Exploring plant-microbe interactions of the rhizobacteria Bacillus subtilis and Bacillus mycoides by use of the CRISPR-Cas9 system
Yi, Yanglei; Li, Zhibo; Song, Chunxu; Kuipers, Oscar P

Published in:
Environmental Microbiology

DOI:
10.1111/1462-2920.14305

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2018

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.
Exploring plant-microbe interactions of the rhizobacteria *Bacillus subtilis* and *Bacillus mycoides* by use of the CRISPR-Cas9 system

Yanglei Yi, Zhibo Li, Chunxu Song and Oscar P. Kuipers ®*

Molecular Genetics, Groningen Biomolecular Sciences and Biotechnology Institute, University of Groningen, Groningen, The Netherlands.

Summary

*Bacillus subtilis* HS3 and *Bacillus mycoides* EC18 are two rhizosphere-associated bacteria with plant growth-promoting activity. The CRISPR-Cas9 system was implemented to study various aspects of plant-microbe interaction mechanisms of these two environmental isolates. The results show that fengycin and surfactin are involved in the antifungal activity of *B. subtilis* HS3. Moreover, this strain emits several other volatile organic compounds than 2,3-butanediol, contributing to plant growth promotion. Confocal laser scanning microscopy observations of the GFP-labelled strain showed that HS3 selectively colonizes root hairs of grass (*Lolium perenne*) in a hydroponic system. For *B. mycoides* EC18, we found that the wild-type EC18 strain and a ΔasbA (petroptenin-deficient) mutant, but not the ΔshbB (bacillibactin-deficient) and ADKO (asbA and dhbB double knockout) mutants, can increase the plant biomass and total chlorophyll. All the mutant strains have a reduced colonization capability on Chinese cabbage (*Brassica rapa*) roots, at the root tip and root hair region compared with the wild-type strain. These results indicate that the siderophore, bacillibactin, is involved in the plant growth promoting activity and could affect the root colonization of *B. mycoides*. Collectively, the CRISPR-Cas9 system we developed for environmental isolates is broadly applicable and will facilitate deciphering the mechanisms of *Bacillus*-plant interactions.

Introduction

Plant growth-promoting rhizobacteria (PGPR) are soil bacteria that are able to colonize the surface of the root (and sometimes root inner tissues) and to stimulate plant growth and health (Vacheron *et al*., 2013). The use of PGPR as supplements to, or replacements of, chemical fertilizers or pesticides have steadily increased in the last decades (Adesemoye and Kloeper, 2009). A large diversity of bacterial species has been reported to have PGPR activity. *Bacillus* is one of the PGPR that received most extensive attention due to its specific metabolic and physiological traits including secretion of antimicrobial or signal peptides and formation of stress resistant-endospores (*Kumar et al*., 2011), which facilitate the formulation into commercial fertilizers or biocontrol agents.

*B. subtilis* is widely recognized as a model organism for studying plant-microbe interaction, because it was found in association with different plants as a good colonizer, which is highly important for biocontrol application. The colonization of *B. subtilis* on roots surfaces involves chemotaxis and biofilm formation mechanisms (*Beauregard et al.*, 2013; Allard-Massicotte *et al*., 2016). After colonization, *B. subtilis* benefits the plant growth in various ways, including suppressing plant pathogens by the secretion of antimicrobial compounds, such as fengycin (*Romero et al*., 2007) and/or the induction of systematic resistance (*Ongena et al*., 2007). Moreover, direct plant growth promotion effects can be achieved by the secretion of cytokine hormones and volatiles that modify plant hormone homeostasis. Apart from *B. subtilis*, other *Bacillus* species with biocontrol and plant growth promotion (PGP) potential have broadened the application capacity of this genus. For instance, the rhizosphere-associated *B. mycoides* can actively colonize root surfaces and form biofilm-like matrix, while some of the strains are even capable of entering root tissues and use an endophytic life strategy (*Yi et al*., 2017). It has been reported that *B. mycoides* increases disease resistance of sugar beet through the elicitation of systemic resistance (*Bargabus et al*., 2002) or oxidative burst (*Bargabus et al*., 2003) of the host. The biocontrol effects of *B. mycoides* against *Botrytis cinerea* and *Pythium*...
Bacillus undomesticated hampers the application of this method since most of the (Vagner by an antibiotic marker or a toxic gene (Suzuki Bacillus, which involved a second counter selection step two-step system was developed for non-transformable vector require a relatively high transformation ef
mosomal gene by a mutated allele carried on a suicide methods for ple, enabling gene deletion/inactivation/insertion in differ-
study plant interaction mechanisms is hampered by the PGPR properties is being appreciated, the dif
methods for

directed mutagenesis in environmental

cas

B. subtilis

168 by Altenbuchner (2016). The plasmid pJOE8999 contains a cas9 gene controlled by a mannose inducible promoter and a sgRNA driven by a constitutive promoter. A similar system has been developed for B. subtilis ATCC6051 (Zhang et al., 2016). A year after, Park and coworkers described a two-plasmid CRISPR-Cas9 system to delete large fragments of in the B. subtilis chromosome (So et al., 2017). However, those methods are developed either for model strains or for undomesticated strains with natural transformability.

B. subtilis HS3 and B. mycoides EC18 were isolated from grass rhizosphere and potato endosphere respectively. B. subtilis strain HS3 displays excellent antifungal and plant growth promoting activity, while B. mycoides EC18 has good endophytic and plant growth promotion potential. Both strains are recalcitrant to conventional genetic manipulation methods. Inspired by the high genome editing efficiency in prokaryotic organisms of the CRISPR-Cas9 system, we attempted to implement this system in these two rhizosphere-associated Bacillus strains. In order to further investigate the molecular mechanisms of their plant-microbe interactions, we describe a high efficient genome editing method based on the CRISPR-Cas9 system. By applying this method, we generated three and two mutants in B. subtilis HS3 and B. mycoides EC18, respectively, with potential relevance for their biocontrol abilities. Genetic, phenotypic and microscopic analyses were conducted to assess functions of the mutants during plant-Bacillus interactions.

