



HAL
open science

Impacts of Atmospheric CO₂ and Soil Nutritional Value on Plant Responses to Rhizosphere Colonization by Soil Bacteria

Alex Williams, Pierre Pétriacq, David J Beerling, T E Anne Cotton, Jurriaan Ton

► **To cite this version:**

Alex Williams, Pierre Pétriacq, David J Beerling, T E Anne Cotton, Jurriaan Ton. Impacts of Atmospheric CO₂ and Soil Nutritional Value on Plant Responses to Rhizosphere Colonization by Soil Bacteria. *Frontiers in Plant Science*, 2018, 9, pp.1493. 10.3389/fpls.2018.01493 . hal-02626609

HAL Id: hal-02626609

<https://hal.inrae.fr/hal-02626609v1>

Submitted on 26 May 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License



Impacts of Atmospheric CO₂ and Soil Nutritional Value on Plant Responses to Rhizosphere Colonization by Soil Bacteria

Alex Williams^{1,2}, Pierre Pétriacq^{2,3,4}, David J. Beerling¹, T. E. Anne Cotton¹ and Jurriaan Ton^{1,2*}

¹ Department of Animal and Plant Sciences, University of Sheffield, Sheffield, United Kingdom, ² P³ Institute for Translational Plant and Soil Biology, Department of Animal and Plant Sciences, University of Sheffield, Sheffield, United Kingdom, ³ UMR 1332 Fruit Biology and Pathology, INRA-Bordeaux & University of Bordeaux, Villenave d'Ornon, France, ⁴ Plateforme Métabolome du Centre de Génomique Fonctionnelle de Bordeaux, INRA – Bordeaux, Villenave d'Ornon, France

OPEN ACCESS

Edited by:

Corné M. J. Pieterse,
Utrecht University, Netherlands

Reviewed by:

Ana Pineda,
Netherlands Institute of Ecology
(NIOO-KNAW), Netherlands
Pascale Beauregard,
Université de Sherbrooke, Canada

*Correspondence:

Jurriaan Ton
j.ton@sheffield.ac.uk

Specialty section:

This article was submitted to
Plant Microbe Interactions,
a section of the journal
Frontiers in Plant Science

Received: 29 March 2018

Accepted: 25 September 2018

Published: 22 October 2018

Citation:

Williams A, Pétriacq P,
Beerling DJ, Cotton TEA and Ton J
(2018) Impacts of Atmospheric CO₂
and Soil Nutritional Value on Plant
Responses to Rhizosphere
Colonization by Soil Bacteria.
Front. Plant Sci. 9:1493.
doi: 10.3389/fpls.2018.01493

Concerns over rising atmospheric CO₂ concentrations have led to growing interest in the effects of global change on plant-microbe interactions. As a primary substrate of plant metabolism, atmospheric CO₂ influences below-ground carbon allocation and root exudation chemistry, potentially affecting rhizosphere interactions with beneficial soil microbes. In this study, we have examined the effects of different atmospheric CO₂ concentrations on *Arabidopsis* rhizosphere colonization by the rhizobacterial strain *Pseudomonas simiae* WCS417 and the saprophytic strain *Pseudomonas putida* KT2440. Rhizosphere colonization by saprophytic KT2440 was not influenced by sub-ambient (200 ppm) and elevated (1,200 ppm) concentrations of CO₂, irrespective of the carbon (C) and nitrogen (N) content of the soil. Conversely, rhizosphere colonization by WCS417 in soil with relatively low C and N content increased from sub-ambient to elevated CO₂. Examination of plant responses to WCS417 revealed that plant growth and systemic resistance varied according to atmospheric CO₂ concentration and soil-type, ranging from growth promotion with induced susceptibility at sub-ambient CO₂, to growth repression with induced resistance at elevated CO₂. Collectively, our results demonstrate that the interaction between atmospheric CO₂ and soil nutritional status has a profound impact on plant responses to rhizobacteria. We conclude that predictions about plant performance under past and future climate scenarios depend on interactive plant responses to soil nutritional status and rhizobacteria.

Keywords: CO₂, PGPR, global change, rhizosphere, ISR

INTRODUCTION

Atmospheric CO₂ influences microbial biomass and diversity in the rhizosphere (Paterson et al., 1997). The plant-mediated effects of atmospheric CO₂ on soil microbial communities are well documented (Wiemken et al., 2001; Montealegre et al., 2002), indicating a dominant, plant-mediated mechanism. It is likely that the variation in root- microbe interactions under different

atmospheric conditions are due to changes in root exudates which are estimated to contain between 5 and 40% of plant photosynthetically fixed carbon (Lynch and Whipps, 1990; Hinsinger et al., 2006; Marschner, 2012). Since rhizodeposition of carbon (C) increases under elevated CO₂ (eCO₂; Phillips et al., 2009; Eisenhauer et al., 2012), it can be expected that rhizosphere colonization by microbes relying on C from plant exudates will also be enhanced (Lipson et al., 2005; Kassem et al., 2008; Eisenhauer et al., 2012). While it is clear that CO₂ alters overall microbial community composition across a range of different soil-types (Montealegre et al., 2002; Janus et al., 2005), the extent to which eCO₂ affects microbial interactions in the rhizosphere remains controversial. Using chloroform fumigation extraction to estimate microbial biomass, previous studies have reported both positive and negative relationships with eCO₂ (Rice et al., 1994; Ross et al., 1995; Kassem et al., 2008; Eisenhauer et al., 2012). It also remains contentious in how far eCO₂ induces shifts between fungal or bacterial communities, and the resultant effects on the functioning on rhizosphere microbes (Ross et al., 1995; Lipson et al., 2005; Drigo et al., 2008).

Early research on plant growth responses and the presence of specific rhizosphere microbes to eCO₂ have suggested a possible relationship between eCO₂, plant growth and increases in colonization by plant growth-promoting rhizobacteria (PGPR; O'Neill et al., 1987). PGPRs are often closely associated with plant roots and should, therefore, be more reliant on plant-derived C (Denef et al., 2007). Although many studies have addressed the effects of eCO₂ on plant-rhizobia and plant-mycorrhiza interactions (e.g., Rogers et al., 2009; Mohan et al., 2014), little is known about the specific impacts of eCO₂ on PGPR (Drigo et al., 2008). Considering that PGPR modulate a range of agronomically important plant traits, including plant growth, abiotic stress tolerance and resistance to pests, and diseases (Lugtenberg and Kamilova, 2009), this knowledge gap limits our ability to predict how anthropogenic global change will impact crop production and food security. Furthermore, the impacts of CO₂ across a range of CO₂ conditions, including sub-ambient CO₂ (saCO₂), remain poorly documented (Field et al., 2012). In a CO₂ gradient study (200–600 ppm), microbial biomass and soil respiration from a grassland ecosystem were not clearly related to CO₂ concentration (Gill et al., 2006). By contrast, analysis of fungal communities, using pyrosequencing of internal transcribed spacer sequences, revealed a positive relationship between operational taxonomic unit richness and CO₂ concentration that was soil-type dependent (Procter et al., 2014). While these studies suggest that atmospheric CO₂ impacts on plant-beneficial microbes in the rhizosphere, it remains difficult to ascertain the underpinning mechanisms and predict the corresponding plant responses to altered colonization by these microbes. Most studies on the effects of CO₂ gradients on rhizosphere microbes involved field experiments, which are prone to environmental variability, such as nutrient availability, soil moisture, temperature, soil pH, and plant species present (Freeman et al., 2004; Castro et al., 2010; Classen et al., 2015; Dam et al., 2017) and do not allow the manipulation of bacteria in the rhizosphere, hence preventing examination of their function.

