed thoroughly with sterile distilled water, and treated with 2.5% sodium hypochlorite for 3 min. *Medicago sativa* cv. Iroquois seeds were treated with 75% ethanol for 2 min followed by 2.5% sodium hypochlorite for 15 min with gentle shaking. Following thorough rinsing, the treated seeds were placed into sealed Petri plates containing 1% agar at room temperature in the dark for 24 h.
Nodulation kinetics were determined by the growth pouch method. Both *M. truncatula* and *M. sativa* were used as hosts to test the nodulation of the *S. meliloti* strains. Germinated seedlings were transferred to growth pouches (MEGA International). Each pouch contained 5 ml Fahraeus medium (Fahraeus, 1957) with six seedlings. Pouches were put in a growth chamber under the following conditions: 18 h day/6 h night cycle (22 ºC light/18 ºC dark), and 60 % relative humidity. After 4 days in the growth pouch, the roots were inoculated with 150 µl of appropriate bacterial suspension (OD600 adjusted to 0.01) per plant. The pouches were wrapped with PVC film and returned to the growth chamber. The plants were visually screened for nodule formation by observing the root system every second day for a minimum of 4 weeks. Bacteria were recovered from nodules as described by Doherty et al. (1988) and dilutions were plated on LB plates containing appropriate antibiotics.

For assays in the growth chamber, plants were grown in sterile pots (4 x 4 inches, 9 plantlets per pot) containing Jensen’s N-free plant nutrient solution (Jensen, 1942) treated vermiculite (Sta-Green, St Louis, USA), as described previously (Aneja & Charles, 1999). The plants were inoculated 5 days after germination, with the appropriate *S. meliloti* strains. Each seedling was inoculated with 5 ml of the cell suspension (OD600 adjusted to 0.12). The control seedlings were inoculated with 5 ml of 10 mM MgSO4. Each treatment included three replicates, where each replicate consisted of one pot with nine plants. The pots were covered with PVC film and placed in randomized blocks with six replicates, where each replicate consisted of one pot with nine plants. The pots were covered with PVC film and placed in randomized blocks in a growth chamber under the conditions previously described. Plants were harvested at 14, 21 and 49 days after inoculation (d.a.i.). Nitrogen fixation activity was determined by the acetylene reduction method as follows. Ten millilitres of acetylene gas (generated by the reaction of water and calcium carbide) was injected into stoppered 100 ml bottles containing plants inoculated with various *S. meliloti* strains. The bottles were incubated for 3 h before analysis. A 200 µl sample from each bottle was analysed for the presence of acetylene and ethylene using a gas chromatograph (ThermoFinnigan, Trace GC 2000) equipped with an HP-AL/M column (30 m, J&W Scientific, Agilent Technologies) and a flame-ionization detector. The flow rate of the carrier gas was 35 ml min−1, air at 350 ml min−1, and helium as the makeup gas at 30 ml min−1. The oven program was 100 ºC isocratic for 6 min. Following the acetylene reduction assay, the nodules were stripped off the roots, counted, dried at 80 ºC for 48 h, and weighed (nodule number corresponded to nodule dry weight). The shoot dry weight of the plants was also measured. Phenyloexis of bacteria recovered from nodules were checked on the appropriate media. The presence of pink cylindrical nodules on healthy dark-green plants was taken as evidence that nitrogen fixation was occurring.

**Nodule sectioning, staining and microscopy.** Nodules were fixed in a solution of 2.5 % (v/v) glutaraldehyde in 0.05 M sodium cacodylate (pH 7.3) overnight to adequately fix all the cells. The fixative was washed out by three successive 10 min washes in 0.05 M sodium cacodylate and the nodules were postfixed in 1 % (w/v) osmium tetroxide (OsO4) in 0.05 M sodium cacodylate for 1 h at room temperature. The osmium fixation was followed by three 10 min washes in distilled water before beginning the acetone dehydration series (10, 20, 30, 50, 70, 95 %, and 3 x 100 % acetone each for approximately 20 min). Once dehydrated, the samples were gradually infiltrated with Spurr’s resin (Polysciences Co.) by successive changes of acetone/resin mixes over approximately 48 h at room temperature (3:1 for 1 h, 1:1 for overnight, 1:3 for 3–4 h, then 100 % resin overnight). Samples then were embedded into Beem capsules full of fresh Spurr’s resin and placed at 60 ºC for 24 h to polymerize. Sections (longitudinal) with a thickness of 90 nm were made with a Leica Ultratwin UCT diamond knife and placed on a 200-mesh copper grid. Imaging was performed with a Zeiss 10CA transmission electron microscope at 60 kV accelerating voltage and at room temperature.