Results and discussion

Implementation of CRISPR-Cas9 systems in B. subtilis HS3 and B. mycoides EC18

The all-in-one CRISPR-Cas9 genome editing system pJOE8999 has been established for the model strain of B. subtilis 168 previously (Altenbuchner, 2016). The shuttle vector pJOE8999 has a pUC minimal origin of replication (ori) to facilitate the cloning in E. coli and a gram-positive temperature permissive ori pET194TS, which is permissive in B. subtilis below 37 °C and non-permissive above 42 °C. The cas9 gene is controlled by a mannose inducible promoter and the sgRNA is driven by a strong constitutive promoter. Although this system is highly efficient in B. subtilis 168 via natural transformation, the implementation of such system in an environmental Bacillus strain has not been reported. The gene deletion of this system depends on a double-cross-over allelic exchange event, which normally happens at a low frequency (Leloup et al., 1997). Since many environmental strains lack a functional competence system, electroporation was chosen to incorporate the plasmid into bacterial strains. In B. subtilis HS3, the transformation efficiency reached to (4.2 ± 1.1) × 10^3 cfu µg^{-1} DNA when using pNW33n plasmid. We transformed pJOE8999_gsigFHR into HS3 to delete the sigF gene. In order to increase the probability of double-cross-over events before the induction of cas9 gene, the cells were cultured overnight at 28 °C, 200 r.p.m. directly after electroporation in 1 ml

© 2018 The Authors. Environmental Microbiology published by Society for Applied Microbiology and John Wiley & Sons Ltd., Environmental Microbiology, 20, 4245–4260
LBSP medium without antibiotic and mannose. After plating the transformed cultures on LB agar with 10 \( \mu \)g ml\(^{-1} \) kanamycin and 0.2% mannose, approximately 200 colonies were obtained per \( \mu \)g plasmid DNA. Colony PCR with primer HS3_sigFcheckF and HS3_sigFcheckR showed a 100% editing efficiency (number of colonies with desired fragment size/total colony checked; Supporting Information Fig. S2). The mutant was cured from plasmids and confirmed by PCR (Fig. 1A). Then, it was subjected to microscope observation for the sporulation ability. As shown in Fig. 1C and D, almost all wild-type cells complete the sporulation process and contain phase-bright forespores. In comparison, the mutant \textit{B. subtilis} HS3\( \Delta \)sigF cells have an abnormal morphology caused by a failure to form proper spores.

Genetic manipulation tools for \textit{B. mycoides} have not been developed so far. Since the pJOE8999 system had high efficiency in the environmental isolate \textit{B. subtilis} HS3, we developed a similar system, pYCR, for \textit{B. mycoides} (Supporting Information Fig. S1). In order to knockout the \textit{sigF} gene, plasmid pYCR_gsigFHR was transformed into \textit{B. mycoides} EC18 by electroporation as described previously (Yi and Kuipers, 2017). The transformed cells were cultured in BHIS medium overnight and plated on LB agar plates with 100 \( \mu \)g ml\(^{-1} \) spectinomycin and 0.2% mannose. After incubation for 24 h at 30\(^{\circ}\)C, the transformants showed heterogeneity in colony size (Supporting Information Fig. S3). However, only the big colonies could grow when single colonies were inoculated into LB medium with 100 \( \mu \)g ml\(^{-1} \) spectinomycin. Thus, we speculated that the small colonies were possibly false positive colonies. Several ‘true’ transformants (big colonies) were checked by colony PCR with primers EC18_sigFcheckF and EC18_sigFcheckR. Ten out of thirteen colonies showed the expected mutant fragment size, which resulted in an editing efficiency of 77% (Supporting Information Fig. S2). The plasmid-cured mutant was confirmed by PCR and then grown in sporulation medium for microscopic observation. As shown in Fig. 1D and E, the EC18 wild-type strain has entered the last stage of sporulation.

![Fig. 1](image-url)

**Fig. 1.** CRISPR-Cas9-mediated knockout of \textit{sigF} gene in \textit{B. subtilis} HS3 and \textit{B. mycoides} EC18. A. Colony PCR confirmation for the deletion of the 121-bp of the \textit{sigF} gene in \textit{B. subtilis} HS3. B, C. Microscopic observation of forespores formed by HS3\( \Delta \)sigF and HS3 wild-type (WT) strains. Normal forespores were formed in HS3 WT and abnormal cell morphology was observed in the HS3\( \Delta \)sigF mutant due to the deletion of \textit{sigF}. D. Colony PCR confirmation for the deletion of the 60-bp of the \textit{sigF} gene in \textit{B. mycoides} EC18. (E-F) Microscopic observation of forespores formed by EC18\( \Delta \)sigF and EC18 wild-type. Normal forespores were formed in EC18 WT, while an abnormal cell morphology was observed in the EC18\( \Delta \)sigF mutant due to the deletion of \textit{sigF}. 

© 2018 The Authors. Environmental Microbiology published by Society for Applied Microbiology and John Wiley & Sons Ltd., *Environmental Microbiology*, 20, 4245–4260
and phase-bright forespores can be observed, while the mutant strain EC18Δsfp showed an abnormal cell morphology and some cells lysed.

**Fengycin and surfactin lipopeptides are involved in antifungal activity of B. subtilis HS3**

Production of antimicrobials by rhizobacteria is one of the major mechanisms for its antagonistic activity against phytopathogens, and they have great application potential being used as biocontrol agents. It has been reported that lipopeptides are the main antifungal compounds produced by *Bacillus* during the interactions with fungi (Zihalirwa Kulimushi et al., 2017). Antagonistic experiments showed that *B. subtilis* HS3 has significant antifungal activity against several phytopathogenic fungi (data not shown). In order to investigate if lipopeptides are (partially) responsible for the antifungal activity, we knocked out the 4′-phosphopantetheinyl transferase encoding gene (*sfp*) which is required for the production of several lipopeptide antibiotics (Quadri et al., 1998). The editing plasmid pJOE8999gsfpHR was transformed into HS3 by electroporation. The mutant colony was cured for plasmid and checked for the loss of a 188 bp fragment by PCR with the primers HS3_sfpcheckF and HS3_sfpcheckR (Fig. 2A). The mutation of the *sfp* gene resulted in loss of lipopeptide production, which was confirmed by reversed-phase-high-performance liquid chromatography (RP-HPLC; Fig. 2B). Furthermore, when the *sfp* gene was knocked out in HS3, antifungal activities were abolished against *Rhizoctonia solani* and *Fusarium culmorum*.