In this study, we have investigated the impacts of a pre-industrial concentration of saCO₂ and a worst-case scenario projected concentration of eCO₂ on rhizosphere colonization of Arabidopsis roots by two well-characterized soil bacteria: the rhizosphere colonizer *Pseudomonas simiae* WCS417 (previously named *Pseudomonas fluorescens* WCS417; Berendsen et al., 2015) and the saprophytic soil colonizer *Pseudomonas putida* KT2440. We demonstrate that increasing CO₂ levels boost root colonization by WCS417 in soil with relatively low C and nitrogen (N) content. Interestingly, these effects were associated with contrasting growth and resistance responses by the host plant, demonstrating that high atmospheric CO₂ concentration can have profound and counterintuitive effects on plant growth and resistance due to altered rhizosphere interactions.

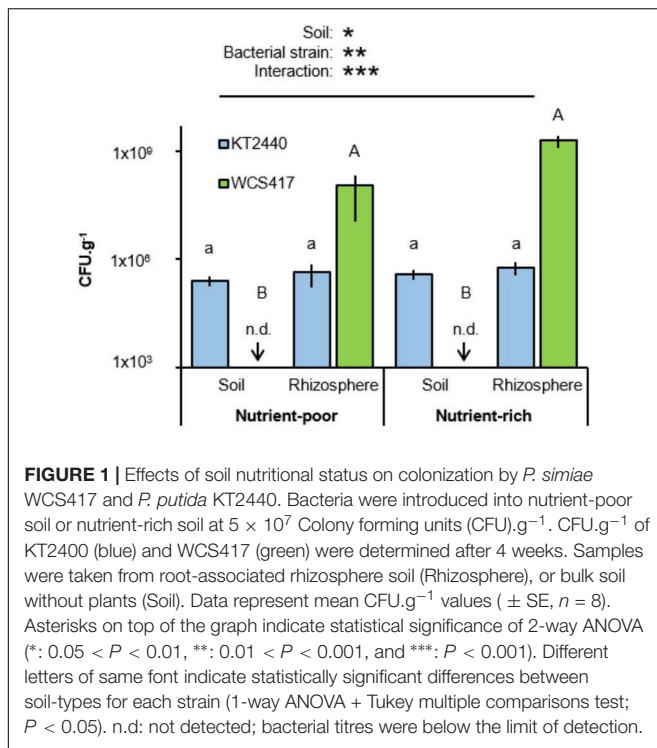
RESULTS

Impacts of Atmospheric CO₂ on Rhizosphere Colonization by Soil Bacteria Depends on Soil Quality and Bacterial Species

C and N content are markers for soil quality (Gil-Sotres et al., 2005), which has a direct impact on the performance of PGPR (e.g., Egamberdiyeva, 2007; Agbodjato et al., 2015). To examine the importance of soil quality on rhizosphere colonization by two well-studied soil bacteria, Arabidopsis was cultivated either in artificial nutrient-poor soil (1:9 sand:compost; v/v) with low C- and N-contents, or in nutrient-rich soil (2:3 sand:compost; v/v) with relatively high C and N content (Table 1). Soils were inoculated with 5×10^7 colony forming units (CFU).g⁻¹ soil of *P. simiae* WCS417, a rhizosphere colonizer (Rainey, 1999; Zamioudis et al., 2014), or *P. putida* KT2440, a more generalist saprophytic soil colonizer (Weinel et al., 2002). Soil with and without Arabidopsis plants (accession Col-0) were left for 4 weeks before sampling for quantification of bacterial colonization through enumeration of CFU on selective agar medium. Two-way ANOVA of CFU values revealed a statistically significant interaction between soil and bacterial strain ($P = 0.023$; Figure 1 and Supplementary Table S1), indicating that the two strains colonize the soil-types and soil compartments to different extents. Indeed, statistical analysis by Tukey *post hoc* tests revealed that titres of the rhizobacterial strain WCS417 were significantly higher in the rhizosphere of Arabidopsis compared to those in plant-free bulk soil, where the level of colonization by this strain remained below the CFU detection limit (Figure 1). This rhizosphere-specific colonization by WCS417 was apparent in both soil-types (Figure 1). By contrast, the generalist saprophyte KT2440 colonized rhizosphere and bulk

TABLE 1 | C and N concentrations in nutrient-rich and poor-soil.

	Carbon (C)		Nitrogen (N)		C:N
Nutrient-poor	2.58%	−0.15	0.21%	−0.01	12.29
Nutrient-rich	18.78%	−0.48	0.37%	−0.03	51.02



soil from both soil-types with equal efficiencies, although its levels of rhizosphere colonization remained orders of magnitude lower than that of WCS417 (Figure 1).

To examine whether atmospheric CO₂ alters rhizosphere colonization by WCS417 and KT2440, Arabidopsis was cultivated for 4 weeks in both soil-types at *sa*CO₂ (200 ppm), ambient CO₂ (*a*CO₂; 400 ppm) or *e*CO₂ (1200 ppm) before quantification of rhizosphere colonization. Interestingly, in nutrient-poor soil, rhizosphere titres of WCS417 bacteria increased statistically from *sa*CO₂ to *e*CO₂, whereas this effect of CO₂ was absent in nutrient-rich soil (Figure 2A). Furthermore, the statistically significant interaction between CO₂ and soil-type indicates that the stimulating effect of CO₂ on rhizosphere colonization by WCS417 depends on soil nutritional status (two-way ANOVA; $P = 0.006$; Figure 2A and Supplementary Table S2A). By contrast, rhizosphere titres of KT2440 were not statistically altered by CO₂, soil-type, or the interaction thereof (two-way ANOVA; $P = 0.541$; Figure 2B and Supplementary Table S2B), indicating that the colonization by this saprophytic strain is unaffected by soil nutritional status and atmospheric CO₂. Hence, the stimulatory impacts of atmospheric CO₂ on rhizosphere colonization by soil bacteria depend on soil quality and bacterial species.