**For light microscopy, sections (longitudinal) 0.9 µm thick were dried onto glass slides and stained with 1 % (w/v) periodic acid, followed by treatment with Schiff’s reagent. Photographs were taken on a Nikon E600 light microscope.**

**Statistical analysis.** All the data presented for PHB, glycogen, EPS, nodule numbers, acetylene reduction assays, shoot dry weight and nodule dry weight are given as means with standard errors. The significance of the results was assessed using Student’s *t* test.

**RESULTS**

**Construction of the mutant strains**

There are two predicted glycogen-synthase-encoding genes in the *S. meliloti* genome (Galibert et al., 2001). The *glgA1* gene (Smc03924) predicts a 480 amino acid product, while the *glgA2* gene (Smh20704) predicts a 486 amino acid product. While *glgA1* is found in a cluster with other glycogen-related genes located on the chromosome, *glgA2* is located on megaplasmid pSymB and is not associated with such genes. A *glgA1* mutation was constructed by in-frame deletion, preserving the expression of the downstream *pgm* gene, while a *glgA2* mutation was constructed by disruption of the gene with the OsPl5m interposon. A pre-existing Tn5-generated mutation of the PHB-synthase-encoding gene *phBC* was combined with *glgA1* and *glgA2* mutations to make all combinations of double mutants, and the triple mutant by transduction (Table 1). The mutants were confirmed by Southern blot analysis (data not shown here).

**S. meliloti** strains lacking *phbC* function do not produce PHB

PHB production was assayed in *S. meliloti* strains, using the wild-type strain Rm1021 and a previously described *phbC* mutant strain as controls. As previously reported, no PHB production was detected in any of the tested strains grown in rich TY medium. However, PHB production can reach more than 20 % of cell dry weight when the strain (e.g. Rm1021) is grown in YMB medium (Table 2). PHB was not detectable in free-living cells of any mutants containing the *phbC* mutation (Rm11105, Rm11480, Rm11481 and Rm11483) (Table 2), indicating that strains containing the *phbC* mutation lack the ability to produce PHB. The production of PHB decreased significantly in the *glgA1* mutants (Rm11479 and Rm11482).

**S. meliloti** strains lacking *glgA1* function do not produce glycogen

Glycogen was not detectable in any of the mutants containing the *glgA1* mutation, but the *glgA2* mutation did not affect glycogen accumulation (Table 2). The *glgA1* mutation also resulted in significantly less PHB production than in the wild-type. The production of glycogen was significantly higher in the *phbC* single mutant (Rm11105) than it was in the wild-type or *glgA2* mutants in MOPS and YMB media (Table 2). PGM assays were performed to confirm that the *glgA1* mutant was a non-polar mutant. The
results showed that PGM activity in the glgA1 mutant (5.88 mU mg⁻¹) was similar to that in the wild-type strain (4.91 mU mg⁻¹).

**EPS is not detectable in phbC mutants, but is increased in glgA mutants**

All tested strains grew normally and formed similar-sized colonies on complete medium (TY). However, on MOPS and YMB plates, the wild-type strain Rm1021, the glgA single mutant strains (Rm11478 and Rm11479) and the double mutant (Rm11482) exhibited mucoid morphology (EPS production), while the colony size of the phbC mutants (e.g. Rm11105, Rm11480, Rm11481 and Rm11483) was reduced significantly. The colonies appeared to have severely reduced levels of EPS. The quantitative assay confirmed that the glgA double mutant (Rm11482) had significantly increased levels of EPS after growth in MOPS medium (0 mM phosphate), but levels were normal after growth in YMB medium (3 mM phosphate), while the glgA1 or glgA2 single mutant produced almost the same amount of EPS as the wild-type under the same condition. As previously reported (Aneja et al., 2004), no EPS was detected in YMB cultures of any mutants containing the phbC mutation (Table 2), although succinoglycan production was detected in LB-agar-grown colonies stained with calcofluor (data not shown).