© 2018 The Authors. Environmental Microbiology published by Society for Applied Microbiology and John Wiley & Sons Ltd.,

**Environmental Microbiology, 20, 4245–4260**

<table>
<thead>
<tr>
<th>Strains or plasmids</th>
<th>Relevant characteristic</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>E. coli</em> MC1061</td>
<td>F-, araD139, D ara-1leu7696, D lacX74, galU, galK, hsdR2, mcrA, mcrB1, rpsL</td>
<td>Lab stock</td>
</tr>
<tr>
<td><em>B. subtilis</em> HS3</td>
<td>isolated from grass rhizosphere</td>
<td>This study</td>
</tr>
<tr>
<td><em>B. mycoides</em> EC18</td>
<td>isolated from potato endosphere</td>
<td>Yi et al. (2017)</td>
</tr>
<tr>
<td><em>B. subtilis</em> HS3Δsfp</td>
<td>HS3 derivative, Δsfp</td>
<td>This study</td>
</tr>
<tr>
<td><em>B. subtilis</em> HS3ΔalsD</td>
<td>HS3 derivative, ΔalsD</td>
<td>This study</td>
</tr>
<tr>
<td><em>B. subtilis</em> HS3Δsfp</td>
<td>HS3 derivative, GFP inserted into the chromosome.</td>
<td>This study</td>
</tr>
<tr>
<td><em>B. mycoides</em> EC18Δsfp</td>
<td>EC18 derivative, Δsfp</td>
<td>This study</td>
</tr>
<tr>
<td><em>B. mycoides</em> EC18ΔalsA</td>
<td>EC18 derivative, ΔalsA</td>
<td>This study</td>
</tr>
<tr>
<td><em>B. mycoides</em> EC18ΔdhbB</td>
<td>EC18 derivative, ΔdhbB</td>
<td>This study</td>
</tr>
<tr>
<td><em>B. mycoides</em> EC18ΔADKO</td>
<td>EC18 derivative, ΔalsA, ΔdhbB</td>
<td>This study</td>
</tr>
<tr>
<td><em>B. mycoides</em> EC18ΔGFP</td>
<td>EC18 derivative, GFP inserted into the chromosome.</td>
<td>This study</td>
</tr>
<tr>
<td><em>B. mycoides</em> EC18ΔA-GFP</td>
<td>EC18 derivative, ΔalsA, GFP inserted into the chromosome.</td>
<td>This study</td>
</tr>
<tr>
<td><em>B. mycoides</em> EC18ΔD-GFP</td>
<td>EC18 derivative, ΔdhbB, GFP inserted into the chromosome.</td>
<td>This study</td>
</tr>
<tr>
<td><em>B. mycoides</em> EC18ΔAD-GFP</td>
<td>EC18 derivative, ΔalsA, ΔdhbB, GFP inserted into the chromosome.</td>
<td>This study</td>
</tr>
<tr>
<td>pYCR</td>
<td>PUC ori, spec R, rep pWVO1, gRNA, Pm Man-cas9.</td>
<td>This study</td>
</tr>
<tr>
<td>PDR111_GFP(Sp)</td>
<td>bla amE, Phyperspank, specR, lacI ‘amyE’</td>
<td>Overkamp et al. (2013)</td>
</tr>
<tr>
<td>pNW-sfGFP(SPS6)</td>
<td><em>E. coli-Bacillus</em> shutter vector, Ppt-sGFP(SPS6), cmR</td>
<td>Yi et al. (2018)</td>
</tr>
<tr>
<td>PAW068</td>
<td>PUC ori, C9 transposase, rep pWVO1, cmR, specR</td>
<td>Wilson et al. (2007)</td>
</tr>
<tr>
<td>pJOE8999gsigFHR</td>
<td>pJOE8999 derivative, containing 20-nt spacer targeting sigF and fused up- and down- homologous fragment.</td>
<td>This study</td>
</tr>
<tr>
<td>pJOE8999gsfpHR</td>
<td>pJOE8999 derivative, containing 20-nt spacer targeting sfp and fused up- and down- homologous fragment.</td>
<td>This study</td>
</tr>
<tr>
<td>pJOE8999galsDHR</td>
<td>pJOE8999 derivative, containing 20-nt spacer targeting alsD and fused up- and down- homologous fragment.</td>
<td>This study</td>
</tr>
<tr>
<td>pJOE8999gdhdHR</td>
<td>pJOE8999 derivative, containing 20-nt spacer targeting bdhA and fused up- and down- homologous fragment.</td>
<td>This study</td>
</tr>
<tr>
<td>pJOE8999gamyGFP</td>
<td>pJOE8999 derivative, containing 20-nt spacer targeting α-amylase gene, and a gfp gene between the fused up- and down- homologous fragment.</td>
<td>This study</td>
</tr>
<tr>
<td>pYCRgsigFHR</td>
<td>pYCR derivative, containing 20-nt spacer targeting sigF and fused up- and down- homologous fragment.</td>
<td>This study</td>
</tr>
<tr>
<td>pYCRgasbHR</td>
<td>pYCR derivative, containing 20-nt spacer targeting asbA and fused up- and down- homologous fragment.</td>
<td>This study</td>
</tr>
<tr>
<td>pYCRgdhdHR</td>
<td>pYCR derivative, containing 20-nt spacer targeting dhbB and fused up- and down- homologous fragment.</td>
<td>This study</td>
</tr>
<tr>
<td>pYCRgamyGFP</td>
<td>pYCR derivative, containing 20-nt spacer targeting α-amylase gene, and a gfp gene between the fused up- and down- homologous fragment.</td>
<td>This study</td>
</tr>
</tbody>
</table>
To characterize the lipopeptide compounds, mass spectra of the fractions collected from HPLC were subjected by MALDI-TOF analysis. The mass spectra of the eight peaks showed a series of the masses ranging from m/z value 1017.95 to 1543.21 (Supporting Information Fig. S4), which can be divided into two groups corresponding to fengycin (peak 1–3) and surfactin (peak 4–8) families of lipopeptides (Pathak and Keharia, 2014; Yang et al., 2015). These results confirmed the importance of fengycin and surfactin families of lipopeptides in the antifungal activity of HS3 against plant pathogens, which provide valuable information when further develop this strain into biocontrol agent.