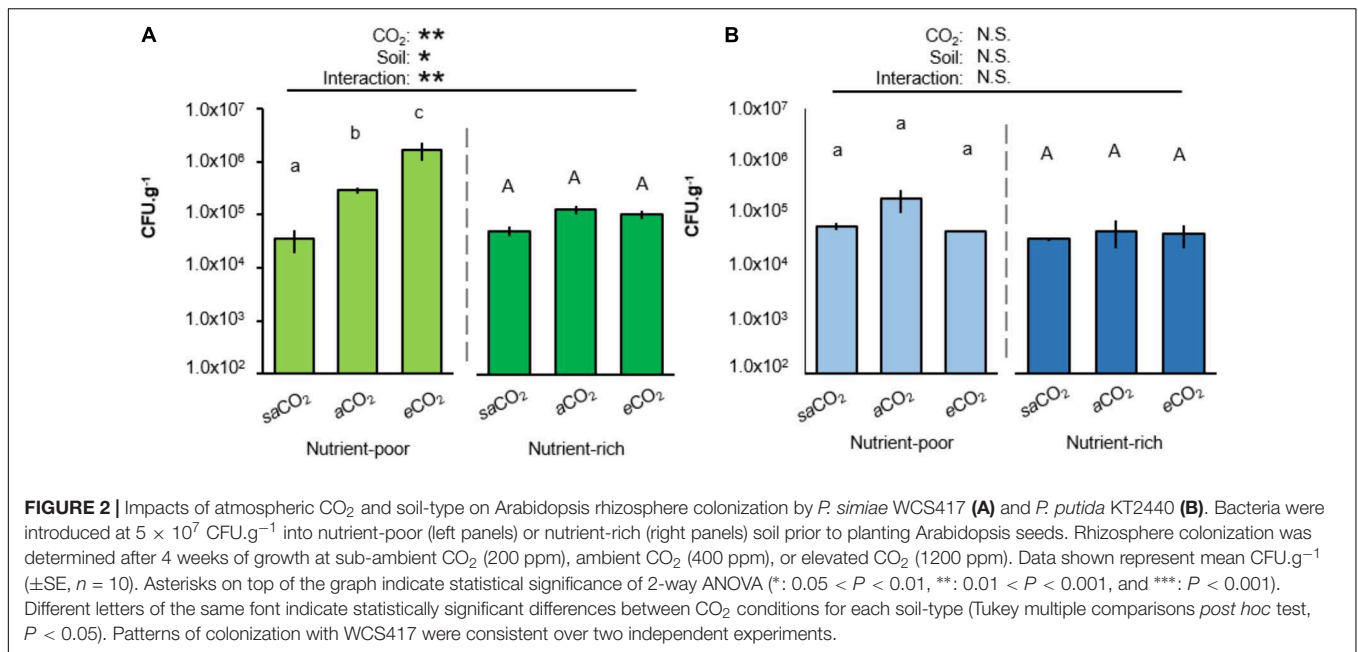
Atmospheric CO₂ Influences Plant Growth Responses to *P. simiae* WCS417 on Nutrient-Poor Soil

To assess the influence of CO₂ on plant growth responses to rhizobacteria, control- (i.e., mock inoculated) and WCS417-inoculated plants were examined for rosette areas after

5 weeks of growth. In the absence of WCS417, rosette sizes increased statistically from *sa*CO₂ to *e*CO₂, which was apparent in both nutrient-poor and nutrient-rich soil (Figure 3A and Supplementary Table S3A). Furthermore, application of WCS417 did not influence the growth of plants on nutrient-rich soil (Figure 3A). This was confirmed by two-way ANOVA, which did not indicate a statistically significant interaction between bacterial treatment and CO₂ ($P = 0.432$; Supplementary Table S3B). Conversely, in nutrient-poor soil, WCS417 had a statistically significant effect on rosette size and also showed a statistically significant interaction with CO₂ by 2-way ANOVA ($P < 0.001$; Supplementary Table S3B). This indicates that the effects of WCS417 on shoot growth are dependent on atmospheric CO₂ concentration. Subsequent *t*-tests revealed that WCS417 statistically increased rosette size at *a*CO₂ and repressed at *e*CO₂ (Figure 3A). Since PGPR have been reported to affect root and shoot growth differentially through impacts on auxin and cytokinin levels (Vacheron et al., 2013), we also determined root biomass. As is shown in Figure 3B, root dry weights in nutrient-poor soil mirrored the effects of WCS417 on rosette area on this soil-type: the bacteria increased root biomass at *a*CO₂, while they increased root biomass at *e*CO₂. As for the average rosette area, the effects of WCS417 on root biomass were statistically significant and showed a statistically significant interaction with CO₂ (Supplementary Table S3C). Together, these results suggest that WCS417 has a plant growth-promoting effect at *sa*CO₂ and *a*CO₂, but that it reduces plant growth at *e*CO₂.

Atmospheric CO₂ Influences Systemic Resistance Responses to *P. simiae* WCS417 on Both Nutrient-Poor and Nutrient-Rich Soil

Arabidopsis develops induced systemic resistance (ISR) upon root colonization by WCS417 (Pieterse et al., 1996). Since WCS417 colonization of the Arabidopsis rhizosphere is CO₂-dependent (Figure 2A), we examined impacts of CO₂ on ISR. To this end, leaves of control- and WCS417-inoculated plants were challenge-inoculated with the necrotrophic leaf fungus *Plectosphaerella cucumerina*. Disease progression was quantified at 8 and 13 days post-inoculation (dpi) by lesion diameter in both nutrient-poor and nutrient-rich soil. For each time-point/soil-type combination (apart from 8dpi in nutrient-rich soil), two-way ANOVA revealed a statistically significant effect of CO₂ on disease resistance (in each case $P < 0.001$; Supplementary Tables S4A–D), which manifested itself as increased resistance at *e*CO₂ compared to *sa*CO₂ and *a*CO₂ (Figure 4). There was also a statistically significant interaction between bacterial treatment and CO₂ in nutrient-poor soil which was apparent at 8 and 13 dpi in nutrient-poor soil, but was not significant at 13 dpi in nutrient-rich soil (two-way ANOVA; $P < 0.001$, $P = 0.004$, and $P = 0.087$, respectively; Supplementary Tables S4A–D). This indicates that the effects of WCS417 on systemic resistance depend on atmospheric CO₂ concentration. Subsequent *t*-tests revealed that WCS417 reduced lesion diameters at both *a*CO₂ and *e*CO₂ in nutrient-poor and nutrient-rich soils, which



