Regulation of Cell Wall-Bound Invertase in Pepper Leaves by Xanthomonas campestris pv. vesicatoria Type Three Effectors

Sophia Sonnewald1*, Johannes P. R. Priller1, Julia Schuster1, Eric Glickmann2*, Mohammed-Reza Hajirezaei2, Stefan Siebig1, Mary Beth Mudgett3, Uwe Sonnewald1

1 Lehrstuhl für Biochemie, Friedrich-Alexander Universität Erlangen-Nürnberg, Erlangen, Germany, 2 Institut für Pflanzenbiochemie, Gatersleben, Germany, 3 Department of Biology, Stanford University, Stanford, California, United States of America

Abstract

Xanthomonas campestris pv. vesicatoria (Xcv) possess a type 3 secretion system (T3SS) to deliver effector proteins into its Solanaceae host plants. These proteins are involved in suppression of plant defense and in reprogramming of plant metabolism to favour bacterial propagation. There is increasing evidence that hexoses contribute to defense responses. They act as substrates for metabolic processes and as metabolic semaphores to regulate gene expression. Especially an increase in the apoplastic hexose-to-sucrose ratio has been suggested to strengthen plant defense. This shift is brought about by the activity of cell wall-bound invertase (cw-Inv). We examined the possibility that Xcv may employ type 3 effector (T3E) proteins to suppress cw-Inv activity during infection. Indeed, pepper leaves infected with a T3SS-deficient Xcv strain showed a higher level of cw-Inv mRNA and enzyme activity relative to Xcv wild type infected leaves. Higher cw-Inv activity was paralleled by an increase in hexoses and mRNA abundance for the pathogenesis-related gene PRQ. These results suggest that Xcv suppresses cw-Inv activity in a T3SS-dependent manner, most likely to prevent sugar-mediated defense signals. To identify Xcv T3Es that regulate cw-Inv activity, a screen was performed with eighteen Xcv strains, each deficient in an individual T3E. Seven Xcv T3E deletion strains caused a significant change in cw-Inv activity compared to Xcv wild type. Among them, Xcv lacking the xopB gene (Xcv ΔxopB) caused the most prominent increase in cw-Inv activity. Deletion of xopB increased the mRNA abundance of PRQ in Xcv ΔxopB-infected pepper leaves, but not of PitS and Acre31, two PAMP-triggered immunity markers. Inducible expression of XopB in transgenic tobacco inhibited Xcv-mediated induction of cw-Inv activity observed in wild type plants and resulted in severe developmental phenotypes. Together, these data suggest that XopB interferes with cw-Inv activity in planta to suppress sugar-enhanced defense responses during Xcv infection.

Introduction

Xanthomonas campestris pv. vesicatoria (Xcv), recently re-classified as X. euvesicatoria) is a Gram-negative bacterium that causes bacterial spot disease in tomato (Solanum lycopersicum) and pepper (Capsicum annuum) plants. The bacteria enter the plant through small wounds or stomata and colonize the intercellular space (apoplast). Infection of susceptible plants induces macroscopically visible disease symptoms, so-called water-soaked lesions that become later necrotic [1]. The pathogenicity of Xcv and many other pathogenic bacteria depends on a type 3 secretion system (T3SS) which mediates the secretion of bacterial effector proteins, termed type 3 effector proteins (T3Es), directly into the host cell [2]. The T3SS machinery is encoded by the hrp (hypersensitive response and pathogenicity) gene cluster [3]. Mutants lacking a functional T3SS cannot translocate effector proteins and are unable to elicit a defense-associated hypersensitive response in resistant plants or to establish disease in susceptible plants [4].

Xcv is predicted to deliver at least 28 T3Es into plant cells. Candidate T3Es were shown to be secreted experimentally and/or were predicted based on bioinformatic analyses of the complete genomic sequence [5–7]. In a compatible interaction, these effector proteins are important virulence factors that modify cellular processes to suppress host immune responses and to provide a favorable environment for bacterial propagation [8,9]. In an incompatible interaction, plant resistance (R) proteins recognize the action of certain T3Es in resistant host plants. This recognition is often associated with a hypersensitive response (HR), a rapid, localized cell death response preventing bacterial multiplication [4]. Thus, T3E proteins can either act as virulence and/or avirulence factors that promote bacterial growth or induce plant immunity.

Plant immunity relies on two overlapping signaling pathways that perceive potential pathogens and trigger appropriate defense responses [10,11]. The first, referred to as PAMP-triggered...
Regulation of cw-Inv by Xcv Type Three Effectors

Immunity (PTI), is induced by the recognition of conserved pathogen- (microbe-) associated molecular pattern (P/MAMP) such as flagellin or lipopolysaccharides by specific extracellular receptors termed pattern recognition receptors [11,12]. This perception elicits a variety of downstream responses like the production of reactive oxygen species, a calcium burst, the stimulation of mitogen-activated protein kinase (MAPK) cascades, an increased expression of numerous pathogenesis-related (PR) proteins, as well as cell wall strengthening by the deposition of the glucose polymer callose (recently summarized by [12]). The second layer of defense is referred to as effector-triggered immunity (ETI). During ETI, R-proteins directly or indirectly recognize specific T3Es and initiate defense signal transduction cascades similar to that for PTI [10,11]. In general, ETI responses are stronger and more prolonged compared to PTI responses.

Activation of plant defense responses, like reinforcement of the cell wall, production of reactive oxygen species or the accumulation of antimicrobial compounds requires energy, reducing power and carbon skeletons that can be fueled by carbohydrates [13–15]. In fact, the availability of sugars was shown to play a role for plant resistance against pathogens and the phenomenon of high-sugar resistance was recognized in the mid-1950’s [16]. The increased metabolic activity is probably fed by an enhanced flow of sucrose to the site of infection [17] or reduced sucrose export [18]. This is accompanied by increased expression and activity of cell wall-bound invertase (cw-Inv), which has been observed upon infection with plant pathogens in numerous studies [13,19–22]. Cw-Inv catalyzes the cleavage of the transport sugar sucrose into glucose and fructose, which are not transported in the phloem and therefore accumulate at the site of formation. Generally, cw-Inv is mainly active in carbohydrate consuming sink tissue, while its activity is usually low in mature source leaves with high photosynthetic capacity [17,21]. Therefore, cw-Inv is thought to be a key enzyme for supplying sink organs with carbohydrates and was shown to be important for developmental processes like seed or pollen development (summarized in [23]). Moreover, expression of cw-Inv was shown to be stimulated by glucose, sucrose, phytohormones and by treatment with different elicitors like chitosan and polygalacturonic acid and with non-metabolizable sugars [24–27]. Hence this enzyme appears to play an important role to various abiotic and biotic stress responses.

An accumulation of soluble sugars has been observed along with an increased cw-Inv activity in response to pathogen attack in both compatible [20,21,22] and incompatible interactions [13,22], but this occurs more rapidly and to greater extent in incompatible interactions. Hence, a fast increase of hexoses appeared to be important for an efficient and successful defense response. This is supported by the observation that high levels of sugars by expressing a yeast invertase in either the apoplast or in the vacuole of transgenic tobacco plants mediated resistance against potato virus Y [14,20]. In contrast, repression of cw-Inv activity in tobacco using an RNAi approach resulted in a lower amount of available hexoses and caused an impaired defense response following infection with Phytophthora nicotianae [13]. Increasing sugar content during later infection stages, however are likely to support pathogen nutrition resulting in disease development [28]. Interestingly, infection of cw-Inv-silenced tomato plants with Xcv provided no evidence that reduced hexose levels restricted bacterial growth [21]. Instead, lower cw-Inv activity was linked to delayed symptom development, a slower reduction of photosynthesis and a decelerated rate of pathogen-induced senescence which was most likely caused by the absence of hexose signals [21].

In fact, besides being a source of carbon skeletons and energy, soluble sugars are known to act as signaling molecules. For instance, increasing glucose levels lead to a repression of genes involved in photosynthesis and reserve mobilization and to an up-regulation of defense gene expression (summarized in [29]). Accordingly, down-regulation of photosynthetic gene expression and activity together with an induced expression of PR genes has been found in numerous plant-pathogen interactions (for review see [30,31]). Thus in a compatible interaction, the induction of cw-Inv activity may also contribute to the regulation of defense responses and photosynthesis by the generation of hexose signals.