Volatiles produced by B. subtilis HS3 promote grass growth.

2,3-Butanediol is known to be a bacterial volatile organic compounds (VOC) that stimulate plant growth (Ryu et al., 2003). B. subtilis is capable of converting acetoin to 2,3-butanediol by the enzyme 2,3-butanediol dehydrogenase (BDH), which is encoded by the bdhA gene (Nicholson, 2008). The biosynthesis of acetoin involved the enzymes acetolactate synthase and acetolactate decarboxylase. The genes encoding these enzymes are alsS and alsD (Renna et al., 1993). In order to block the 2,3-butanediol, or both acetoin and 2,3-butanediol production in B. subtilis HS3, we deleted the bdhA and alsD gene by the editing vector pJOE8999_galsDHR and pJOE8999_gbhdHR respectively. After transformation, the colonies on LB-Km plates were checked by colony PCR. The primers HS3_alsDcheckF and HS3_alsDcheckR were used for HS3_ΔalsD mutant, and the primers HS3_bdhAcheck-F and HS3_bdhAcheck-R were used for HS3_ΔbdhA mutant.

As shown in Fig. 3A, both mutants showed the expected smaller fragment size than the wild-type. In order to detect the 2,3-butanediol production, wild-type and mutant strains were grown in LB medium containing 2% glucose, and the culture supernatant was run on silica gel TLC. A standard
2,3-butanediol was included as a control. The TLC results showed that the HS3 wild-type strain produced 2,3-butanediol, while the two mutants abolished the production (Fig. 3B). Grass seedlings (*Lolium perenne*) were exposed to VOCs produced by either wild-type HS3 or the mutants. Shoot and root biomass were increased approximately 2–3-fold compared with control plants for both wild-type HS3 and the mutants, and there was no significant difference between the wild-type strain and the mutants (Fig. 3C and D). Collectively, these results indicate that *B. subtilis* HS3 may emit other VOCs than 2,3-butanediol to mediate the growth of plants, which was beyond the scope of this study, but worthwhile to be further investigated in future work.

*B. subtilis* HS3 colonization of grass root observed by confocal laser scanning microscopy

The colonization of roots by rhizobacteria is the initial step in the interaction between beneficial bacteria and the host plant (Ahmad et al., 2011). Investigating the colonization...
behaviour and establishment of bacteria in the root system is of great ecological interest. Moreover, monitoring inoculated bacteria is essential for the assessment of the effectiveness and consistent performance of inoculated PGPR. A prerequisite for such a study is the ability to track a specific microbe in the complex rhizosphere environment (Kluepfel, 1993). A classical approach is to introduce antibiotic resistance to the bacterium, then plate and enumerate the introduced bacterium on selective medium. However, this method is indirect and has several drawbacks including marker instability and high background from antibiotic resistance microbial populations (Benizri et al., 2001). In situ methods coupled with molecular techniques can better capture microbial activity and interactions with the host (Nawy, 2016). Fluorescent protein (FP) labelling system for in situ studies allows direct visualization of the tagged bacteria at the single-cell level, without the addition of exogenous substrates (Larrainzar et al., 2005). To study bacterial-host interactions, inserting the FP gene into bacterial chromosome provides an advantageous approach, since plasmid-based FP labelling is mostly instable, and the fluorescence signal show heterogeneously among different cells (Rodriguez et al., 2006). The CRISPR-Cas9 system is a convenient and efficient method to perform marker-free genome insertions.

In a previous study, we selected an optimized gfp for rhizosphere Bacilli (Yi et al., 2018). The optimized gfp was introduced to the editing plasmid, pJOE8999_gamyGFP, which was transformed into HS3 by electroporation. The chromosomal GFP insertion was confirmed by colony PCR with the primers HS3_GFPcheckF and HS3_GFPcheckR. The anticipated fragment size of 3399 bp was obtained (Fig. 4A). Fluorescent microscopy

Fig. 4. Insertion of gfp gene into the chromosome of B. subtilis HS3 by CRISPR-Cas9 system and the observation of GFP-tagged cells in the grass rhizosphere from a hydroponic system. A. Colony PCR confirmation for the insertion of the gfp gene into B. subtilis HS3 chromosome. B. Fluorescent microscopic observation of the GFP-tagged HS3 cells. The HS3 GFP cells showed homogeneously green auto-fluorescence. C–H. In planta observation of B. subtilis HS3 cells in the rhizosphere of grass grown in a hydroponic system. Low amounts of colonization were found at the root tip, while strong colonization was exclusively observed at root hairs.
showed that HS3_GFP cells were expressing GFP homogeneously (Fig. 4B). The GFP-labelled strain was inoculated with grass plants. After 2 and 3 days of inoculation, the intact grass roots were visualized by confocal laser scanning microscopy (CLSM) immediately after sampling. The gfp-tagged cells could be clearly detected on the root surface but not in all parts. No colonization was observed at the root tip (Fig. 4C). Interestingly, low colonization was observed at the older basal root parts. But strong colonization was only found on the root hairs (Fig. 4D–H). Similar bacteria colonization pattern was reported by Prieto et al. (2011) when Pseudomonas spp. was inoculated into olive roots.

Siderophores produced by B. mycoides promote the growth of iron-starved plants

Siderophores are low-molecular-weight iron chelators produced by bacteria and fungi under iron-limiting conditions and facilitate the solubilization and transport of iron into the cell by the cognate transport system (Schalk et al., 2011). Siderophores might also play an important role in plant-microbe interactions, since PGPR that produce siderophores combat the pathogenic microorganisms sequestering Fe$^{3+}$ near the roots (Shilev, 2013). Moreover, the bacterial siderophores are often used by plants as iron source contributing to plant nutrition. For example, siderophores from strain Chryseobacterium C138 are effective in supplying Fe to iron-starved tomato plants by the roots (Radzki et al., 2013). The genome comparison analysis revealed two gene clusters responsible for siderophore biosynthesis in B. mycoides EC18: the asb operon for petrobactin and the dhb operon for bacillibactin (Supporting Information Fig. S5) and siderophore production was confirmed (Fig. 5B). It has been shown that petrobactin was required for B. anthracis growth both in iron-depleted conditions and in macrophages (Cendrowski et al., 2004). The presence of petrobactin biosynthesis gene (asbA) has been used as a marker gene for screening PGPR Bacillus (Lyngwi et al., 2016).