**Growth of mutant strains in minimal medium**

The growth of the various S. meliloti strains was determined in M9 containing different carbon sources at 30°C (Table 3). The growth of the glgA2 mutant, Rm11478, was similar to that of the wild-type, except for a slight reduction in growth rate in acetate and D-3-hydroxybutyrate (D-HB). The phbC single mutant (Rm11105) grew similarly to the wild-type on glucose, sucrose, fructose and succinate. However, the growth of Rm11105 was reduced severely on acetate and D-HB. In contrast, the glgA1 mutant (Rm11479) grew similarly to the wild-type on acetate and D-HB, but grew much more slowly than the wild-type on glucose, fructose, succinate, and especially sucrose. As expected from the growth of the single mutant, phbC double and triple mutants (Rm11480, Rm11481 and Rm11483) grew poorly on acetate and D-HB; the growth of glgA1 double and triple mutants (Rm11480, Rm11482 and Rm11483) was reduced severely on glucose, sucrose, fructose and succinate compared with the wild-type (Table 3). Interestingly, although the glgA1 mutant (Rm11479) grew very slowly on sucrose, when this mutation was combined with others, the corresponding strains (Rm11480, Rm482, and Rm11483) grew much better than the glgA1 single mutant.

**Absence of carbon storage synthesis in S. meliloti results in delay of nodule formation**

To address the question of whether glycogen or PHB production is required for effective symbiosis between legume and S. meliloti, we performed plant inoculation experiments using both M. truncatula and M. sativa. Plant seedlings were inoculated with S. meliloti strains and the appropriate controls. Nodule kinetics assays in growth pouches showed that all mutant strains, especially the phbC mutants, caused nodule formation delay compared with the wild-type strain, but the phenomenon was more clearly expressed on M. truncatula than M. sativa (Fig. 1). In all cases, nodules were cylindrical and pink.

**PHB synthesis is important for N₂ fixation in M. truncatula and younger M. sativa nodules**

For the wild-type Rm1021 strain, the nodulation assay demonstrated a severe reduction in acetylene reduction activity (ARA) at 49 d.a.i. compared to the level of ARA at 21 d.a.i. At 41 d.a.i., all treatments had similar shoot dry weight for both M. truncatula and M. sativa, reflecting the early stage of N₂ fixation. Inoculation with phbC mutants (Rm11105, Rm11480, Rm11481 and Rm11483) resulted in significantly lower nodule dry weight and ARA on both M.

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**Table 2. Phenotypes of the wild-type and mutants**

For all strains, PHB, glycogen and EPS were not detected in TY culture. ND, Not detectable due to poor growth in YMB medium. Values in the same column with different superscript letters are significantly different (P<0.05).

<table>
<thead>
<tr>
<th>Strain</th>
<th>Genotype</th>
<th>PHB (% cell dry wt)</th>
<th>Glycogen (µg per 10⁹ cells)</th>
<th>EPS per cell dry wt (g)</th>
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</thead>
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<tr>
<td></td>
<td></td>
<td>YMB</td>
<td>MOPS</td>
<td>YMB</td>
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<tr>
<td>Rm1021</td>
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<td>Rm11482</td>
<td>glgA1ΔPsI, glgA2::ΩSpSm</td>
<td>16.8ᵇ</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Rm11483</td>
<td>glgA1ΔPsI, glgA2::ΩSpSm, phbC::Tn5</td>
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</tr>
</tbody>
</table>
Table 3. Doubling time (h) of the wild-type and mutants on different carbon sources