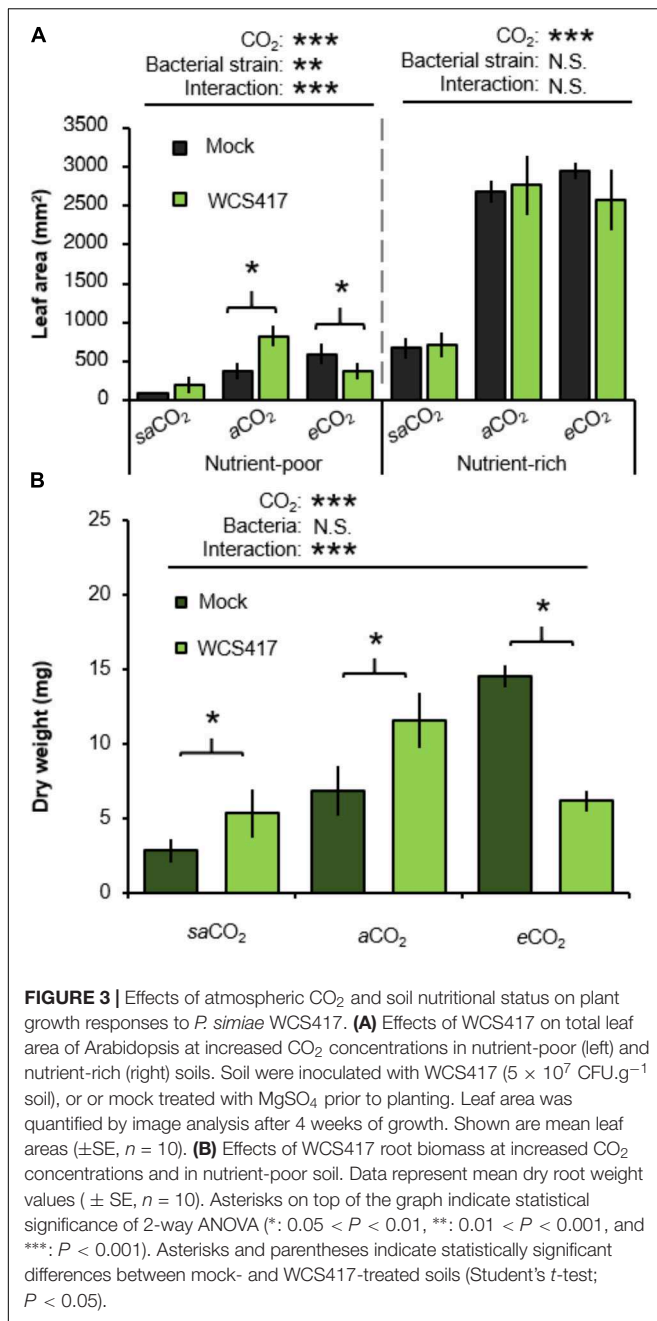
was statistically significant at either 8 or 13 dpi (**Figure 4**). Surprisingly, at *sa*CO₂, treatment of nutrient-poor soil with WCS417 statistically increased lesion diameters at both 8 and 13 dpi, suggesting induced systemic susceptibility (ISS). This response was absent when plants were grown on nutrient-rich soil at *sa*CO₂, where WCS417 did not have a statistically significant effect on lesion diameter by *P. cucumerina* (**Figure 4**). Hence, the effect of WCS417 on systemic plant immunity varies from induced susceptibility to induced resistance, depending on the atmospheric CO₂ concentration and soil nutritional status.

DISCUSSION

To date, only few studies have investigated effects of atmospheric CO₂ on rhizosphere colonization by PGPRs. While previous work has shown that *e*CO₂ increases bacterial and fungal biomass in the rhizosphere (Kassem et al., 2008), our study is the first to report effects of *sa*CO₂ and *e*CO₂ on rhizosphere colonization by selected soil bacteria. Procter et al. (2014) reported an increase in fungal species richness and enhanced relative abundance of selected fungi with *e*CO₂, which varied according to soil-type (Procter et al., 2014). Furthermore, a grassland free air CO₂ enrichment (FACE) experiment revealed that initial C accumulation occurred predominantly in arbuscular mycorrhizal fungi (AMF; Denef et al., 2007), which are symbiotic and rely on host-derived carbon (e.g., Lindahl et al., 2010). Although mycorrhizal root colonization is influenced by different factors than rhizobacterial root colonization, it is plausible that increased C deposition at *e*CO₂ has more pronounced effects in C-poor soil-types, where root-associated microbes will be more reliant on plant-derived C. Indeed, the rhizobacterial WCS417 strain showed increasing rhizosphere colonization at rising CO₂

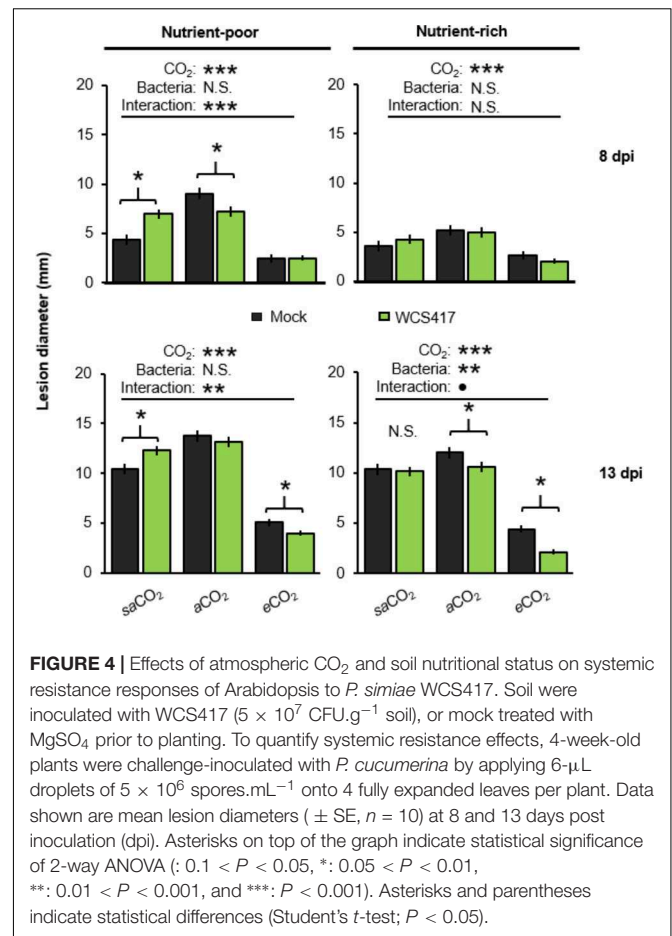
concentrations, which was most pronounced in nutrient-poor soil (**Figure 2**). Moreover, the differential effects of CO₂ on KT2440 and WCS417 help to explain why CO₂ has been reported to have effects on some bacterial soil communities, while others remain unaffected (Rice et al., 1994; Ross et al., 1995; Kassem et al., 2008; Eisenhauer et al., 2012). Exactly what changes in rhizosphere chemistry drive these community effects, requires further research.