In order to determine whether petrobactin and bacillibactin are involved in the B. mycoides-plant interaction, we generated mutants of these two operons. The 20-nt
Fig. 6. Insertion of GFP into the chromosome of *B. mycoides* EC18 by CRISPR-Cas9 system and the observation of GFP-tagged cells in the rhizosphere of Chinese cabbage from a hydroponic system. A. Colony PCR confirmation for the insertion of the *gfp* gene in the chromosome *B. mycoides* EC18 and mutants. B. Fluorescent microscopic observation of the GFP-tagged *B. mycoides* wild-type and mutants cells. The EC18 WT as well as all the mutants’ cells showed homogeneously green auto-fluorescence. C–F. *In planta* observation of *B. mycoides* wild-type and mutant cells colonized in the rhizosphere of Chinese cabbage grown in a hydroponic system.
The spacer sequence was designed within the open reading frame of \( \text{asbA} \) and \( \text{dbhB} \) gene (Supporting Information Fig. S5). The spacer sequences as well as 1 kb flanking the up- and downstream region were introduced into pYCR to generate the editing plasmid pYCR\(_{\text{gasbHR}}\) and pYCR\(_{\text{gdhbHR}}\). The editing plasmids were transformed into \( B. \text{mycoides} \) EC18, and the transformants on LB-SPEC100 (with 0.2% mannone) plates were checked by colony PCR to assess the successful knockout. The colonies with expected knockout size were cured from the plasmid, which resulted in the clean knockout strain \( B. \text{mycoides} \) EC18\(\Delta\text{asbA}\) and \( B. \text{mycoides} \) EC18\(\Delta\text{dbhB}\). To make the \( \text{asbA} \) and \( \text{dbhB} \) double knockout strain \( B. \text{mycoides} \) ADKO, the plasmid pYCR\(_{\text{gdhbHR}}\) was transformed into the electro-competent cell of EC18\(\Delta\text{asbA}\), and the transformants were selected and confirmed as before. Colony PCR for \( \Delta\text{asbA} \), \( \Delta\text{dbhB} \) and the double knockout mutant ADKO showed that all the mutants have expected smaller fragment sizes compared with the wild-type strain: 463 bp for EC18\(\Delta\text{asbA}\) and 650 bp for EC18 wild type using primers EC18\_asb\_checkF and EC18\_asb\_checkR, and 184 bp for EC18\(\Delta\text{dbhB}\) and 299 bp for EC18 wild type using primers EC18\_dbh\_checkF and EC18\_dbh\_checkR (Fig. 5A). The siderophore production of all the mutants and the wild type were inspected by O-CAS agar (Fig. 5B). The production of siderophores by EC18\(\Delta\text{asbA}\) is comparable to that of wild-type. In contrast, the EC18\(\Delta\text{dbhB}\) had little production, and no siderophore production was detected from the double knockout EC18 ADKO. In the hydroponic system, the wild-type EC18 and the mutant EC18\(\Delta\text{asbA}\) increased the total chlorophyll content of Chinese cabbage significantly. There were no significant differences of the total chlorophyll of the plants treated with EC18\(\Delta\text{dbhB}\) and EC18 ADKO when compared with the control group (Fig. 5C). Biomass was also increased in the plants treated with wild type EC18 and EC18\(\Delta\text{asbA}\), with no significant difference between them. On the other hand, \( \Delta\text{dbhB} \) mutant and double mutant ADKO abolished the plant growth promoting effect completely (Fig. 5D). These results indicate that bacillibactin is the main siderophore produced by \( B. \text{mycoides} \) and contributes to the plant growth promoting effects.

Siderophore-deficient strains show reduced plant colonization ability

Since the strain EC18\(\Delta\text{dbhB}\) and EC18ADKO were unable to promote plant growth, we further compared their plant colonization capacity with the wild-type strain. The \( \text{gfp} \) gene with a strong constitutive promoter \( \text{Ppta} \) was inserted into the chromosome of the strain EC18, EC18\(\Delta\text{asbA}\), EC18\(\Delta\text{dbhA}\) and EC18ADKO to generate the GFP-tagged strain EC18-GFP, EC18\(\Delta\text{A-GFP}\), EC18\(\Delta\text{D-GFP}\) and EC18\(\Delta\text{AD-GFP}\). All the strains were checked by PCR with the primers EC18\_GFP\_gcheckF and EC18\_GFP\_gcheckR binding the flanking region of the spacer sequence in the chromosome. The anticipated 3434 bp amplicon size (Fig. 6A) and homogeneous fluorescence of the cells (Fig. 6B) indicate the \( \text{gfp} \) insertion was successful and functional. The GFP-tagged strains were inoculated with the Chinese cabbage roots in a hydroponic system. After 2 days, the plant roots were collected for analysing \( B. \text{mycoides} \) colonization. The direct CLSM observation showed that the wild-type strain colonizes all plant root regions in a heterogeneous manner: a few cells colonize at the root tip, while most cells colonize the root hair initiation region, and a large number of cells aggregated at the junction region of main root and lateral root (Fig. 6C). The petropectin mutant strain EC18\(\Delta\text{A-GFP}\) showed less colonization on the root tip and root hair region, compared with the wild-type control, while the lateral root emergence site was colonized by large bacterial populations (Fig. 6D). For the bacillibactin mutant EC18\(\Delta\text{D-GFP}\) and the double knockout strain EC18\(\Delta\text{AD-GFP}\), the colonization of root tip and root hair regions was only occasionally observed. The cells of the two strains were arranged in microcolonies at the junctions of lateral roots with the primary roots (Fig. 6E &F).

The colonization of the wild-type \( B. \text{mycoides} \) and the siderophore-deficient strains were further compared at population level by colony counting assay. In line with the CLSM observation results, all mutant strains have a decreased ability to colonize plant roots compared with the wild-type EC18. The colonization rate of wild-type strain is more than twofolds higher than that of siderophore-deficient mutants (Supporting Information Fig. S6). The fate of the inoculated bacterial cells was followed by calculating the percentage of spores formed in the rhizosphere. About 19.1% of the total bacterial cells of the wild-type EC18 were heat-resistant spores, which was significantly higher than that in all mutant groups (Supporting Information Fig. S6).