<table>
<thead>
<tr>
<th>Strain</th>
<th>Genotype</th>
<th>TY</th>
<th>Glucose</th>
<th>Sucrose</th>
<th>Fructose</th>
<th>Succinate</th>
<th>Acetoacetate</th>
<th>D-HB</th>
</tr>
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<tbody>
<tr>
<td>Rm1021</td>
<td>Wild-type</td>
<td>4.1</td>
<td>5.8</td>
<td>5.5</td>
<td>5.2</td>
<td>6.3</td>
<td>15.7</td>
<td>12.1</td>
</tr>
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<td>phbC::Tn5</td>
<td>4.1</td>
<td>5.1</td>
<td>6.0</td>
<td>4.6</td>
<td>6.3</td>
<td>30.1</td>
<td>26.4</td>
</tr>
<tr>
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<td>glgA2::ΩSpSm</td>
<td>4.1</td>
<td>5.1</td>
<td>4.8</td>
<td>4.9</td>
<td>6.1</td>
<td>16.8</td>
<td>13.6</td>
</tr>
<tr>
<td>Rm11479</td>
<td>glgA1ΔPsfl</td>
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<td>13.9</td>
<td>62.7</td>
<td>20.5</td>
<td>9.6</td>
<td>16.5</td>
<td>12.1</td>
</tr>
<tr>
<td>Rm11480</td>
<td>phbC::Tn5, glgA1ΔPsfl</td>
<td>4.5</td>
<td>13.9</td>
<td>23.5</td>
<td>19.8</td>
<td>9.5</td>
<td>35.4</td>
<td>31.4</td>
</tr>
<tr>
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<td>phbC::Tn5, glgA2::ΩSpSm</td>
<td>3.9</td>
<td>5.1</td>
<td>5.1</td>
<td>4.3</td>
<td>7.1</td>
<td>31.4</td>
<td>29.5</td>
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<tr>
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<td>glgA1ΔPsfl, glgA2::ΩSpSm</td>
<td>4.0</td>
<td>10.4</td>
<td>22.8</td>
<td>20.1</td>
<td>9.5</td>
<td>18.1</td>
<td>10.6</td>
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<tr>
<td>Rm11483</td>
<td>glgA1ΔPsfl, glgA2::ΩSpSm, phbC::Tn5</td>
<td>4.4</td>
<td>20.2</td>
<td>27.9</td>
<td>20.8</td>
<td>16.2</td>
<td>33.8</td>
<td>34.2</td>
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</table>

*truncatula* and *M. sativa* (Fig. 2), but the effect was much more pronounced on *M. truncatula*. At 21 d.a.i., phbC mutants had significantly lower shoot dry weight than the wild-type on *M. truncatula*. However, on *M. sativa*, the phbC mutants performed differently. Some of them (Rm11105 and Rm11480) had significantly lower shoot dry weight than the non-infected control. However, inoculation with the phbC single mutant (Rm11105) resulted in similar nodule dry weight and ARA to the wild-type in the older *M. sativa* plants (Fig. 2).

**Fig. 1.** Kinetics of nodulation on *M. truncatula* (a) and *M. sativa* (b) in growth pouches. Strains used were Rm1021 (wild-type) (●), Rm11105 (phbC::Tn5) (■), Rm11478 (glgA2::ΩSpSm) (▲), Rm11479 (glgA1ΔPsfl) (×), Rm11480 (phbC::Tn5, glgA1ΔPsfl) (□), Rm11481 (phbC::Tn5, glgA2::ΩSpSm) (△), Rm11482 (glgA1ΔPsfl, glgA2::ΩSpSm) (+), and Rm11483 (glgA1ΔPsfl, glgA2::ΩSpSm, phbC::Tn5) (−). Values represent the mean of three replicates (six plants per replicate).

Block of glycogen synthesis results in low levels of N₂ fixation in *M. truncatula* nodules, but not in younger nodules of *M. sativa*

At 14 d.a.i., even though all treatments gave similar shoot dry weights on both *M. truncatula* and *M. sativa*, the glycogen mutants (Rm11478, Rm11479 and Rm11482) had significantly lower ARA than the wild-type strain on *M. truncatula*. On *M. sativa*, these mutants had significantly higher ARA than the wild-type strain. At 21 d.a.i., all the glycogen mutants gave lower shoot dry weights than the wild-type on *M. truncatula*, but similar shoot dry weights to the wild-type strain on *M. sativa*, while these mutants had lower nodule dry weight and ARA than the wild-type strain on both *M. truncatula* and *M. sativa* (Fig. 2). After 7 weeks (49 d.a.i.), plants inoculated with glgA1 or glgA2 mutants (Rm11478, Rm11479 and Rm11482) exhibited decreased shoot dry weight, nodule dry weight and ARA on both *M. truncatula* and *M. sativa*.

Ultrastructural analysis of phbC and glgA mutants

Electron micrographs of *M. truncatula* nodule (longitudinal) sections showed that bacteroids mutated in glgA1, glgA2 or phbC were similar to the wild-type. Sections through nodule infection threads showed that wild-type bacteria contained PHB granules. As would be
expected for a mutant lacking PHB, there were no PHB granules present in \( \text{phbC} \) mutant Rm11105 bacteria inside infection threads (Fig. 3).