Understanding the molecular function, mechanisms and structure of bacterial T3Es as well as the identification of their host targets is a major goal to unravel the molecular basis of plant-bacterial interactions. T3Es mimic eukaryotic proteins in structure and function and use a variety of biochemical mechanisms to target specific host proteins [32,33]. However, the functional analysis of T3Es is often hindered by their overlapping properties and by the fact that inactivation of individual effectors often has no significant effect on bacterial virulence [34,35]. Nevertheless, for some Xcv T3Es, the molecular function and first host target proteins could be identified [36,37]. For instance, AvrBs2, which is present in many Xanthomonas pathogens, was shown to be important for their virulence [36]. Recently, Zhao et al. [39] demonstrated that AvrBs2 contains an active glycerolphosphodiesterase domain which is required for its virulence function but not for its recognition by the Bs2 resistance protein. AvrBs3, another T3E, is the best characterized member of a large family of transcription activator like T3Es [36,40]. They harbor functional domains typical for eukaryotic transcription activators, like a nuclear localization signal, an acid activation domain and a central repeat region consisting of nearly identical repeats of usually 34 amino acids which mediate host DNA binding in a highly specific manner. AvrBs3 was shown to bind directly to the promoter region of target genes like upa20 (up-regulated by AvrBs3) which encodes a basic helix-loop-helix transcription factor and is a cell-growth regulator causing the enlargement of mesophyll cells observed in susceptible pepper plants [40]. XopN interacts with an atypical receptor-like kinase and 14-3-3 proteins in tomato and suppresses PTI during an early stage of infection [41,42]. XopJ and XopN, two other T3Es from Xcv were shown to suppress basal defense by either inhibiting secretion or an yet unknown mechanism, respectively [43,44]. Moreover, several effector proteins of Xcv inhibited growth of yeast cells under normal or stress conditions and also induced cell death or chlorosis when transiently expressed in tomato or Nicotiana benthamiana [45].

Here we investigated the role of cw-Inv during the compatible interaction between Xcv and its host pepper. We examined the possibility that Xcv employs T3Es to modulate cw-Inv activity during infection to promote pathogenesis. We show that induction of cw-Inv is suppressed by the translocation of T3Es, which may prevent the generation of hexose-mediated signals. Eighteen different Xcv mutants deficient in individual T3Es were tested for their effect on cw-Inv activity upon infection of pepper leaves. Among them, infection with Xcv ΔtopB caused the strongest and most robust induction of cw-Inv activity similar to a T3SS-deficient mutant (Xcv ΔtopB1), indicating that this effector plays a key role in suppression of cw-Inv activity. Moreover, inducible expression of XopB in transgenic tobacco inhibited Xcv-mediated induction of cw-Inv activity observed in wild type plants and resulted in severe developmental phenotypes. These data suggest that XopB interferes with cw-Inv activity in planta to suppress sugar-enhanced defense responses during Xcv infection.
Results

Xcv Suppresses cw-Inv Expression and Activity of Pepper Leaves in a T3SS-dependent Manner

An increase in cw-inv mRNA expression has been observed after infection of plants with both virulent and avirulent pathogens, however the timing of induction was different [30,31]. An early induction of cw-inv transcripts and the accompanied accumulation of hexoses at the infection site are thought to meet the increased energy demand for defense responses and have been associated with plant resistance during incompatible interactions [13,29]. However, the role of cw-inv during compatible interactions is less clear. Here we tested the hypothesis that Xcv T3Es contribute to successful colonization of pepper plants by suppressing cw-inv activity to prevent the generation of hexose signals and thereby suppress the down-regulation of photosynthesis and the activation of defense responses.

Susceptible pepper plants were infected with Xcv wild type strain 85-10 and the T3SS-deficient mutant strain Xcv ΔhrpB1 [46], which cannot deliver T3Es into plant cells, and the response on cw-inv mRNA expression and enzyme activity was tested. These experiments were carried out in a contained growth cabinet (see Materials and Methods) and the bacterial density used for infection was 5×10^7 colony forming units (cfu) ml^{-1}. Under these conditions, the first disease symptoms appeared 2 days after Xcv wild type infection, which were visible as water-soaked lesions (Fig. 1A). Later, the Xcv-infected leaves became chlorotic and necrotic and eventually abscised. In contrast, infection with Xcv ΔhrpB1 caused no visible symptoms at the same time point (Fig. 1A). For control purposes, pepper leaves were infiltrated with 10 mM MgCl2 (Mock-control).

To investigate the impact of Xcv infection on cw-inv expression, total RNA was isolated from infected pepper leaves and subjected to a Northern blot analysis. In addition, we also monitored the mRNA expression of the pathogenesis-related protein Q (PRQ) and ribulose-1,5-bisphosphate carboxylase (RbcS). The PRQ gene is induced upon infection and sugar floating [47], and was used as a marker gene for sugar-mediated defense. The RbcS gene served as a marker for photosynthetic gene expression. As shown in Fig. 1B, a low level of cw-inv and PRQ transcripts was detected at 12 h and 18 h after MgCl2 infiltration in control leaves, reflecting the wounding response in the host leaves due to the infiltration process. Infection with Xcv wild type caused no significant changes in mRNA abundance for cw-inv or PRQ. The mRNA level for RbcS however was reduced in Xcv-infected leaves at 48 h post-inoculation compared to the MgCl2 inoculated leaves (Fig. 1B). Reduced RbcS mRNA levels correlated with the appearance of disease symptom development at 48 h post-inoculation (Fig. 1A and B). In contrast, infection with Xcv ΔhrpB1 resulted in a progressive accumulation of cw-inv- and PRQ-specific transcripts from 12 to 48 h post-inoculation, whereas RbcS mRNA levels were reduced at 48 h post-inoculation (Fig. 1B). These data suggest that one or more T3Es from Xcv may regulate the expression and/or stability of cw-inv in pepper leaves during infection.

Next, cw-inv activity was determined following infection with Xcv wild type or Xcv ΔhrpB1 to analyze whether changes in mRNA abundance were also reflected at the enzyme activity level. Xcv wild type infection led to a stimulation of cw-inv enzymatic activity 48 h after infiltration (Fig. 2A), which is in accordance with previous studies [21,31]. However, a rapid and stronger induction of cw-inv activity was measured in pepper leaves infected with the T3SS-deficient strain Xcv ΔhrpB1 (Fig. 2A), coinciding with changes in cw-inv mRNA abundance (Fig. 1B).

Control pepper leaves inoculated with 10 mM MgCl2 showed no changes in cw-inv activity at 24 or 48 h post-inoculation (Fig. 2A).

Plants contain three different isoforms of invertases, namely vacuolar (vac), cw-bound and neutral invertases, with different biochemical properties and sub-cellular localization [23]. Based on their pH optima, vac-inv and cw-inv are referred to as acidic soluble and insoluble invertases, respectively. We next investigated if the activity of vac-inv was regulated by Xcv T3Es. As illustrated in Fig. 2B, there was approximately a two-fold increase in the activity of vac-inv within 2 days after infection with either Xcv wild type or Xcv ΔhrpB1 indicating that Xcv induces vac-inv activity although to lower extent compared to that of cw-inv. In contrast to cw-inv, the activity of vac-inv does not appear to be regulated by T3Es.

Infection with Xcv Wild Type and Xcv ΔhrpB1 Causes Changes in the Amounts of Soluble Sugars and a Decreased Rate of Photosynthesis

Since an increase in cw-inv activity upon infection with pathogens was found to be accompanied by an accumulation of soluble sugars [13,14,18–20,22], we next determined the content of soluble sugars (i.e. glucose, fructose and sucrose) from total extracts of Xcv wild type- and Xcv ΔhrpB1-infected leaves. Sucrose content was not affected by Xcv wild type infection, but increased by 50% in response to infection with the T3SS-deficient Xcv ΔhrpB1 strain (Fig. 3). The amount of glucose and fructose in pepper leaves decreased significantly following Xcv wild type infection by 48 h post-inoculation (Fig. 3). In contrast, there was an about 2-fold increase in the amount of hexoses after infection with Xcv ΔhrpB1 (Fig. 3), which accompanied the strong increase in cw-inv activity (Fig. 2A).

Next we measured photosynthetic capacity in infected leaves because decreased amounts of RbsS-specific transcripts were detected after inoculation with Xcv wild type and Xcv ΔhrpB1 (Fig. 3B). In accordance with the reduced expression of RbsS, the photosynthetic capacity (calculated as effective quantum yield) decreased after infection of pepper leaves with both Xcv wild type and Xcv ΔhrpB1 reaching 60% and 64% of the initial values after 48 h (Fig. 4).

Cw-inv Induction is Mediated by Xcv PAMPs

Cw-inv is known to be induced by PAMPs like chitosan and polygalacturonic acid or an elicitor preparation from the necrotrophic fungus Fusarium oxysporum [24,25]. To investigate whether cw-inv induction after Xcv infection is due to structural components that may act as PAMPs, cultures of Xcv wild type or Xcv ΔhrpB1 were heat-inactivated and subsequently used for infiltration into pepper leaves.