In conclusion, we implemented the CRISPR-Cas9 system to perform gene knockout and chromosomal insertion in environmental \( B. \text{subtilis} \) HS3 and \( B. \text{mycoides} \) EC18 strains. The high efficiency in the two phylogenetically distant \( \text{Bacillus} \) species implies the great potential of the CRISPR-Cas9 system in genome editing of rhizosphere Bacilli. The generated mutants were used to study various traits in plant-microbe interactions. By interrupting the \( \text{spf} \) gene in \( B. \text{subtilis} \) HS3, we demonstrated that the surfactin and fengycin family lipopeptides are responsible for the antagonistic activity against two relevant fungal pathogens. Moreover, we revealed that 2,3-butanediol is not the main VOC produced by HS3 to promote grass growth. Using a single-copy GFP-tagged
mutant, we showed that HS3 selectively colonizes on root hairs. In B. mycoides EC18, by interrupting two siderophore biosynthesis gene clusters via our CRISPR-Cas9 system, we highlighted the important role of petrobactin, in the plant growth promoting and root colonization.

Experimental procedures

Bacterial strains and growth conditions

Strains used in this study are shown in Table 1. E. coli MC1061 was used for plasmid construction. B. subtilis HS3 and B. mycoides EC18 were isolated from grass rhizosphere (Groningen, the Netherlands) and potato endosphere (Wijster, the Netherlands) respectively. E. coli and B. subtilis were grown in Lysogeny Broth (LB-Lennox: 1% Bacto-Tryptone, 0.5% Bacto-yeast extract, 0.5% NaCl) at 37 °C, 220 r.p.m. B. mycoides was grown in brain heart infusion (Bacto™ BHI, BD Bioscience, France) medium at 30 °C, 200 r.p.m. When required, antibiotics were added to the medium in the following final concentrations: 30 μg ml⁻¹ or 10 μg ml⁻¹ of kanamycin for E. coli and B. subtilis HS3 respectively. 100 μg ml⁻¹ of spectinomycin for both E. coli, and B. mycoides EC18. 0.2% of mannose was added to the medium to induce the cas9 expression. Solid media were prepared by adding 1.0% (wt/vol) agar (Bacto Agar, BD Bioscience, France).

DNA manipulation and oligonucleotides

Genomic DNA was isolated using GenElute bacterial genomic DNA kit (Sigma-Aldrich, USA) according to the manufacturer’s instruction. Plasmid DNA isolation, PCR products clean-up and gel extraction were performed using commercial NucleoSpin kits (Macherey-Nagel GmbH, Germany). Restriction, ligation, agarose gel electrophoresis and transformation of E. coli were performed as established protocols. Phusion (Thermo Scientific) polymerases were used for PCR to construct plasmid and DreamTaq polymerases DNA (Thermo Scientific) was used for colony PCR. Annealing reaction was carried out in annealing buffer containing 10 mM Tris (pH 8.0) and 50 mM NaCl with 10 μM of each oligonucleotide. Reaction tubes were heated to 95 °C for 5 min and cool to room temperature slowly. Oligonucleotides are listed in Supporting Information Table S1.

Plasmid construction

The plasmid pJOE8999 (Altenbuchner, 2016) was used for B. subtilis HS3 genome editing. For each mutant, the 20-nt protospacer sequence was designed by a web-based tool Benchling (https://www.benchling.com/) with B. subtilis 168 as reference genome and ‘NGG’ as PAM (Protospacer adjacent motif) sequence. The sequence with high on-target and off-target scores was chosen. As a proof of principle, the sigF gene was chosen because it is conserved in Bacilli. sigF encodes the forespore specific transcription factor σF that controls genes required for the early stages of prespore development (Hilbert and Piggot, 2004). To make a 121-bp deletion in the sigF gene, pJOE8999_gsigFHR was constructed in two steps. Plasmid pJOE8999 was first digested by Bsal resulting a 7423 bp fragment, which was ligated with the annealing product of primers HS3_gsigF_R and HS3_gsigF_F to generate plasmid pJOE8999_gsigF. A fragment of ~1 kb upstream and downstream of the spacer sequence was amplified by HS3_gsigFHR1_F & HS3_gsigFHR1_R and HS3_gsigFHR2_F & HS3_gsigFHR2_R primer sets respectively. The two fragments were connected by overlap PCR with the primers HS3_gsigFHR1_F and HS3_gsigFHR2_R, then digested with SfiI, purified and ligated into pJOE8999_gsigF to give plasmid pJOE8999_gsigFHR. In a similar way, pJOE8999_gbdtHR, pJOE8999_galsDHR, pJOE8999_gsfHR vectors were constructed with designed primers (see Supporting Information Table S1) to make bdhA, alsD and sfp gene knockout mutant. To insert a GFP into the genome, an α-amylase gene was chosen as integration location. pJOE8999_gamy vector was constructed by inserting HS3_gamy_F and HS3_gamy_R annealing product into Bsal site. Then a 2259 bp fragment including the whole α-amylase gene was amplified from the B. subtilis HS3 genome by primer set HS3_amy1F_sfi & HS3_amy2R_sfi and ligated into the SfiI site of pJOE8999_gamy to obtain pJOE8999_gamyFL. The pJOE8999_gamyFL vector was used as a template to be amplified by primers HS3_amy1R and HS3_amy2F. The resulting PCR product was ligated with a gfp fragment obtained from pNW33N_sfGFP(SPS6) by EcoRI and HindIII cutting to give pJOE8999_gamyGFP.