Light micrographs of nodules (longitudinal sections) infected with Rm1021 and glycogen mutants (Rm11478, Rm11479) showed that the plant cells were filled with starch granules only in the defined region of the nodules (Fig. 4a–c). However, nodules formed by either the \( \text{phbC} \) mutant Rm11105 or the triple mutant Rm11483 (\( \text{glgA1} \text{glgA2 phbC} \)) showed a remarkable increase in the amount of starch dispersed throughout the nodule, especially the \( \text{phbC} \) single mutant Rm11105 (Fig. 4d, e). In all cases, starch accumulation occurred mainly in non-infected interstitial host cells.

**DISCUSSION**

It is well established that PHB and glycogen both function as major carbon storage compounds in rhizobia. The study of their respective roles in the process of root nodulation is somewhat complicated by the potential overlap in their functions. The application of mutational analysis in the well-characterized \( \text{S. meliloti} \) Rm1021 was designed to address the roles of PHB and glycogen metabolism in the free-living state and in symbiosis with both \( \text{M. truncatula} \) and \( \text{M. sativa} \). The differing results on the two hosts emphasize the potential for host-dependent effects that should not be ignored.

**Fig. 2.** Symbiotic properties of the wild-type and mutant strains on \( \text{M. truncatula} \) (a) and \( \text{M. sativa} \) (b). Strains used were Rm1021 (wild-type) (WT), Rm11105 (\( \text{phbC} \text{}:\text{Tn5} \)) (c), Rm11478 (\( \text{glgA2} \text{::SpSm} \)) (a2), Rm11479 (\( \text{glgA1} \text{PstI} \)) (a1), Rm11480 (\( \text{phbC} \text{}:\text{Tn5, glgA1} \text{PstI} \)) (a1/c), Rm11481 (\( \text{phbC} \text{}:\text{Tn5, glgA2} \text{::SpSm} \)) (a2/c), Rm11482 (\( \text{glgA1} \text{PstI, glgA2} \text{::SpSm} \)) (a1/a2), and Rm11483 (\( \text{glgA1} \text{PstI, glgA2} \text{::SpSm, phbC} \text{}:\text{Tn5} \)) (a1/a2/c). Plants were grown and inoculated under growth chamber conditions as described in Methods. Dry weights and acetylene reduction were measured at 14 d.a.i. (white bars), 21 d.a.i. (stippled bars) and 49 d.a.i. (black bars). The experiment included an uninoculated control (plants grown in absence of bacteria). Values represent the mean ± SD of three replicates (nine plants per replicate).

**Fig. 3.** Electron micrographs of \( \text{M. truncatula} \) nodules infected with the wild-type and \( \text{phbC} \) mutant. (a) Nodule infected with Rm1021; (b) nodule infected with Rm11105 (\( \text{phbC} \)); (c) infection threads containing Rm1021; (d) infection threads containing Rm11105 (\( \text{phbC} \)).
The presence in the Rm1021 genome of two different genes predicted to encode glycogen synthase, the central enzyme of glycogen synthesis, needed to be clarified. Under the free-living growth conditions that we tested in this study, only glgA1 is required for glycogen synthesis, while glgA2 is not. Furthermore, the glucose growth deficiency of the glgA1 deletion mutant is similar to what has been reported with R. tropici (Marroqui et al., 2001) and R. leguminosarum bv. viciae (Lodwig et al., 2005) glgA mutants. The inhibition of glucose utilization might be due to feedback events that occur when the glycogen synthesis pathway is not available to accommodate some of the glucose that is taken up by the cell. This suggests that glycogen synthesis is used to balance the metabolism of glucose within the cell.

Whether the glgA2-encoded enzyme contributes to glycogen synthesis in symbiosis remains to be determined. While glgA2 does not appear to be directly involved in glycogen synthesis, it appears to influence nodulation and N₂ fixation by an unknown mechanism. On M. sativa especially, the decrease in symbiotic efficiency in older nodules resulting from the glgA2 mutation is striking.