For these and the following experiments, about 6-week-old susceptible pepper plants grown in the greenhouse were used for infections. Under these conditions, non-treated Xcv wild type induced clear disease symptoms after 3 days post infection (dpi). Samples were taken daily until 3 dpi. For control purposes, pepper leaves were infiltrated with 10 mM MgCl2.

Cw-inv activity was strongly induced in pepper leaves inoculated with heat-inactivated Xcv compared to pepper leaves inoculated with non-treated Xcv wild type (Fig. 5). The increase in cw-inv activity brought about by inoculation with the heat-inactivated Xcv wild type strain was similar to those after infection with both alive and inactivated Xcv ΔhrpB1 strains. These data confirm that cw-inv activity is triggered by exposure to Xcv PAMPs. Moreover, they further suggest that Xcv T3Es(s) suppress cw-inv activity.
To test whether the cw-Inv elicitor activity is of proteinaceous nature, heat-inactivated Xcv preparations were treated with proteinase K and trypsin, which were applied simultaneously. After heat-inactivation of the proteases, Xcv cells were pelleted and re-suspended. Subsequently, the treated Xcv cells were infiltrated into pepper leaves and the effect on cw-Inv activity was determined (Fig. 5). Interestingly, the induction of cw-Inv activity due to infection with Xcv ΔhrpB1 or the heat-inactivated Xcv wild type was abolished by protease treatment, indicating that the signal responsible for cw-Inv induction is likely a proteinaceous compound.

Identification of Bacterial T3Es Involved in Suppression of cw-Inv Activity

The strong induction of cw-Inv mRNA abundance and enzyme activity after infection with the T3SS-deficient Xcv ΔhrpB1 strain suggests that Xcv T3Es directly or indirectly regulate the function of cw-Inv in leaves. To begin to unravel the underlying mechanism, we aimed at identifying individual T3Es that significantly modulate cw-Inv enzymatic activity during Xcv infection. Xcv is predicted to utilize approximately 28 T3Es based on experimental data or bioinformatic analyses [5–7]. Eighteen different Xcv strains harbouring mutations in genes encoding T3Es were tested for their effect on cw-Inv activity upon infection and compared to the Xcv wild type response. Individual Xcv mutant strains were either generated within this study, by overlapping extension PCR and subsequent triparental mating, or have been generated and described in previous studies (Table 1). For the experiments, samples were taken before (0), 2 and 3 dpi, since clear differences in cw-Inv activity were detectable at these time points (Fig. 5). For control purposes, leaves were infiltrated with 10 mM MgCl₂ and with Xcv ΔhrpB1. A typical set of data is shown in Fig. S1. As described before, cw-Inv activity was induced after infection with the Xcv wild type strain. However, the increase in cw-Inv activity was much stronger when T3SS-deficient strains (Xcv ΔhrpB1 or Xcv ΔhrpF) were inoculated (Fig. S1). The different effector mutants were repeatedly tested in different sets of experiments. Due to the cultivation of plants in greenhouse there was a high variation (about 62%) in cw-Inv activity after Xcv wild type infection of pepper leaves over the different experiments. To enable comparison of individual data sets and to determine which T3E has a significant effect on cw-Inv activity, the cw-Inv activity was calculated upon infection with the individual Xcv mutant strains and the deviation to the cw-Inv activity caused by Xcv wild type was determined as percentage. The values obtained from up to nine different screenings were compiled and the mean (percentage) was calculated (Fig. 6). Only those T3E mutant strains that caused

Figure 1. Infection of susceptible pepper leaves with Xcv wild type or with the T3SS-deficient Xcv ΔhrpB1 strain. Impact on symptom development and transcript accumulation of cw-Inv, PRQ and RbcS. Fully mature leaves of young pepper plants were infected with the Xcv wild type (wt), the Xcv ΔhrpB1 using a concentration of 5 x 10⁸ cfu ml⁻¹, and as control with 10 mM MgCl₂. A.) Formation of disease symptoms after Xcv wild type inoculation of susceptible pepper leaves. Only the lower halves of leaves were infiltrated. Pictures were taken 3 days post infection. B.) For Northern Blot analysis total RNA was isolated from leaf material taken before (0 h) and 3, 6, 12, 18, 24 and 48 hours post infection (hpi). Thirty micrograms of total RNA were loaded per each lane. The Northern blot was probed with [³²P]-labeled cDNA fragments of cw-inv, PRQ, RbcS and cytosolic GAPDH as control. Results of a representative experiment are shown which have been repeated three times. doi:10.1371/journal.pone.0051763.g001
highly significant (p-value < 0.01) changes compared to Xcv wild type were considered. Overall, seven Xcv T3E mutants showed a significantly different response 2 and/or 3 dpi compared to Xcv wild type infection: XcvDxopJ, XcvDxopB, XcvDxopE1, XcvDxopE2, XcvDxopD, XcvDxopN, XcvDxopQ (Fig. 6). Five Xcv strains, namely those with mutations in xopE1, xopE2, xopD, xopN and xopQ caused a significant reduced activation of cw-Inv activity. Infection with XcvDxopE1 caused the most prominent effect leading to a 40% and 65% lower induction of cw-Inv activity compared to wild type after 2 and 3 days, respectively (Fig. 6). Infection with two Xcv T3E-deficient mutants led to an increased cw-Inv activity, namely XcvDxopJ and XcvDxopB (Fig. 6). Also inoculation with strains XcvΔxopB2, XcvΔxopX, XcvΔxopA1K tended to induce higher cw-Inv activity compared to Xcv wild type, but due to higher variation these changes are not statistically significant or are less significant (p-value < 0.05) (Fig. 6, Fig. S1). Infection of pepper leaves with XcvΔxopJ only led to 30% higher cw-Inv activity compared to Xcv wild type 2 dpi, while XcvΔxopB infections elicited an increase in cw-Inv activity to 191% and 233% after 2 and 3 dpi, respectively. Overall, XcvΔxopB infections resulted in the strongest increase of cw-Inv activity compared to any other Xcv T3E mutant strain tested which led us to conclude that this effector plays a key role in suppression of cw-Inv activity. Therefore in further work, we focused on analysis of XopB.

Effect of xopB Deletion on Gene Expression

To investigate whether XopB alters cw-Inv abundance at the transcriptional level, total RNA was isolated from pepper leaves before and 1–3 dpi with Xcv wild type, XcvΔxopB, XcvΔhrpB1 or 10 mM MgCl₂, and then transcript accumulation of cw-Inv, PRQ, and RbcS was analyzed by Northern blotting (Fig. 7). As expected,
only a low level of cw-Inv and PRQ mRNA was detected in pepper leaves infected with Xcv wild type (Fig. 7). In contrast, infection with either Xcv ΔhrpB1 or Xcv ΔxopB resulted in high levels of cw-Inv and PRQ specific transcripts, which was more pronounced after Xcv ΔhrpB1 treatment. RbcS mRNA abundance decreased after infection with all three Xcv strains and was hardly detectable at 2 and 3 dpi (Fig. 7).

To investigate whether XopB inhibits the expression of other defense-related genes, we analyzed the expression of Ph5 and Ace31. Both genes have been used as markers for PTI in tomato and/or N. benthamina and were shown to be significantly induced upon inoculation with TSSS-deficient strains [41,42,48]. To enable the analysis in pepper plants we used the published sequences of SlActin (AB199316.1), SlPh5 (LEU92956) and NtAce31 (SGN-U434705) to search for orthologous sequences in pepper using the BLAST tool provided by the Solanaceae Genomic Network (http://solgenomics.net/). This led to the identification of the closely related sequences CaActin (SGN-U196461), CaPh5 (SGN-U198671) and CaAce31 (SGN-U198671) which exhibit 89%, 86% and 83% identity, respectively to the query sequences.

Total RNA was isolated from inoculated tissue at 6 h and 24 h after inoculation and relative abundance of specific mRNAs was ascertained by quantitative real-time PCR. Relative expression values for each treatment were compared to that obtained at time point “0 h” which was arbitrary set to 1 (Fig. 8). There was a large increase in Ph5- and Ace31-specific transcripts in pepper leaves 24 h after inoculation with Xcv ΔhrpB1 compared to those infected with Xcv wild type (Fig. 8). This indicates that Ph5 and Ace31 mRNA abundance in pepper were induced in response to Xcv ΔhrpB1 and that Xcv T3Es suppress their expression. Strikingly, infection with Xcv ΔxopB infection did not cause significant changes in Ph5 or Ace31 mRNA levels as compared to the response caused by Xcv ΔhrpB1 infection (Fig. 8). This suggests that XopB does not affect the mRNA abundance of the two PTI-associated genes, but regulates the expression of cw-Inv and PRQ (Fig. 7).