Since B. mycoides has a low thermotolerance at 37 °C, the temperature sensitive ori of pJOE8999 was changed from pET194ts to PWVO1, which is amplification permissive at 30 °C and non-permissive at 37 °C. The pJOE8999 backbone without pET194ts was amplified by primers pJOE-PET194_F and pJOE-PET194_R and the PWVO1 ori was amplified by primer PWVO1_F and PWVO1_R from plasmid PAW068. The two fragments were connected by Quick-fusion cloning to generate pJOE-PWVO1. Plasmid pYCR was constructed by isolating the SpecR cassette as a 1025 bp XhoI/PstI fragment from PDR111_GFP(Sp) (Overkamp et al., 2015) and ligating it with the XhoI/PstI-digested pJOE-PWVO1. The construction scheme of the CRISPR/CAS plasmid pYCR used in B. mycoides is shown in Supporting Information Fig. S1. When designing the 20-bp protospacer sequence in Benchling, the B. mycoides ATCC6462
genomic sequence was used as reference and ‘NGG’ as PAM. As a proof-of-principle trial, a 60-bp deletion of sigF gene was achieved using plasmid pYCR_sigFHR. The procedure to produce pYCR_sigFHR was the same as that described for pJOE8999_sigFHR. Plasmid pYCR was first digested with Bsal and ligated with the oligo annealing product of EC18_gsigF_F and EC18_gsigF_R to get the plasmid pYCR_sigF. Then a ~2 kb fragment combined with an upstream and a downstream fragment of the sigF spacer sequence was inserted at the SfiI site of pYCR_gsigF to generate pYCR_sigFHR. In a similar way, vector pYCR_gasbHR, pYCR_gdhbHR and pYCR_gamyGFP were constructed. For GFP insertion at the α-amyase gene locus, the vector pYCR_gamyGFP was generated with the same procedure as for pJOE8999_gamyGFP. All the plasmids are listed in Supporting Information Table S1.

Electroporation and mutant generation

The electroporation factors including growth media, growth stage, electroporation buffer, pulse strength and recovery incubation time were optimized step-by-step for B. subtilis HS3. Briefly, one B. subtilis HS3 colony was inoculated in LBSP medium (LB medium supplemented with 50 mM KH2PO4 and K2HPO4, and 0.5 M sorbitol) overnight, then diluted 50 times in LBSP medium until the OD600 nm reached 0.65. The cell culture was centrifuged 10 min at 4000 g, 4°C and the supernatant was discarded. The cell pellet was washed with pre-chilled electroporation buffer (0.25 M sorbitol in 10% glycerol solution) for four times and suspended in 1 ml electroporation buffer. 100 μl aliquots were flash frozen in liquid nitrogen and stored at −80°C until use. For B. mycoides CE18, the electroporation was performed as described previously (Yi and Kuipers, 2017).

About 1–2 μg plasmids were added into B. subtilis HS3 or B. mycoides CE18 electro-competent cells and exposed to a single pulse in a Gene Pulser System (Bio-Rad, USA) with the settings 25 μF, 10 kV cm⁻¹, 200 Ω. After electroporation, 1 ml growth media were directly added to the cells and incubated for 16–18 h at 28°C, 200 r.p.m. The whole cultures were then plated on LB plate with corresponding antibiotic (10 μg ml⁻¹ kanamycin for HS3 and 100 μg ml⁻¹ spectinomycin for EC18) and 0.2% mannose to activate the cas9 gene expression. After incubation at 28°C for 24 h, potential mutants were randomly picked and subjected to colony PCR with primers binding the flanking region of deletion or insertion sites on the genome (Supporting Information Table S1). A control was included using the genomic DNA as a template for PCR. PCR products were purified and verified by DNA sequencing. Colonies showing expected knockout band size were grown in LB liquid media with appropriate antibiotic and 0.2% mannose at 28°C, 200 r.p.m. overnight to remove any unedited cells. Edited bacterial cells carrying the knockout plasmid were inoculated into growth medium (LB for B. subtilis and BHI for B. mycoides) without antibiotic and grown at plasmid replication-defective temperatures (45°C for B. subtilis and 37°C for B. mycoides) to stationary phase. Two more rounds of growth were conducted by diluting the stationary phase culture into fresh medium. Then a serial dilution of the culture was plated on LB agar plates in the absence of antibiotics and incubated at plasmid replication-defective temperatures overnight to curing the plasmid. Plasmid-cured candidates were identified by the loss of antibiotic resistance.

Microscopy

For microscopic observation of sporulating cells of B. subtilis HS3 and B. mycoides CE18, the wildtype strains, as well as their sigF gene mutant HS3ΔsigF and EC18ΔsigF were first grown on LB agar plates overnight at 30°C. A single colony was inoculated into Schaeffer’s sporulation medium (Schaeffer et al., 1965) at 30°C, 200 r.p.m. After growing for 30 h to a late stage of sporulation, 1 μl of the diluted culture was loaded on a 1.0% agarose microscopy slide. Samples were observed by a Nikon Ti-E microscope equipped with a CoolsnapHQ2 camera, a 40x phase contrast objective, and an Intensilight light source. Pictures were taken with 0.35 s of exposure for phase contrast.

For the detection of fluorescent signals of the GFP insertion mutant, cells were grown in LB liquid medium overnight at 30°C. 200 r.p.m. One microliter of the diluted cell cultures was observed as described before. Pictures were taken with the following settings: 0.35 s of exposure for phase contrast, 2 s exposure for fluorescence at 440–490 nm excitation via a dichroic mirror of 495 nm and an emission filter at 500–505 nm. The final pictures were generated by ImageJ software.

HPLC and MALDI-TOF

Lipopeptides were extracted as previously described (Vater et al., 2002). Briefly, B. subtilis HS3 and its sfp mutant were grown in 200 ml LB broth at 28°C, 220 r.p.m. for overnight. The supernatant was collected by centrifugation (10000 x g, 10 min) and acidify by adding 6 M HCl to a final pH of 2.0. After overnight acidify at 4°C, the precipitation was collected by centrifugation (5000 x g, 20 min) and extracted with 10 ml methanol for 2 h. The crude extracts were filter sterilized with 0.45 μm Durapore™ membrane.

To check the lipopeptide extraction, crude extracts were subjected to HPLC equipped with Aeris wide pore
bated at 28 °C for 5 days. An agar plug (5 mm diameter) with fungal hyphae was then inoculated into a new PDA agar plate. To prepare bacteria inoculums, an overnight culture of \textit{B. subtilis} HS3 and its \textit{sfp} mutant were pelleted and suspended in sterile MQ water to a final OD600nm of 1.0. Subsequently, 5 μl of each inoculum was spotted 2 cm away from the fungi plug symmetrically. Plates were sealed with parafilm and incubated at 28 °C for 5 days.