We have shown that plants inoculated with PHB synthase mutants exhibited significantly reduced symbiotic properties (e.g. nodule formation kinetics, nodule dry weight and shoot dry weight). In other words, the ability to synthesize PHB can result in increased infection and is important for N₂ fixation. This may be partially due to the reduction of EPS in mutants containing an interrupted phbC gene. EPS is essential for the early infection process (Frayse et al., 2003) and plays a signalling role during nodulation (Niehaus & Becker, 1998), and mutants of S. meliloti unable to produce EPS are unable to invade and thus form ineffective nodules (Leigh & Walker, 1994). S. meliloti has at least two types of EPS: succinoglycan (EPSI) (Leigh & Walker, 1994) and galactoglucon (EPSII) (Glazebrook & Walker, 1989). A correlation between PHB metabolism and EPSI synthesis has been demonstrated (Aneja et al., 2004). However, mechanisms of regulation have not been characterized, and it is not known whether EPSI synthesis is affected by PHB metabolism during infection. Prior to symbiosis, S. meliloti maintains a store of carbon in the form of PHB when excess carbon is available, so that this polymer is presumably able to provide energy for cell division and invasion of the infection thread. EPS is synthesized during growth in high-carbon media (Mendrygal & Gonzalez, 2000); therefore this may occur in the rhizosphere as well. If PHB supplies extra carbon, the bacterium is better able to synthesize the required EPSs and initiate adherence, signalling, and infection of the nodule.

Previous ultrastructural studies have indicated that PHB granules are present in S. meliloti cells inside infection threads (Paau et al., 1978), but they disappear when cells are...
released from the infection threads, and mature bacteroids do not contain visible granules of PHB (Hirsch et al., 1983; Vasse et al., 1990). The absence of granules in the infection threads of M. truncatula infected with the phbC mutant Rm11105 reinforces the identification of the granules observed in Rm1021 during infection as PHB. It also confirmed that the PHB reserves are degraded by Rm1021 bacteria when they leave the infection thread and differentiate into bacteroids. Moreover, PHB-nonproducing mutants of S. meliloti have been described previously; these mutants are able to induce nitrogen-fixing nodules on M. sativa (Povolo et al., 1994; Willis & Walker, 1998), but are less competitive than wild-type (Povolo et al., 1994). Our results are consistent with these previous reports. We add the observation that PHB synthesis is important for N2 fixation in older M. truncatula nodules.

Our light microscopy observations show that in M. truncatula nodules infected with the wild-type strain Rm1021 a large amount of intercellular starch accumulation occurs in the II/III interzone as described for the pea nodules and alfalfa nodules (Lodwig et al., 2005; Vasse et al., 1990). This suggests that starch is the important carbon storage compound in M. truncatula nodules. We also observed that M. truncatula nodules containing either Rm11478 (glgA1 mutant) or Rm11479 (glgA2 mutant) had similar nodule zonation compared with Rm1021. This implies that glycogen synthesized by bacteria or bacteroids may not significantly influence the amount of carbon from the plant. However, the exact role and site of glycogen accumulation or degradation in the symbiosis remains to be elucidated. The phbC mutant Rm11105 and the triple mutant Rm11483 (glgA1 glgA2 phbC) had a different nodule zonation compared with Rm1021. These mutants had a large accumulation of starch distributed throughout the nodule rather than being limited to the II/III interzone as is the case for the wild-type and glgA mutants. Cutting a number of the different nodule longitudinal sections and then microscopically counting starch granules confirmed this observation. This result is contrary to what has been described for pea nodules infected with PHB synthesis mutants in which starch is depleted (Lodwig et al., 2005), and we believe that the starch accumulation that we observe is consistent with lower symbiotic nitrogen fixation and therefore reduced carbon demand on the plant.

Overall, we showed that neither the absence of PHB, glycogen, or both, completely abolishes the symbiotic capabilities of S. meliloti. However, our data suggest that both PHB and glycogen are influential in the nodulation and N2 fixation capabilities of S. meliloti. It is now widely accepted that carbon is supplied to the bacteroids in the form of dicarboxylic acids by plants to fuel nitrogen fixation (Lodwig & Poole, 2003). However, it is remarkable how imprecise our knowledge of much of bacteroid metabolism remains (Lodwig & Poole, 2003). With the ongoing S. meliloti Rm1021 functional genomics efforts, the data generated here will help to contribute towards a more complete picture of carbon metabolism occurring within this model microsymbiont during the transition from freeliving to bacteroid states. Studies on carbon metabolism should enlighten us on the strategies that rhizobia use to survive and compete in the rhizosphere and in association with the host plant.

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REFERENCES