Figure 4. Changes in pepper leaf photosynthetic capacity after Xcv infection. Rate of photosynthesis, represented as effective quantum yield of photosystem II, was measured in susceptible pepper leaves 2, 6, 24 and 48 hours post infection (hpi) with the Xcv wild type strain (wt, black bars) and Xcv ΔhrpB1 (grey bars) and compared to 10 mM MgCl2 (white bars) inoculated control leaves. Values represent the mean ± SE of four measurements performed with independent plants. The experiment was repeated twice with similar results.

doi:10.1371/journal.pone.0051763.g004

Figure 5. Cw-Inv activity of susceptible pepper leaves infected with heat-inactivated and protease-treated preparations of Xcv cells. Xcv wild type (wt) and Xcv ΔhrpB1 were grown over night in NYG medium and prepared as described in material and methods. Subsequently, cells were heat-inactivated at 95°C for 20 min. An aliquot of each cell culture was digested with proteases (proteinate K and trypsin) for 2 h at 60°C. After heat-inactivation for 10 min, cells were pelleted and re-suspended in 10 mM sterile MgCl2 and adjusted to OD500 = 1. Heat-inactivated Xcv cells with or without protease treatment were used for inoculation of pepper leaves. Samples were taken before (0 d), 1, 2 and 3 days post infections (dpi) and cw-Inv activity was measured. Values represent the mean of four independent samples ± SD. Similar results were obtained in an independent experiment.

doi:10.1371/journal.pone.0051763.g005

Complementation of the Effect of Xcv ΔxopB on cw-Inv Activity

To confirm that suppression of cw-Inv is brought about by deletion of xopB, two complementation constructs were generated using the pBRR1MCS5 vector [49] that expresses the gene of interest under control of the lacZ promoter. To this end, a 2.6 kb genomic fragment encompassing the xopB region (~649 till 1949 bp) was amplified by PCR from the Xcv wild type strain (85-10). The fragment was cloned into the pBRR1MCS5 vector in both orientations referred to as pBRR::xopB(+) and pBRR::xopB(-). These constructs were conjugated into the Xcv ΔxopB mutant strain. The resulting Xcv strains were used for infection experiments and compared to the Xcv wild type and Xcv ΔxopB strains in which the empty vector was inserted. Activity of cw-Inv in pepper leaves was measured 1, 2, and 3 dpi. As expected, Xcv wild type infection resulted in the induction of cw-Inv activity (Fig. 9). However, the level of Xcv-induced cw-Inv activity was high compared to other experiments (Fig. 6, Fig. S1) reflecting the experimental variation detected under the conditions tested on different days. Nonetheless, the induction of cw-Inv activity in response to Xcv ΔxopB infection was higher than that triggered by Xcv wild type (Fig. 9A). Strikingly, the induction of cw-Inv activity by the xopB deletion strain could be overcome by introducing both plasmids. Thus, the cw-Inv activity after infection with Xcv ΔxopB containing the plasmid pBRR::xopB in either direction was comparable to that after Xcv wild type inoculation indicating that the effect of the xopB deletion could be complemented (Fig. 9A). The presence of XopB protein was confirmed by western blot analysis using an anti-XopB antibody that was generated against His-tagged XopB purified from E. coli (Fig. 9B). In the western blot, XopB protein expression could be detected upon infection with the Xcv ΔxopB strains containing
Impairs Plant Growth and Development
Suppresses Induction of cw-Inv Activity and Severely Expression of xopB in Transgenic Tobacco Plants

Table 1. Xanthomonas campestris pv. vesicatoria strains used in this study.

<table>
<thead>
<tr>
<th>Strain</th>
<th>Gene No.</th>
<th>Characteristics</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xcv B5-10, wild type</td>
<td></td>
<td>Pepper race 2, wild type strain 85-10, Rif&lt;sup&gt;a&lt;/sup&gt;</td>
<td>[82]</td>
</tr>
<tr>
<td>Xcv ΔxopB&lt;sup&gt;1&lt;/sup&gt;</td>
<td>XCO0427</td>
<td>h&lt;sup&gt;b&lt;/sup&gt;P&lt;sup&gt;b&lt;/sup&gt; deletion mutant of 85-10</td>
<td>[46]</td>
</tr>
<tr>
<td>Xcv ΔxopF&lt;sup&gt;1&lt;/sup&gt;</td>
<td>XCO0411</td>
<td>h&lt;sup&gt;b&lt;/sup&gt;P&lt;sup&gt;b&lt;/sup&gt; deletion mutant of 85-10</td>
<td>[63]</td>
</tr>
<tr>
<td>Xcv ΔavrB&lt;sup&gt;1&lt;/sup&gt;</td>
<td>XCO0532</td>
<td>avrB&lt;sup&gt;b&lt;/sup&gt; deletion mutant of 85-10</td>
<td>This study</td>
</tr>
<tr>
<td>Xcv ΔavrX&lt;sup&gt;1&lt;/sup&gt;</td>
<td>XCO0471</td>
<td>avrX&lt;sup&gt;b&lt;/sup&gt; deletion and frameshift mutant of 85-10</td>
<td>This study</td>
</tr>
<tr>
<td>Xcv Δxop&lt;sup&gt;B&lt;/sup&gt;</td>
<td>XCO0581</td>
<td>xop&lt;sup&gt;B&lt;/sup&gt; deletion mutant of 85-10</td>
<td>[70]</td>
</tr>
<tr>
<td>Xcv Δxop&lt;sup&gt;B&lt;/sup&gt; (Δ1257)</td>
<td>XCO0581</td>
<td>xop&lt;sup&gt;B&lt;/sup&gt; deletion mutant of 85-10</td>
<td>This study</td>
</tr>
<tr>
<td>Xcv ΔxopC&lt;sup&gt;1&lt;/sup&gt;</td>
<td>XCO2435</td>
<td>xopC&lt;sup&gt;1&lt;/sup&gt; deletion mutant of 85-10</td>
<td>[34]</td>
</tr>
<tr>
<td>Xcv Δxop&lt;sup&gt;D&lt;/sup&gt;</td>
<td>XCO0437</td>
<td>xopD deletion mutant of 85-10</td>
<td>[83]</td>
</tr>
<tr>
<td>Xcv ΔxopE&lt;sup&gt;1&lt;/sup&gt;</td>
<td>XCO0294</td>
<td>xopE&lt;sup&gt;1&lt;/sup&gt; deletion mutant of 85-10</td>
<td>This study</td>
</tr>
<tr>
<td>Xcv ΔxopE&lt;sup&gt;2&lt;/sup&gt;</td>
<td>XCO2280</td>
<td>xopE&lt;sup&gt;2&lt;/sup&gt; deletion and frameshift mutant of 85-10</td>
<td>This study</td>
</tr>
<tr>
<td>Xcv ΔxopF&lt;sup&gt;1&lt;/sup&gt;</td>
<td>XCO0414</td>
<td>xopF&lt;sup&gt;1&lt;/sup&gt; deletion mutant of 85-10</td>
<td>[83]</td>
</tr>
<tr>
<td>Xcv ΔxopF&lt;sup&gt;2&lt;/sup&gt;</td>
<td>XCO2942</td>
<td>xopF&lt;sup&gt;2&lt;/sup&gt; deletion mutant of 85-10</td>
<td>This study</td>
</tr>
<tr>
<td>Xcv ΔxopG&lt;sup&gt;1&lt;/sup&gt;</td>
<td>XCO1298</td>
<td>xopG deletion mutant of 85-10</td>
<td>This study</td>
</tr>
<tr>
<td>Xcv ΔxopJ&lt;sup&gt;1&lt;/sup&gt;</td>
<td>XCO2156</td>
<td>xopJ deletion mutant of 85-10</td>
<td>[70]</td>
</tr>
<tr>
<td>Xcv ΔxopN&lt;sup&gt;1&lt;/sup&gt;</td>
<td>XCO2444</td>
<td>xopN deletion mutant of 85-10</td>
<td>[83]</td>
</tr>
<tr>
<td>Xcv ΔxopO&lt;sup&gt;1&lt;/sup&gt;</td>
<td>XCO1055</td>
<td>xopO deletion mutant of 85-10</td>
<td>[83]</td>
</tr>
<tr>
<td>Xcv ΔxopP&lt;sup&gt;1&lt;/sup&gt;</td>
<td>XCO1236</td>
<td>xopP deletion mutant of 85-10</td>
<td>[83]</td>
</tr>
<tr>
<td>Xcv ΔxopQ&lt;sup&gt;1&lt;/sup&gt;</td>
<td>XCO4438</td>
<td>xopQ deletion mutant of 85-10</td>
<td>[83]</td>
</tr>
<tr>
<td>Xcv ΔxopX&lt;sup&gt;1&lt;/sup&gt;</td>
<td>XCO0572</td>
<td>xopX deletion mutant of 85-10</td>
<td>This study</td>
</tr>
<tr>
<td>Xcv Δe&lt;sup&gt;c&lt;/sup&gt;f&lt;sup&gt;1&lt;/sup&gt;</td>
<td>XCO3785</td>
<td>ecf deletion mutant of 85-10</td>
<td>This study</td>
</tr>
<tr>
<td>Xcv ΔxopA&lt;sup&gt;1&lt;/sup&gt;</td>
<td>XCO4428</td>
<td>xopA&lt;sup&gt;1&lt;/sup&gt; deletion mutant of 85-10</td>
<td>This study</td>
</tr>
<tr>
<td>Xcv ΔxopA&lt;sup&gt;1&lt;/sup&gt;K&lt;sup&gt;1&lt;/sup&gt;</td>
<td>XCO3786</td>
<td>xopA&lt;sup&gt;1&lt;/sup&gt;K&lt;sup&gt;1&lt;/sup&gt; deletion mutant of 85-10</td>
<td>This study</td>
</tr>
<tr>
<td>Xcv wt+pBBR1MC55 EV&lt;sup&gt;1&lt;/sup&gt;</td>
<td></td>
<td>wild type strain 85-10 containing pBBR1MC55 plasmid, Rif&lt;sup&gt;a&lt;/sup&gt;, Genta&lt;sup&gt;b&lt;/sup&gt;</td>
<td>This study</td>
</tr>
<tr>
<td>Xcv Δxop&lt;sup&gt;B&lt;/sup&gt;+pBBR1MC55 EV&lt;sup&gt;1&lt;/sup&gt;</td>
<td>xopB deletion mutant of 85-10 containing pBBR1MC55 plasmid, Rif&lt;sup&gt;a&lt;/sup&gt;, Genta&lt;sup&gt;b&lt;/sup&gt;</td>
<td>This study</td>
<td></td>
</tr>
<tr>
<td>Xcv Δxop&lt;sup&gt;B&lt;/sup&gt;+pBBR&lt;xopB&lt;sup&gt;(+-)&lt;/sup&gt;&gt;&lt;sup&gt;1&lt;/sup&gt;</td>
<td>xopB deletion mutant of 85-10 containing pBBR:xopB plasmid to restore wild type, Rif&lt;sup&gt;a&lt;/sup&gt;, Genta&lt;sup&gt;b&lt;/sup&gt;</td>
<td>This study</td>
<td></td>
</tr>
<tr>
<td>Xcv Δxop&lt;sup&gt;B&lt;/sup&gt; (Δ1257)+pBBR1MC55 EV&lt;sup&gt;1&lt;/sup&gt;</td>
<td>xopB deletion mutant of 85-10 containing pBBR1MC55 plasmid, Rif&lt;sup&gt;a&lt;/sup&gt;, Genta&lt;sup&gt;b&lt;/sup&gt;</td>
<td>This study</td>
<td></td>
</tr>
<tr>
<td>Xcv Δxop&lt;sup&gt;B&lt;/sup&gt; (Δ1257)+pBBR:xopB&lt;sup&gt;(+-)&lt;/sup&gt;</td>
<td>xopB deletion mutant of 85-10 containing pBBR:xopB plasmid to restore wild type, Rif&lt;sup&gt;a&lt;/sup&gt;, Genta&lt;sup&gt;b&lt;/sup&gt;</td>
<td>This study</td>
<td></td>
</tr>
</tbody>
</table>