**Effects of bacterial VOCs on plants and 2,3-butanediol detection**

To determine the effects of VOCs on the growth of perennial ryegrass (\textit{Lolium perenne}), seedlings were exposed to the VOCs emitted by the wild-type \textit{B. subtilis} HS3 or the mutants in a dual-dish plates system. The dual-dish plates were prepared with a small petri dish containing LB (with 1% glucose) agar fixed in a large round petri dish containing 1/2 MS agar (Duchefa Biochemie). For surface sterilization, grass seeds were pre-treated with 0.3 M HCl for 6 h, followed by a 5 min bath in 2% sodium hypochlorite and then rinsed with sterile water for 10 times. The sterile seeds were sown on wet filter paper in a square plate, which was sealed with parafilm and then incubated at 25 °C in the dark. After sown and germination for 5 days, the grass seedlings were then transferred to dual dish plates on 1/2 MS medium. After 2 days, 5 μl overnight bacterial culture (diluted to OD600 = 1.0) was inoculated on LB medium in the dual-dish plates. Plates were sealed with parafilm and incubated in the climate chamber (25/21 °C of day/night, 16/8 h of day/night, 120 μmol m⁻² s⁻¹, 70% humidity). After 7 days, the plant dry weights were measured.

The production of 2,3-butanediol in the \textit{B. subtilis} HS3 culture was detected by thin layer chromatography (TLC) as described before (Saran et al., 2014). Briefly, the bacteria were grown in 10 ml Erlenmeyer flasks containing LB medium supplemented with 1% glucose at 30 °C, 150 r.p.m. for 48 h. The culture was then collected and centrifuged at 10 000 × g for 10 min to spin down the cells. The supernatant was spotted on silica gel TLC plates and use 70:30:1.5 of the hexane: ethyl acetate:glacial acetic acid as the mobile phase. Butanediol was visualized after the plates were sprayed with vanillin reagent and incubated at 100 °C until the spots were visible.

**Siderophore detection**

Siderophore detection assay was performed using the overlay chrome azurol S (O-CAS) method (Pérez-Miranda et al., 2007). Iron-deprived LB medium was made by stirring 5 g chelax 100 resin (Sigma, USA) with 100 ml LB for 1 h. Strains were inoculated on iron-deprived LB agar plate at 30 °C overnight. The overlay CAS was applied to the plates and a change in colour was observed after a period of 1 h.

**Effects of a siderophore-producing/-deficient strain on iron-starved plants**

Chinese cabbage seeds were first washed with sterilized water to remove dust and particles. The seeds were then immersed in 2%-3% sodium hypochlorite for 5 min and rinsed with distilled water. Finally, seeds were dipped in 70% ethanol for 2–3 min followed by thorough rinsing with sterile water. The surface sterilized seeds were aseptically placed on 25% iron-deprived Hoagland medium solidified with 1% agar. The plates were incubated for germination and growth in a climate chamber (21 °C, 16/8 h of day/night, ~120 μmol m⁻² s⁻¹, 72% humidity) for 1 week. The seedlings were transferred to a 3 L hydroponic system containing 25% Hoagland’s solution (without EDTA as chelate agent) and continued to grow for 2 days. Hoagland solution was aerated by air pump through a 0.45 μm filter membrane. 10 ml of \textit{B. mycoides} wild-type or mutant strain in exponential growth phase were collected by centrifugation at 10 000 × g for 1 min. The cell pellet was resuspended in sterile water and added to the hydroponic system with final concentration of 2–3 × 10⁴ CFU/ml cells. After 2 weeks of co-culturing, plants were harvested and the fresh and dry weight of root and shoot were measured. The total chlorophyll content was determined according to the method of Amon (1949).

**Monitoring of bacterial colonization on plant roots**

Grass seeds were germinated on wet filter paper under sterile conditions as described before. The seedlings were transferred to a hydroponic system containing 1 l of 1/2 MS liquid medium and grown for 2 days. Then, the overnight culture of \textit{B. subtilis} HS3_GFP was centrifuged at 10 000 r.p.
m. for 1 min. The cell pellet was suspended with ½ MS and inoculated to grass plants at a final concentration of 10⁶ CFU ml⁻¹. After 2 and 3 days of co-culturing with bacteria, root samples were used for observation by a confocal laser scanning microscope (CLSM, LSM 800, Carl Zeiss, Germany). The CLSM was equipped with diode lasers and GaAsP detector. Images for fluorescence and bright field light channels were taken simultaneously. The CLSM settings were adjusted as follows: 0.2% power of the 488 nm laser line was set for excitation and 509–546 nm was set as emission wavelength. The pinhole size was 25 μm and pixel scanning time was 2.06 μs. The line scanning time was 2.47 ms with a line averaging of 2.

GFP labelled *B. mycoides* EC18 wild-type and siderophore deficient mutants were visualized in the rhizosphere of Chinese cabbage. Seven days old iron-starved seedlings were transferred to 25% Hoagland (EDTA was omitted) and grown for 2 days. *B. mycoides* EC18-GFP, EC18ΔAA-GFP, EC18ΔD-GFP and EC18ΔAD-GFP were grown overnight. Bacterial cells were collected at 10000 r.p.m. for 1 min and then inoculated to Chinese cabbage plants at a final concentration of 10⁶ CFU ml⁻¹. After 2 days of inoculation, the bacterial colonization of the wild type and mutant strains was compared at single cell level by CLSM observation, and at population level by colony counting. The colony counting assay was carried out as described by Dietel et al., with some modifications (Dietel et al., 2013). Briefly, roots were rinsed by sterile PBS before transferred into a 1.5 ml Eppendorf tube containing 1 ml PBS. A mild sonication treatment (Dietel et al., 2013) β-lactose dehydrogenase (EDTA was omitted) was recorded. The suspension was serially diluted and plated on LB agar plates. In parallel, a portion of the suspension was heated at 70 °C for 15 min prior to plating to calculate the number of bacterial spores in the rhizosphere. The plates were incubated at 30 °C overnight and the colony-forming unit (CFU) was counted.

**Acknowledgements**

We thank Dr. Auke van Heel in our group for his suggestions and comments on the manuscript. Y. Yi and Z. Li were financially supported by the Chinese Scholarship Council (CSC). C. Song was financially supported by Dutch NWO-TTW program Back to the Roots. The authors declare no conflict of interest.

**References**


large genomic deletion in *Bacillus subtilis* Front Microbiol. 8: 1167.