KT2440 was originally isolated from benzene-contaminated soils in Japan (Nakazawa and Yokota, 1973). Accordingly, it survives well in root-free bulk soils. However, this strain has also been reported to colonize the rhizosphere of plants, in particular of grasses (Molina et al., 2000). The rhizosphere of many grass species, such as maize, contain relatively high concentrations of aromatic benzoxazinoids (Neal et al., 2012). KT2440 is highly tolerant to the antimicrobial activity of benzoxazinoids and responds to these chemicals by positive chemotaxis (Neal et al., 2012), explaining why this strain is a strong colonizer of the maize rhizosphere. By contrast, KT2440 did not show increased colonization of the *Arabidopsis* rhizosphere in comparison to plant-free control soil (**Figure 1**), suggesting that KT2440 is not majorly influenced by the rhizosphere chemistry of *Arabidopsis*. WCS417, on the other hand, showed relatively high levels of colonization in the rhizosphere, but failed to sustain colonies in plant-free control soil (**Figure 1**), which is typical for a rhizobacterial species. WCS417 was originally isolated from the rhizosphere of wheat (Lamers et al., 1988) and has since been shown to colonize the rhizosphere of a wide range of plant species (Berendsen et al., 2015). Interestingly, a recent report has shown the iron-regulated secondary metabolite scopoletin in *Arabidopsis* root exudates selectively inhibits soil-borne pathogens, while ISR-inducing rhizobacteria, including WCS417, are highly tolerant to the antimicrobial effect of scopoletin (Stringlis et al., 2018). Hence, the recruitment



and establishment of rhizosphere-colonizing bacteria not only depends on primary metabolites, but also on their sensitivity to secondary metabolites. The extent to which the exudation of scopoletin, and other possible rhizosphere chemicals, are influenced by atmospheric CO₂ in Arabidopsis requires further investigation.

Rhizosphere colonization by PGPR promotes shoot and root development through different mechanisms (Lugtenberg and Kamilova, 2009). For instance, *Pseudomonas fluorescens* WCS365 has been shown to convert exuded tryptophan into the plant growth hormone auxin (Kamilova et al., 2006). In nutrient-poor soil, growth promotion by WCS417 was apparent under both



*sa*CO₂ and *a*CO₂ (Figure 3). However, WCS417 repressed plant growth at *e*CO₂ (Figure 3), indicating potentially pathogenic activity. This hypothesis is supported by the colonization data (Figure 2), which revealed >10 fold higher colonization of WCS417 at *e*CO₂ compared to that at *a*CO₂. It is tempting to speculate that such high densities at the root surface are perceived as hostile by the host immune system, triggering a growth-repressing immune response. The continuum between mutualism and pathogenic lifestyles is a recognized phenomenon for fungal endophytes (Schulz and Boyle, 2005) and other root colonizers (Bever et al., 2012). Interestingly, this plasticity is partially driven by environmental factors, including CO₂ (Anderson et al., 2004; Schulz and Boyle, 2005). Although the relationship between plant-microbial mutualism and environmental factors remains poorly understood (Garrett et al., 2006, 2011; Johnson and Gehring, 2007), the growth repression by WCS417 at *e*CO₂ was marked by relatively high levels of resistance against *P. cucumerina* (Figure 3). While this resistance appears to be an additive result of ISR and *e*CO₂-induced resistance (Williams et al., 2018), it is plausible that these high levels of resistance are associated with costs to plant growth, which become apparent under nutrient-limiting conditions. ISR has been associated with priming of jasmonic acid and ethylene-controlled defenses (Pieterse

et al., 2002). Even though priming is generally considered to be a low-cost defense strategy (van Hulten et al., 2006), the additive effect of *e*CO₂ and ISR may result in constitutive up-regulation of inducible defenses that incur a detectable cost on plant growth under nutrient-limiting conditions. This hypothesis gains support from the observation that WCS417 only represses growth at *e*CO₂ in nutrient-poor soil (Figure 3).

Our study has shown that two well-characterized soil bacteria display different rhizosphere behavior in response to changes in atmospheric CO₂. Moreover, the plant responses to colonization by the rhizobacterial colonizing strain revealed a range of outcomes, including growth repression and induced systemic susceptibility. These findings demonstrate that predictions about impacts of global change and soil quality on crop performance need to take into account the complex interactions taking place in the rhizosphere. This outcome highlights the need for further research on the impacts of future global change on rhizosphere chemistry and the associated root microbiome.

MATERIALS AND METHODS

Plant Cultivation and Growth Conditions

Arabidopsis thaliana (*Arabidopsis*), accession Columbia (Col-0) was cultivated in mx flow 6000 cabinets (Sanyo, United Kingdom) under ambient conditions (*a*CO₂; 400 ppm, i.e., $\mu\text{L L}^{-1}$), sub-ambient CO₂ (*sa*CO₂; 200 ppm), or elevated CO₂ (*e*CO₂; 1200 ppm). CO₂ concentrations were chosen specifically to reflect two aspects of global change; 200 ppm was used as a post-glacial and pre-industrial atmospheric concentration, to imitate *Arabidopsis*' ancestral habit (Beilstein et al., 2010; Beerling and Royer, 2011), and 1200 ppm was selected as worst case representative concentration scenario, as highlighted in the most recent intergovernmental panel on climate change report (IPCC, 2013). Growth chambers were supplemented with compressed CO₂ (BOC, United Kingdom) or scrubbed with Sofnolime 797 (AP diving, United Kingdom) to maintain constant CO₂ levels at indicated concentrations. Plants were cultivated under short-day conditions (8.5: 15.5 h light: dark; 20°C light, 18°C dark; 65% relative humidity). Seeds were stratified for 2 days (d) in the dark at 4°C and planted in 60-mL pots, containing a sand (silica CH52): dry compost (Levington M3) mixture, in a ratio of 2: 3 for nutrient-rich soil, or 1: 9 for nutrient-poor soil (v:v in both instances). Pots with plant-free control soil were set up and maintained under the same growth conditions. All pots were placed in trays to allow for bi-weekly watering. At 7 days after germination, seedlings were thinned to prevent crowding. To limit variation between different CO₂ conditions, and compensate for pseudoreplication generated via chamber effects, experiments were conducted in identical climate chamber models, the exact same batches of seed and soil were used throughout each experiment. Furthermore, plant trays within each chamber were rotated weekly in a randomized fashion to counter positional effects.

Soil Carbon (C) and Nitrogen (N) Concentrations

C and N concentrations in soil-types were determined by the complete combustion method followed by gas chromatography, using an ANCA GSL 20-20 Mass Spectrometer (Sercon PDZ Europa; Cheshire).