doi:10.1371/journal.pone.0051763.t001

either complementation construct. The presence of XopB could also be detected in pepper leaves after infection with the Xcv wild type strain, but not after inoculation of the Xcv xopB deletion strain (Fig. 9B).

To confirm these results, we generated an independent xopB deletion strain Xcv ΔxopB (Δ1257) (bp 259-1515) and complemented it with the pBBR::xopB plasmid. Together with the Xcv wild type which harbors the empty vector, these strains were inoculated into pepper leaves and cw-Inv activity was measured (Fig. S2). Also this xopB deletion strain caused a strong increase in cw-Inv activity compared to Xcv wild type and this induction was abolished by introduction the complementation plasmid.

Expression of xopB in Transgenic Tobacco Plants Suppresses Induction of cw-Inv Activity and Severely Impairs Plant Growth and Development

As an alternative approach to confirm that XopB suppresses cw-Inv activation, we aimed at expressing xopB in transgenic plants. To this end, the open reading frame coding for XopB was cloned and inserted between the CaMV 3SS promoter and octopin synthase polyadenylation signal of the pBinAR vector [50] and the resulting plasmid was transformed into tobacco plants. Several transgenic lines could be regenerated which did not show obvious phenotypic changes in tissue culture. However after transfer into the greenhouse, the transgenic plants exhibited severe phenotypic alterations. Leaf development was significantly affected leading to malformed leaves and a dieback of the apical and lateral meristems (Fig. S3B). Expression of the xopB transgene was verified by Northern blot analysis of selected lines (Fig. S3A). Similar phenotypic changes were observed in transgenic tomato plants transformed with the same construct (Fig. S3C). These heavily impaired transgenic plants did not flower, were sterile and could consequently not be used for further experiments.

To circumvent the problem caused by constitutive expression of xopB in planta, transgenic tobacco plants were generated that express xopB under the control of the ethanol-inducible promoter [51]. More than 70 transgenic plants were obtained which showed no morphological changes in a non-induced situation. To trigger expression of xopB, plants were watered with 1% (v/v) ethanol. Expression of the transgene was analyzed by Northern blotting of
samples taken from young leaves 1 day after ethanol induction (Fig. 10A) and several positive lines were identified. Two transgenic lines (\#22, \#71) were selected for further analysis. Expression of the protein upon ethanol induction was verified in these lines by Western blotting using the XopB-specific antibody (Fig. 10B). The first phenotypic changes became visible in young, developing leaves 2 days after watering with ethanol (Fig. 10C). After 1 week, the morphological alterations of these leaves resembled those observed in transgenic plants with constitutive expression of $xopB$. However, normal new leaves could develop from unaffected lateral meristems and these plants produced normal flowers and seeds (Fig. 10C).

To study the impact of XopB on cw-Inv activity, the transgenic lines \#22 and \#71 were grown together with a transgenic control line which also harbors a kanamycin resistance gene [52]. One day after ethanol treatment, plants were infiltrated with Xcv wild type strain (OD$_{600}$ = 1.0) or 10 mM MgCl$_2$, and cw-Inv activity was measured 1 and 2 dpi. The induction was calculated for each treatment relative to the time point “0” (Fig. 11). Tobacco is a non-host plant for Xcv and a cell death response could be observed 3 to 4 dpi depending on greenhouse conditions (data not shown). In control plants, cw-Inv activity was strongly stimulated by Xcv infection at 1 and 2 dpi, but not by MgCl$_2$ inoculation (Fig. 11). Interestingly, leaves expressing XopB only had a low level of cw-Inv activity during Xcv infection compared to the mock-inoculated transgenic plants. The cw-Inv activity was similar in Xcv-infected non-induced transgenic EtOH:$xopB$ plants and control plants (Fig. 11). These data suggest that XopB suppresses the induction of host cw-Inv activity provoked by Xcv infection.

**Discussion**

Until recently, little was known about the precise function of bacterial T3Es during plant pathogen interaction. The successful characterization of a number of effectors has provided the first insights into how they contribute to the pathogenic lifestyle of bacteria [8,33,36]. Almost two decades ago, it has been suggested...
that T3Es play an essential role in pathogenicity. In a very early study, Jakobek and colleagues showed that *Pseudomonas syringae* pv. *phaseolicola* has evolved strategies to suppress the expression of defense genes such as phenylalanine ammonia-lyase, chalcone synthase, chalcone isomerase and the production of phytoalexins in bean [53]. In addition, microscopic studies revealed that localized cell wall modification and associated papillae formation were caused by *Xcv hrp*-mutants but not by the wild type strain [54]. Using microarrays, Hauck et al. [55] showed that down-regulation of *Arabidopsis* genes involved in cell wall strengthening and plant defense by *P. syringae* DC3000 is caused by T3Es. More recent studies provided evidence that individual bacterial T3Es contribute to suppression of PTI and ETI responses, but only few are major virulence factors since deletion has only little effect on virulence (summarized in [36,39]). Now the identification of their host targets and biochemical activities is the major issue to unravel the molecular basis of plant-bacteria interaction.

Sugars were suggested to contribute to immune responses against pathogens [20,27,47,56]. It is now clear that the sucrose-to-hexose ratio in the apoplastic space has emerged as an important parameter linked to plant immunity which is largely controlled by cw-Inv. In most cases, cw-Inv mRNA expression and enzyme activity are induced at the infection site by diverse pathogens including fungi, oomycetes, viruses and bacteria [18–

---

**Figure 8. Expression of PTI marker genes *Pti5* and *Acre31* in susceptible pepper leaves after infection with different *Xcv* strains.** Leaves of pepper plants were inoculated with *Xcv* wild type (wt), *Xcv ΔhrpB1*, *Xcv ΔxopB* using a concentration of 10^9 cfu ml ^{-1}, and with 10 mM MgCl2. Total RNA was isolated from samples taken before (0 h), 6 h and 24 h after infiltration and reverse transcribed into cDNA. Abundance of *Pti5* (A) and *Acre31* (B) mRNA was detected by qPCR. Data were analysed using MxPro software v4.1. The expression levels of *Pti5* and *Acre31* were normalized with *Actin* and displayed relative to the expression level at time point 0 h which was set to a value of 1. The average ± SE of three replicates is shown. Similar results were obtained in an independent experiment. White bars, MgCl2; light grey, *Xcv* wild type; black, *Xcv ΔhrpB1*, dark grey, *Xcv ΔxopB*.

doi:10.1371/journal.pone.0051763.g008
22]. We show that cw-Inv activity is increased in susceptible pepper leaves after infection with Xcv wild type but this was not associated with increased cw-Inv transcript abundance. The obvious discrepancy between increased cw-Inv enzyme activity and mRNA accumulation may be explained by at least two mechanisms. Firstly, protein turnover may be decreased leading to an increase in the cw-Inv protein amount relative to the mRNA level. Secondly, proteinaceous cw-Inv inhibitor proteins have been discussed in numerous plants species, although their molecular mode of action and their regulation are still under debate [57,58]. Nevertheless, they may be responsible for the in planta modulation of cw-Inv activity. The second hypothesis is in accordance with a report from Bonfig et al. [59].

In a first work, Bonfig et al. reported an accumulation of cw-Inv1 transcript after infection of A. thaliana with P. syringae DC3000 but this was not paralleled by an increased enzyme activity [60]. However, an elevated cw-Inv activity was demonstrated using histochemical activity stain in a subsequent study [59]. The difference in the measurable cw-Inv enzyme activity was explained by the release of cw-Inv enzyme from repression by the cw-Inv invertase inhibitor. Accordingly, the expression of the invertase inhibitor At C/VIF2 was shown to be down-regulated after P. syringae DC3000 infection of A. thaliana plants [59].

Cw-Inv activity is induced by several stimuli including sugars and PAMPs (e.g. chitosan and a crude elicitor preparation of the fungus Fusarium oxysporum f. lycopersici) [24]. In our study, heat-inactivated Xcv cells triggered a strong induction of cw-Inv activity and this induction was abolished by protease-treatment suggesting that proteinaceous compounds or structures from Xcv are most likely the stimulus. Both lipopolysaccharides and the peptide-bearing peptidoglycans from Xanthomonas sp. have been shown to act as PAMPs and elicit basal defense responses [61,62]. The most extensively studied bacterial PAMPs are the small peptides flg22 and elf18 derived from flagellin and the translation elongation factor EF-Tu, respectively. However to date, the respective PAMPs from Xcv have not been associated with a stimulation of PTI in solanaceous plants. While flagellin from some X. campestris
Regulation of cw-Inv by Xcv Type Three Effectors

Infection of pepper plants with the T3SS-deficient strain Xcv ΔxopB1 resulted in a progressive increase in cw-Inv mRNA abundance, which was accompanied by a strong increase in cw-Inv enzyme activity compared plants infected with Xcv wild type. This result led us to conclude that Xcv T3Es are likely involved in the suppression of cw-Inv transcription and enzyme activity. Using the Xcv ΔhrpF mutant lacking the translocation apparatus [65], we could show that delivery of T3Es into plant cells is required to achieve suppression of cw-Inv. Moreover, the elevated cw-Inv activity upon inoculation with the T3SS-deficient strain was paralleled by an accumulation of soluble sugars, while infection with Xcv wild type led to reduced amounts of glucose and fructose. In the latter case, the reduced level of hexoses may be due to bacterial uptake and consumption and/or to a lower accumulation of sugars due to metabolic disturbances. A decrease in the rate of photosynthesis and a reduction in the photosynthesis-related RbcS transcript were observed in the Xcv-infected pepper leaves. Xcv wild type infection causes macroscopically visible disease symptoms (i.e. chlorosis and necrosis) in pepper leaves. As the pathogen multiplies and colonizes its host tissue, it is hypothesized that the pathogen re-directs plant metabolism to allocate nutrients for its own benefit. The outcome of this interaction results in metabolic perturbation in the plant cell as well as host cell leakage which are most likely responsible for a rapid decline in photosynthesis. This is in accordance with the decline in photosynthesis observed after infection with several pathogens [summarized in [30]].

Notably, a decreased rate of photosynthesis and RbcS mRNA expression was also observed after infection with the Xcv ΔxopB1 strain. In this case, bacterial propagation was restricted due to PTI and no disease symptoms were apparent at 2 dpi. The decrease in photosynthetic activity cannot be explained by cell damage caused by bacteria. It could however be due to the cw-Inv dependent generation of sugar signals in the apoplast. In addition to their classical role as a source of carbon and energy, soluble sugars act as signaling molecules and can regulate gene expression [29,66]. An accumulation of soluble sugars, in particular hexoses, is known to down-regulate photosynthetic gene expression [29,30,66] and to increase expression of defense-related genes, such as PRQ [47,66]. Thus, hexoses released by cw-Inv activated during Xcv ΔxopB1 infection of pepper leaves may act as signalling molecules to repress photosynthetic gene expression and to increase PRQ-specific transcript abundance. This assumption is supported by an earlier study in which cw-Inv activity was required to induce senescence-associated and PR- genes (including PRQ) after Xcv infection and was linked to a down-regulation of photosynthetic activity and RbcS mRNA abundance [21]. The results indicate that suppression of cw-Inv may contribute to a longer maintenance of photosynthesis activity and dampening of basal defense. Together, our results suggest that T3Es suppress the induction of cw-Inv activity to minimize the generation of sugar signals in infected plant leaves.

In order to identify Xcv T3E(s) involved in regulation of cw-Inv activity, we performed a screen with eighteen Xcv mutants deficient in individual effectors. Among them, several Xcv deletion strains (e.g. Xcv ΔxopE1, Xcv ΔxopE2, Xcv ΔxopD, Xcv ΔxopN) suppressed cw-Inv activity in peppers leaves relative to that detected in Xcv wild type-infected leaves. This was unexpected from the strong induction caused by T3SS-deficient strains, and may argue for tight regulation of cw-Inv with T3Es acting as activators and suppressors. Hence, they might contribute to activation of cw-Inv activity during later stages of infection.

T3Es acting at the plasma membrane could potentially influence secretion or activity of cw-Inv. XopE1 and XopE2 were shown to harbor a conserved N-myristoylation motif that is most likely responsible for targeting the proteins to the plasma membrane [67]. Using xopE1 and xopE2 deletion strains, no differences in disease and HR development could be detected when compared to Xcv wild type [67]. They belong to the HopX effector family, which is part of the transglutaminase superfamily encompassing proteins with different enzymatic activities (e.g. proteinases; see [67]), but the enzymatic activity of XopE1 and XopE2 is unclear. In our screen, they appeared to promote cw-Inv activity, which needs to be secreted into the extracellular milieu. XopN is involved associated with the host plasma membrane and involved in the suppression of PTI. The Xcv ΔxopN mutant was shown to be impaired in bacterial growth and development of disease symptoms in tomato leaves [41]. This delay may also contribute to a weaker induction of cw-Inv activity. In contrast, tomato leaves infected with Xcv ΔxopD developed disease symptoms like chlorosis and necrosis faster than Xcv wild type infected plants [68]. The authors speculated that XopD may contribute to multiplication of Xcv during later stages of infection by suppressing leaf senescence and symptom development. It was shown that XopD localizes to subnuclear foci and exhibits a DNA-binding domain that may regulate transcription of target genes [68,69].