Soil Treatment With *Pseudomonas Simiae* Wcs417 and *Pseudomonas Putida* KT2440 and Quantification of Bacterial Colonization

To determine impacts of CO₂ on colonization of rhizosphere bacteria, yellow fluorescent protein (YFP)-expressing *P. simiae* WCS417 (Berendsen et al., 2012) was cultivated on selective Lysogeny broth (LB) agar (5 $\mu\text{g mL}^{-1}$ tetracycline and 25 $\mu\text{g mL}^{-1}$ rifampicin). One YFP-fluorescent colony was selected for propagation in an overnight culture of liquid LB, containing the same selective concentrations of tetracycline and rifampicin. The medium was incubated in an orbital shaking incubator for 16 h at 28°C at 200 revolutions per minute (rpm). A similar method was employed for the cultivation of a green fluorescent protein (GFP)-expressing *P. putida* KT2440, which carries a stable chromosome-inserted PA_{1/04/03}-RBSII-*gfp*mut3*-T0-T1 transposon at a negligible metabolic cost (Dechesne and Bertolla, 2005). However, in this case, the bacteria were grown on minimal solid media (M9), after which one GFP-fluorescent colony was selected for propagation in LB liquid medium without selective antibiotics. Soils were inoculated with WCS417 or KT2240 bacteria by adding a bacterial suspension in 10 mM MgSO₄ at a final density of 5×10^7 CFU.g⁻¹, or a mock treatment of 10 mM MgSO₄ alone. Seeds were planted directly on the soil. Four weeks after germination, samples of root adhering rhizosphere soil and control soil (~2 g) were collected, serially diluted and stamp-plated, using a 96-well Replica plater (Sigma-Aldrich, R2383) onto selective LB agar with tetracycline and rifampicin for WCS417, and M9 without antibiotics for GFP-expressing KT2240. Fluorescent colonies were enumerated using a Dark Reader DR195M Transilluminator (Clare Chemical) and normalized to sample weight. The colonization experiments (Figure 2) were repeated once with comparable results.

Plant Growth Analysis

To determine the size of the plants, rosette area was estimated non-destructively from digital photographs (Canon EOS 500D) of rosettes, taken with a size standard. Image analysis involved converting pixels per rosette into area (mm²), using imaging software (Corel Paintshop Pro, ver. X7). To determine root growth, root material plus soil was collected and oven dried using an economy incubator 2 (Weiss Technik, United Kingdom; 60°C). Subsequently, roots were carefully extracted from the surrounding soil and weighed, using an analytical balance (Mettler Toledo AJ100).

Induced Systemic Resistance Assays

To quantify WCS417-mediated ISR, plants were grown in soil with and without WCS417 bacteria as described above.

After 5 weeks of growth, plants were challenge-inoculated with *P. cucumerina* (strain BMM). Lesion diameters were enumerated at 8 and 13 dpi and analyzed using Student's test ($P < 0.05$). To ensure necrotrophic infection, *P. cucumerina* was applied by droplet inoculation ($6 \mu\text{L}$, 5×10^6 spores mL^{-1}) on 4 to 6 fully expanded leaves of plants ($n = 8$), as described previously (Pétriaccq et al., 2016). Disease progression was determined by quantification of lesion diameters at 8 and 13 dpi, which correlates with fungal colonization disease progression (Pétriaccq et al., 2016; Williams et al., 2018). Four lesion diameters per plant were averaged and treated as one biological replicate ($n = 8$). Differences in average lesion diameter between treatments were analyzed for statistical significance by ANOVA (using R, v. 3.1.2).

AUTHOR CONTRIBUTIONS

JT and DB conceived the project. AW, PP, TC, and JT planned the experiments. AW, TC, and PP performed the experiments. JT and DB provided reagents, equipment, and facilities. AW, PP, and JT analyzed the data. AW and JT wrote the paper with feedback from all co-authors.

REFERENCES

- Agbodjato, N. A., Noumavo, P. A., Baba-Moussa, F., Salami, H. A., Sina, H., Sézan, A., et al. (2015). Characterization of potential plant growth promoting rhizobacteria isolated from Maize (*Zea mays* L.) in central and Northern Benin (West Africa). *Appl. Environ. Soil Sci.* 2015:901656. doi: 10.1155/2015/901656
- Anderson, P. K., Cunningham, A. A., Patel, N. G., Morales, F. J., Epstein, P. R., and Daszak, P. (2004). Emerging infectious diseases of plants: pathogen pollution, climate change and agrotechnology drivers. *Trends Ecol. Evol.* 19, 535–544. doi: 10.1016/j.tree.2004.07.021
- Beerling, D. J., and Royer, D. L. (2011). Convergent cenozoic CO₂ history. *Nat. Geosci.* 4, 418–420. doi: 10.1038/ngeo1186
- Beilstein, M., Nagalingum, N., Clements, M., Manchester, S., and Mathews, S. (2010). Dated molecular phylogenies indicate a Miocene origin for *Arabidopsis thaliana*. *Proc. Natl. Acad. Sci. U.S.A.* 107, 18724–18728. doi: 10.1073/pnas.0909766107
- Berendsen, R. L., Pieterse, C. M., and Bakker, P. A. (2012). The rhizosphere microbiome and plant health. *Trends Plant Sci.* 17, 478–486. doi: 10.1016/j.tplants.2012.04.001
- Berendsen, R. L., van Verk, M. C., Stringlis, I. A., Zamioudis, C., Tommassen, J., Pieterse, C. M. J., et al. (2015). Unearthing the genomes of plant-beneficial *Pseudomonas* model strains WCS358, WCS374 and WCS417. *BMC Genomics* 16:539. doi: 10.1186/s12864-015-1632-z
- Bever, J. D., Platt, T. G., and Morton, E. R. (2012). Microbial population and community dynamics on plant roots and their feedbacks in plant communities. *Annu. Rev. Microbiol.* 66, 265–283. doi: 10.1146/annurev-micro-092611-150107.Microbial
- Castro, H. F., Classen, A. T., Austin, E. E., Norby, R. J., and Schadt, C. W. (2010). Soil microbial community responses to multiple experimental climate change drivers. *Appl. Environ. Microbiol.* 76, 999–1007. doi: 10.1128/AEM.02874-09
- Classen, A. T., Sundqvist, M. K., Henning, J. A., Newman, G. S., Moore, J. A. M., Cregger, M. A., et al. (2015). Direct and indirect effects of climate change on soil microbial and soil microbial-plant interactions: what lies ahead? *Ecosphere* 6:130. doi: 10.1890/ES15-00217.1
- Dam, M., Bergmark, L., and Vestergård, M. (2017). Elevated CO₂ increases fungal-based micro-foodwebs in soils of contrasting plant species. *Plant Soil* 415, 549–561. doi: 10.1007/s11104-017-3191-3
- Dechesne, A., and Bertolla, F. (2005). Impact of the microscale distribution of a *Pseudomonas* strain introduced into soil on potential contacts with indigenous bacteria. *Appl. Environ. Microbiol.* 71, 8123–8131. doi: 10.1128/AEM.71.12.8123

FUNDING

The research was supported by a consolidator grant from the European Research Council (ERC; No. 309944 “Prime-A-Plant”) to JT, a Research Leadership Award from the Leverhulme Trust (No. RL-2012-042) to JT, a BBSRC-IPA Grant to JT (BB/P006698/1), and an ERC Grant (No. 322998 “CDREG”) to DB.

ACKNOWLEDGMENTS

We thank David Pardo for practical assistance and Heather Walker for undertaking C N analysis. We also thank Corné Pieterse for providing the YFP-labeled WCS417 strain as well as critical comments on the work and manuscript.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fpls.2018.01493/full#supplementary-material>

- Denef, K., Bubenheim, H., Lenhart, K., Vermeulen, J., Van Cleemput, O., Boeckx, P., et al. (2007). Community shifts and carbon translocation within metabolically-active rhizosphere microorganisms in grasslands under elevated CO₂. *Biogeosciences* 4, 769–779. doi: 10.5194/bg-4-769-2007
- Drigo, B., Kowalchuk, G. A., and Van Veen, J. A. (2008). Climate change goes underground: effects of elevated atmospheric CO₂ on microbial community structure and activities in the rhizosphere. *Biol. Fertil. Soils* 44, 667–679. doi: 10.1007/s00374-008-0277-3
- Egamberdiyeva, D. (2007). The effect of plant growth promoting bacteria on growth and nutrient uptake of maize in two different soils. *Appl. Soil Ecol.* 36, 184–189. doi: 10.1016/j.apsoil.2007.02.005
- Eisenhauer, N., Cesarz, S., Koller, R., Worm, K., and Reich, P. B. (2012). Global change belowground: impacts of elevated CO₂, nitrogen, and summer drought on soil food webs and biodiversity. *Glob. Change Biol.* 18, 435–447. doi: 10.1111/j.1365-2486.2011.02555.x
- Field, K. J., Cameron, D. D., Leake, J. R., Tille, S., Bidartondo, M. I., and Beerling, D. J. (2012). Contrasting arbuscular mycorrhizal responses of vascular and non-vascular plants to a simulated Palaeozoic CO₂ decline. *Nat. Commun.* 3:835. doi: 10.1038/ncomms1831
- Freeman, C., Kim, S.-Y., Lee, S.-H., and Kang, H. (2004). Effects of elevated atmospheric CO₂ concentrations on soil microorganisms. *J. Microbiol.* 42, 267–277.
- Garrett, K. A., Dendy, S. P., Frank, E. E., Rouse, M. N., and Travers, S. E. (2006). Climate change effects on plant disease: genomes to ecosystems. *Annu. Rev. Phytopathol.* 44, 489–509. doi: 10.1146/annurev.phyto.44.070505.143420
- Garrett, K. A., Forbes, G. A., Savary, S., Skelsey, P., Sparks, A. H., Valdivia, C., et al. (2011). Complexity in climate-change impacts: an analytical framework for effects mediated by plant disease. *Plant Pathol.* 60, 15–30. doi: 10.1111/j.1365-3059.2010.02409.x
- Gill, R. A., Anderson, L. J., Polley, H. W., Johnson, H. B., and Jackson, R. B. (2006). Potential nitrogen constraints on soil carbon sequestration under low and elevated atmospheric CO₂. *Ecology* 87, 41–52. doi: 10.2307/20068908
- Gil-Sotres, F., Trasar-Cepeda, C., Leirós, M. C., and Seoane, S. (2005). Different approaches to evaluating soil quality using biochemical properties. *Soil Biol. Biochem.* 37, 877–887. doi: 10.1016/j.soilbio.2004.10.003
- Hinsinger, P., Plassard, C., and Jaillard, B. (2006). Rhizosphere: a new frontier for soil biogeochemistry. *J. Geochem. Explor.* 88, 210–213. doi: 10.1016/j.gexplo.2005.08.041
- IPCC (2013). “Working group I contribution to the IPCC fifth assessment report - summary for policymakers,” in *Climate Change 2013: The Physical Science Basis*,