Figure 11. Inducible xopB expression in transgenic tobacco leaves suppresses cw-Inv activity during Xcv infection. Control plants and two selected transgenic tobacco lines with inducible xopB expression (#22, #71) were watered with 1% ethanol. After 24 h, plantlets were inoculated with a 10^6 cfu ml^-1 suspension of Xcv wild type. Samples were taken directly before inoculation and 1 and 2 days post inoculation (1dpi + EtOH; 2dpi Xcv+ EtOH). Non-ethanol watered plants were also inoculated with Xcv and samples were taken accordingly (1dpi - EtOH; 2dpi - EtOH). For control purposes ethanol-treated and non-treated plants were inoculated with 10 mM MgCl2. Cw-Inv activity was determined from four independent samples and fold changes ± SD were calculated for each sample relative to values obtained before Xcv inoculation. The experiment was repeated with similar results.

doi:10.1371/journal.pone.0051763.g011

pv. campestris strains were shown to elicit FLS2-dependent defense responses in A. thaliana [63], a crude flagellin preparation from Xcv did not stimulate a defense response in tomato cells [64]. Recent publications suggest that conserved components of the T3SS machinery itself may serve as PAMPs that are specifically recognized by receptors to trigger plant immune responses ([39] and references therein). Thus, further experiments are necessary to elucidate the identity of the cw-Inv inducer from Xcv.

Infection of pepper plants with the T3SS-deficient strain Xcv ΔxopB1 induced a progressive increase in cw-Inv mRNA abundance, which was accompanied by a strong increase in cw-Inv enzyme activity compared plants infected with Xcv wild type. This result led us to conclude that Xcv T3Es are likely involved in the suppression of cw-Inv transcription and enzyme activity. Using the Xcv ΔhrpF mutant lacking the translocation apparatus [65], we could show that delivery of T3Es into plant cells is required to achieve suppression of cw-Inv. Moreover, the elevated cw-Inv activity upon inoculation with the T3SS-deficient strain was paralleled by an accumulation of soluble sugars, while infection with Xcv wild type led to reduced amounts of glucose and fructose. In the latter case, the reduced level of hexoses may be due to bacterial uptake and consumption and/or to a lower accumulation of sugars due to metabolic disturbances. A decrease in the rate of photosynthesis and a reduction in the photosynthesis-related RbcS transcript were observed in the Xcv-infected pepper leaves. Xcv wild type infection causes macroscopically visible disease symptoms (i.e. chlorosis and necrosis) in pepper leaves. As the pathogen multiplies and colonizes its host tissue, it is hypothesized that the pathogen re-directs plant metabolism to allocate nutrients for its own benefit. The outcome of this interaction results in metabolic perturbation in the plant cell as well as host cell leakage which are most likely responsible for a rapid decline in photosynthesis. This is in accordance with the decline in photosynthesis observed after infection with several pathogens [summarized in [30]].
In contrast, infection with \( Xcv \Delta xopJ \) or \( Xcv \Delta xopB \) resulted in increased cw-Inv activity at 2 and/or 3 dpi. XopB is a member of YopJ/AvrRsv family of T3Es with SUMO peptidase and acetyltransferase activity. Like XopE1 and XopE2, it localizes to the plasma membrane which is most likely mediated by an N-terminal N-myristoylation motif [43,67]. Furthermore, it could be demonstrated that expression of XopJ in N. benthamiana inhibits secretion of a secGFP marker and that transgenic \( A. thaliana \) plants with inducible expression of XopJ are compromised in their ability to deposit callose. These data led to the suggestion that XopJ interferes with vesicle transport and thereby with cell wall-based defense [43]. Since cw-Inv is also a protein that needs to be secreted, the higher cw-Inv activity measured 2 days after infection with \( Xcv \Delta xopJ \) may be explained by the negative influence of XopJ on protein secretion. The impact on cw-Inv may be overcome by other effectors which may have a redundant function during later stages of infection.

The most prominent effect on cw-Inv was seen after infection with \( Xcv \Delta xopB \). XopB was identified as a HrpG controlled gene via a cDNA-AFLP screen and was shown to be secreted by the T3SS [70,71]. The XopB protein consists of 613 amino acids and sequence comparisons revealed high sequence similarity only to proteins of phytopathogenic bacteria such as to HopD1 from \( Pseudomonas syringae pv. tomato \) and AvrPphD of \( P. syringae pv. phasolicola \), but nothing is known about its biological activity. As observed earlier by Noel et al. [70], inoculation of \( Xcv \Delta xopB \) in susceptible pepper plants revealed no significant differences in timing of symptom development and bacterial growth compared to \( Xcv \) wild type, while in a very recent study, Schulze et al. [71] found that deletion of xopB led to reduced disease symptoms, although multiplication was not impaired compared to \( Xcv \) wild type. The different phenotypes in the mentioned studies were attributed to different environmental conditions. Deletion of xopB did not however influence the ability to elicit an HR in resistant pepper plants [71].

Using a protoplast assay, Schulze et al. [71] showed recently that XopB suppresses flg22-mediated induction of the NHL10 (NDRI1/Hin1-like10) promoter fused to luciferase which served as a reporter for basal defense. However, XopB did not interfere with flg22-triggered activation of MAPKs [71]. Here, we showed that XopB is a key regulator for the induction of cw-Inv and affects both its transcript abundance and its activity. Furthermore, XopB is involved in the suppression of PRQ gene expression. PRQ expression was found to be induced by sugars and saliclycic acid, but sugar-mediated regulation was independent of salicylic acid [20,47]. In contrast, XopB activity did not influence the mRNA abundance of Prb5 and Aven31, two genes associated with PTI in tomato [41,42,48]. This indicates that XopB inhibits a specific set of defense genes including sugar responsive ones.

Schulze et al. [71] concluded from localization studies that XopB is confined to vesicle-like structures in the cytoplasm of the host cell and may inhibit intracellular vesicle trafficking. Vesicle trafficking which is important for correct localisation of PAMP receptors as well as for the export of PR proteins and other extracellular enzymes (like cw-Inv), and antimicrobial peptides appears to be an important part of plant immunity and some T3Es (e.g. Xop) and HopM1) were shown to target the secretion pathway [43,72]. However compared to \( Xcv \Delta xopB \), deletion of xopJ from the \( Xcv \) genome had only a weak effect on cw-Inv in our assays. Whether XopB regulates directly or indirectly cw-Inv by inhibition of protein secretion or by a different mechanism remains to be elucidated.

Ectopic expression of XopB in transgenic tomato and tobacco plants caused severe phenotypic alterations including the appearance of cell death, in particular in young, growing tissue, which finally led to a dieback of meristems. Expression of XopB in yeast cells also resulted in growth inhibition [45] and it caused cell death when transiently expressed in \( N. benthamiana \), but not in \( N. tabacum \) or tomato [45,71]. Thus, XopB may interfere with processes that are important for plant development and plant immunity.

In summary, we could show that induction of cw-Inv in pepper plants is suppressed by \( Xcv \) T3Es with XopB as the key regulator. The suppression of cw-Inv most likely prevents generation of hexoses and thereby the down-regulation of photosynthesis and sugar-enhanced defense. However, the interrelation between XopB, cw-Inv and sugar-mediated defense response needs to be unraviled by further studies. Towards this aim, the identification of host target proteins will be an important step.

### Materials and Methods

#### Bacterial Strains and Growth

Bacterial strains used in this study were as follows: \( Escherichia coli \) DH5A, XL1 Blue and M15, \( Agrobacterium tumefaciens \) C58C1 carrying the pGV2260 virulence plasmid [73] and \( Xanthomonas campestris pv. vesicatoria \) (Xcv) strain 85-10. All modified Xcv strains used in this study are described in Table 1. \( E. coli \) were grown on Luria Broth (LB) medium at 37°C. \( A. tumefaciens \) on yeast-beef extract-peptone (YEB) medium (supplemented with 0.5 g l\(^{-1}\) sucrose and 2 mM MgSO\(_4\)) at 25°C containing appropriate antibiotics. \( Xcv \) strains were cultivated at 30°C on nutrient-yeast-glycerol (NYG) medium supplemented with antibiotics. Antibiotics were added to the media at following final concentrations: ampicillin, 166 μg ml\(^{-1}\); kanamycin, 50 μg ml\(^{-1}\); tetracyclin, 10 μg ml\(^{-1}\); rifampicin, 100 μg ml\(^{-1}\) (NYG); 50 μg ml\(^{-1}\) (LB and YEB); gentamycin 15 μg ml\(^{-1}\).

#### Plant Material, Growth Conditions and Inoculation Experiments

For initial experiments susceptible pepper plants (\( Capsicum annuum \) cv. Early Cal Wonder (ECW)) were cultivated in a growth cabinet with 16 h light (250 μmol quanta m\(^{-2}\) sec\(^{-1}\)) and 8 h darkness. The temperature regime followed the day/night cycle with 28°C and 22°C, respectively, the relative humidity was between 70% and 80%.