- eds T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. (Cambridge: Cambridge University Press), 1–36.
- Janus, L. R., Angeloni, N. L., McCormack, J., Rier, S. T., Tuchman, N. C., and Kelly, J. J. (2005). Elevated atmospheric CO₂ alters soil microbial communities associated with trembling aspen (*Populus tremuloides*) roots. *Microb. Ecol.* 50, 102–109. doi: 10.1007/s00248-004-0120-9
- Johnson, N. C., and Gehring, C. A. (2007). “Mycorrhizas: symbiotic mediators of rhizosphere and ecosystem processes,” in *The Rhizosphere*, eds Z. J. Cardon and J. L. Whitbeck (Amsterdam: Elsevier Inc), 73–100.
- Kamilova, F., Kravchenko, L. V., Shaposhnikov, A. I., Makarova, N., and Lugtenberg, B. (2006). Effects of the tomato pathogen *Fusarium oxysporum* f. sp. *radicis-lycopersici* and of the biocontrol bacterium *Pseudomonas fluorescens* WCS365 on the composition of organic acids and sugars in tomato root exudate. *Mol. Plant Microbe Interact.* 19, 1121–1126. doi: 10.1094/MPMI-19-1121
- Kassem, I. I., Joshi, P., Sigler, V., Heckathorn, S., and Wang, Q. (2008). Effect of elevated CO₂ and drought on soil microbial communities associated with *Andropogon gerardii*. *J. Integr. Plant Biol.* 50, 1406–1415. doi: 10.1111/j.1744-7909.2008.00752.x
- Lamers, J. G., Schippers, B., and Geels, F. P. (1988). “Soil-borne diseases of wheat in the Netherlands and results of seed bacterization with pseudomonads against *Gaeumannomyces graminis* var. *tritici*, associated with disease resistance,” in *Cereal Breeding Related to Integrated Cereal Production*, eds M. L. Jorna and L. A. J. Sloopmaker (Wageningen: Pudoc), 134–139.
- Lindahl, B. D., de Boer, W., and Finlay, R. D. (2010). Disruption of root carbon transport into forest humus stimulates fungal opportunists at the expense of mycorrhizal fungi. *ISME J.* 4, 872–881. doi: 10.1038/ismej.2010.19
- Lipson, D. A., Wilson, R. F., and Oechel, W. C. (2005). Effects of elevated atmospheric CO₂ on soil microbial biomass, activity, and diversity in a chaparral ecosystem. *Appl. Environ. Microbiol.* 71, 8573–8580. doi: 10.1128/AEM.71.12.8573
- Lugtenberg, B., and Kamilova, F. (2009). Plant-growth-promoting rhizobacteria. *Annu. Rev. Microbiol.* 63, 541–556. doi: 10.1146/annurev.micro.62.081307.162918
- Lynch, J. M., and Whipps, J. M. (1990). Substrate flow in the rhizosphere. *Plant Soil* 129, 1–10. doi: 10.1007/BF00011685
- Marschner, H. (2012). *Mineral Nutrition of Higher Plants*, 3rd Edn, London: Academic Press.
- Mohan, J. E., Cowden, C. C., Baas, P., Dawadi, A., Frankson, P. T., Helmick, K., et al. (2014). Mycorrhizal fungi mediation of terrestrial ecosystem responses to global change: mini-review. *Fungal Ecol.* 10, 3–19. doi: 10.1016/j.funeco.2014.01.005
- Molina, L. A., Ramos, C., Duque, E., Ronchel, M. C., García, J. M., Wyke, L., et al. (2000). Survival of *Pseudomonas putida* KT2440 in soil and in the rhizosphere of plants under greenhouse and environmental conditions. *Soil Biol. Biochem.* 32, 315–321. doi: 10.1016/S0038-0717(99)00156-X
- Montealegre, C. M., Van Kessel, C., Russelle, M. P., and Sadowsky, M. J. (2002). Changes in microbial activity and composition in a pasture ecosystem exposed to elevated atmospheric carbon dioxide. *Plant Soil* 243, 197–207. doi: 10.1023/A:1019901828483
- Nakazawa, T., and Yokota, T. (1973). Benzoate metabolism in *Pseudomonas putida* (arvilla) mt 2: demonstration of two benzoate pathways. *J. Bacteriol.* 115, 262–267.
- Neal, A. L., Ahmad, S., Gordon-Weeks, R., and Ton, J. (2012). Benzoxazinoids in root exudates of maize attract *Pseudomonas putida* to the rhizosphere. *PLoS One* 7:e35498. doi: 10.1371/journal.pone.0035498
- O’Neill, E. G., Luxmoore, R. J., and Norby, R. J. (1987). Elevated atmospheric CO₂ effects on seedling growth, nutrient uptake, and rhizosphere bacterial populations of *Liriodendron tulipifera* L. *Plant Soil* 104, 3–11. doi: 10.1007/BF02370618
- Paterson, E., Hall, J. M., Rattray, E. A. S., Griffiths, B. S., Ritz, K., and Killham, K. (1997). Effect of elevated CO₂ on rhizosphere carbon flow and soil microbial processes. *Glob. Change Biol.* 3, 363–377. doi: 10.1046/j.1365-2486.1997.t01-1-00088.x
- Pétriaccq, P., Stassen, J., and Ton, J. (2016). Spore density determines infection strategy by the plant-pathogenic fungus *Plectosphaerella cucumerina*. *Plant Physiol.* 170, 2325–2339. doi: 10.1104/pp.15.00551
- Phillips, R. P., Bernhardt, E. S., and Schlesinger, W. H. (2009). Elevated CO₂ increases root exudation from loblolly pine (*Pinus taeda*) seedlings as an N-mediated response. *Tree Physiol.* 29, 1513–1523. doi: 10.1093/treephys/tp083
- Pieterse, C., van Wees, S. C., Hoffland, E., van Pelt, J. A., and van Loon, L. C. (1996). Systemic resistance in *Arabidopsis* induced by biocontrol bacteria is independent of salicylic acid accumulation and pathogenesis-related gene expression. *Plant Cell* 8, 1225–1237. doi: 10.1105/tpc.8.8.1225
- Pieterse, C. M. J., van Wees, S. C. M., Ton, J., van Pelt, J. A., and van Loon, L. C. (2002). Signalling in rhizobacteria-induced systemic resistance in *Arabidopsis thaliana*. *Plant Biol.* 4, 535–544. doi: 10.1055/s-2002-35441/abstract
- Procter, A. C., Ellis, J. C., Fay, P. A., Polley, H. W., and Jackson, R. B. (2014). Fungal community responses to past and future atmospheric CO₂ differ by soil type. *Appl. Environ. Microbiol.* 80, 7364–7377. doi: 10.1128/AEM.02083-14
- Rainey, P. B. (1999). Adaptation of *Pseudomonas fluorescens* to the plant rhizosphere. *Environ. Microbiol.* 1, 243–257. doi: 10.1046/j.1462-2920.1999.00040.x
- Rice, C. W., Garcia, F. O., Hampton, C. O., and Owensby, C. E. (1994). Soil microbial response in tallgrass prairie to elevated CO₂. *Plant Soil* 165, 67–74. doi: 10.1007/BF00009963
- Rogers, A., Ainsworth, E. A., and Leakey, A. D. B. (2009). Will elevated carbon dioxide concentration amplify the benefits of nitrogen fixation in legumes? *Plant Physiol.* 151, 1009–1016. doi: 10.1104/pp.109.144113
- Ross, D. J., Tate, K. R., and Newton, P. (1995). Elevated CO₂ and temperature effects on soil carbon and nitrogen cycling in ryegrass/white clover turves of an endoaquept soil. *Plant Soil* 176, 37–49. doi: 10.1007/BF00017673
- Schulz, B., and Boyle, C. (2005). The endophytic continuum. *Mycol. Res.* 109, 661–686. doi: 10.1017/S095375620500273X
- Stringlis, I. A., Yu, K., Feussner, K., de Jonge, R., Van Bentum, S., Van Verk, M. C., et al. (2018). MYB72-dependent coumarin exudation shapes root microbiome assembly to promote plant health. *Proc. Natl. Acad. Sci. U.S.A.* 115, E5213–E5222. doi: 10.1073/pnas.1722335115
- Vacheron, J., Desbrosses, G., Bouffaud, M.-L., Touraine, B., Moëgne-Loccoz, Y., Muller, D., et al. (2013). Plant growth-promoting rhizobacteria and root system functioning. *Front. Plant Sci.* 4:356. doi: 10.3389/fpls.2013.00356
- van Hulst, M., Pelsers, M., van Loon, L. C., Pieterse, C. M. J., and Ton, J. (2006). Costs and benefits of priming for defense in *Arabidopsis*. *Proc. Natl. Acad. Sci. U.S.A.* 103, 5602–5607. doi: 10.1073/pnas.0510213103
- Weinel, C., Nelson, K. E., and Tümmler, B. (2002). Global features of the *Pseudomonas putida* KT2440 genome sequence. *Environ. Microbiol.* 4, 809–818. doi: 10.1046/j.1462-2920.2002.00331.x
- Wiemken, V., Laczko, E., Ineichen, K., and Boller, T. (2001). Effects of elevated carbon dioxide and nitrogen fertilization on mycorrhizal fine roots and the soil microbial community in beech-spruce ecosystems on siliceous and calcareous soil. *Microb. Ecol.* 42, 126–135. doi: 10.1007/s002480000080
- Williams, A., Pétriaccq, P., Schwarzenbacher, R. E., Beerling, D. J., and Ton, J. (2018). Mechanisms of glacial-to-future atmospheric CO₂ effects on plant immunity. *New Phytol.* 218, 752–761. doi: 10.1111/nph.15018
- Zamioudis, C., Hanson, J., and Pieterse, M. J. (2014). B-β-Glucosidase BGLU42 is a MYB72-dependent key regulator of rhizobacteria-induced systemic resistance and modulates iron deficiency responses in *Arabidopsis* roots. *New Phytol.* 204, 368–379. doi: 10.1111/nph.12980

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Copyright © 2018 Williams, Pétriaccq, Beerling, Cotton and Ton. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.