For the effector screening and experiments to characterize \( Xcv \Delta xopB \), pepper plants were grown in greenhouse at 26°C with 16 h supplemental light (150–200 μmol quanta m\(^{-2}\) sec\(^{-1}\)) and 50–60% relative humidity. Tobacco plants (\( Nicotiana tabacum \) cv. Samsun NN) were grown in tissue culture under a 16 h light/8 h dark regime at 50% relative humidity on Murashige Skoog medium containing 2% (w/v) sucrose. Transgenic plants were selected on kanamycin in tissue culture and further cultivated in the greenhouse with 16 h supplemental light (150–200 μmol quanta m\(^{-2}\) sec\(^{-1}\)) at 25°C and at 22°C during 8 h of darkness. Expression of xopB was induced by watering individual pots with 50 ml 1% (v/v) ethanol.

\( Xcv \) strains were infiltrated at the abaxial side of fully expanded leaves of 5–6 week-old plants using a needless syringe. \( Xcv \) strains were grown over night in NYG medium. Bacteria were harvested by centrifugation at 5000 g for 20 min at 4°C, washed with 10 mM sterile MgCl\(_2\), followed by a second centrifugation step. The bacterial cells were re-suspended in 10 mM MgCl\(_2\) and adjusted to a final concentration of 5 × 10\(^5\) cfu ml\(^{-1}\) or 10\(^5\) cfu ml\(^{-1}\) (OD\(_{560}\) = 1).
Bacterial Elicitor Preparation
Xce stains grown over night in NYG medium were prepared as described above and adjusted to OD<sub>600</sub> = 1. Cells were heat-inactivated by incubation at 95°C for 20 min in a water bath. An aliquot was subjected to treatment with proteinase K (Sigma-Aldrich) and trypsin (Sigma-Aldrich) at 0.2 mg mL<sup>-1</sup> for 2 h at 60°C. After heat-inactivation for 10 min, cells were pelleted and re-suspended in 10 mM sterile MgCl<sub>2</sub> to give an OD<sub>600</sub> = 1. Heat-inactivated Xce cells with or without additional proteinase K and trypsin treatment were used for infection experiments.

Construction of Xcv Deletion Mutants
To generate Xce deletion mutants primers listed in Table S1 were used. Gene deletions were introduced by overlap extension PCR using genomic DNA from Xce wild type strain 85-10 as template. DNA fragments were cloned into pGEM-T easy (Promega, Madison, USA) and sequenced. Fragments were excised using added restriction sites (see Table S1) and cloned into the pOK vector. Plasmids were introduced into Xce by conjugation using pRK2013 as helper plasmid in triparental matings as described by Huguet et al. [74].

Construction of Xcv ΔxopB Complementation Plasmids
To complement Xce ΔxopB [70] and Xce ΔxopB (Δ1257) a genomic fragment was amplified by PCR from DNA of Xcv (85-10) using the primers given in Table S1. The fragment (−649 to +1949) was cloned into pCR blunt vector (Invitrogen, Karlsruhe, Germany) and sequenced. Subsequently, a 2.6 kB fragment was excised using BamHI restriction sites and inserted into the broad host range vector pBBR1MCS5 [49] creating pBBR::xopB(+). DNA fragments were cloned into pGEM-T easy template. DNA fragments were cloned into pGEM-T easy (Promega, Madison, USA) and sequenced. Fragments were excised using added restriction sites (see Table S1) and cloned into the pOK vector. Plasmids were introduced into Xce by conjugation using pRK2013 as helper plasmid in triparental matings as described by Huguet et al. [74].

Generation of Transgenic Tobacco Plants
The open reading frame of xopB (accession no. AF527779) was amplified from genomic DNA of Xcv strain 85-10 using the gene-specific primers xopB<sub>5</sub>′ GTC GAC AAC AAT GAA GGC AGA GCT CAC ACG ATC C and xopB<sub>3</sub>′ GGG TTG GTG. The resulting PCR fragment was sub-cloned into the pCR blunt vector (Invitrogen, Karlsruhe, Germany). The xopB fragment was excised using the BamHI restriction sites and inserted into the broad host range vector pBBR1MCS5 [49] creating pBBR::xopB(+). The fragment was excised using the SalI restriction sites and inserted into a pUCl-based plasmid between a chimeric aacA promoter and a 35S terminator [51,75]. The resulting aacA expression cassette was excised and inserted into pBin19-derived vector pS53::aacA using the AsI restriction sites yielding the construct EtOH::xopB. Stable transformation of tobacco plants was performed by Agrobacterium-mediated gene transfer as described previously [76].

RNA Isolation and Northern Blot Analysis
Isolation of total RNA was performed as described in Logemann et al. [77]. For Northern blot analysis 20–30 μg of total RNA were separated on 1.5% formaldehyde containing agarose gels and blotted onto nylon membrane (GeneScreen, NEN, Boston, USA) by capillary blotting overnight. The membranes were pre-hybridized and hybridized at 65°C. cDNA fragments of pathogenesis-related protein Q (PRQ) [74] (Acc. No. X54456), cell wall invertase (cw-inv) [74] (Acc. No. X81834), cystolic glyceraldehyde 3-phosphate dehydrogenase (GAPDH) [74] (Acc. No. AF527779) and ribulose-1,5-bisphosphate carboxylase small subunit (RbcS) [74] (Acc. No. X02353) were used as probes and radioactively labeled with [32P] dCTP by means of the High Prime Kit (Roche, Basel, Switzerland). After stringent washing, radioactive membranes were exposed to X-ray films (Kodak) over night at −70°C.

Enzyme Activity Assays
Leaf discs (0.5 cm<sup>2</sup>) were homogenised with 50 mM Tris buffer, pH 6.8, containing 5 mM MgCl<sub>2</sub>, 5 mM β-mercaptoethanol, 1 mM EDTA, 1 mM EGTA, 15% (v/v) glycerol and 0.1 mM Pefabloc proteinase inhibitor. The extracts were centrifuged for 10 min at 13,000 rpm at 4°C. An aliquot of the supernatant was desalted by centrifugation through Sephadex G-25 medium equilibrated in extraction buffer. The desalted extract was used for measurement of vacuolar (vac) invertase activity as described in [21]. Protein concentrations were determined using the Bio-Rad protein assay. The pellet was washed twice with 5 mM Tris buffer, pH 7.0, and centrifuged for 10 min at 13,000 rpm and 4°C. The activity of cell wall invertase (cw-inv) was determined by resolving the pellet in 10 mM sodium acetate buffer, pH 5.0, containing 0.1 M sucrose and incubating the mixture at 37°C for 90 min. The mixture was neutralized by adding an aliquot of 1 M Tris-HCl, pH 8.0, and subsequently heat-inactivated at 95°C for 5 min. The amount of glucose formed was measured as described in [78].

Determination of Soluble Sugars
Leaf discs (0.5 cm<sup>2</sup>) were extracted with 0.5 ml 80% (v/v) ethanol and incubated at 80°C for 90 min. After centrifugation at 4°C for 5 min at 13,000 rpm, cleared supernatants were transferred into new tubes and evaporated to dryness at 40°C. The residue was resolved in 250 μl water. An aliquot was used for determination of soluble sugars using an enzyme-coupled assay as described in [78].

Chlorophyll Fluorescence
Chlorophyll fluorescence was measured using a PAM-2000 portable fluorometer (Walz, Effeltrich, Germany). After removing plants from the growth chamber leaves were quickly exposed to 750 μmol quanta m<sup>−2</sup> s<sup>−1</sup> white light for 10 min before the maximum fluorescence yield (Fm′) was measured during a 0.8 sec pulse of white light with an intensity of 3,500 μmol quanta m<sup>−2</sup>s<sup>−1</sup>. The used light intensity of 750 μmol quanta m<sup>−2</sup>s<sup>−1</sup> was close to light saturation of photosynthesis. Effective quantum yield of PSII in the light (Ψ<sub>PSII</sub>) was calculated according to the equation: Ψ<sub>PSII</sub> = (Fm′ − F<sub>m</sub>) / Fm′ where F<sub>m</sub> is the steady state fluorescence in the light adapted state.

Generation of XopB Antibody and Immunoblotting
To obtain recombinant His<sub>6</sub>-tagged XopB, the coding region of xopB was amplified by PCR using the primers FP_XopB 5′-GGATCCAGGCGAGCTCACAGAT1′-3′ and RP_XopB 5′-GTCGACCTTACGGTTAGCGGCCG-3′ and cloned into pQE-9 (Qiagen, Hilden, Germany) using BamHI and SalI restriction sites. The construct was transformed into E. coli M15 (pREP4) cells. His<sub>6</sub>XopB protein expression was induced at OD<sub>600</sub> = 0.7 with 1 mM IPTG at 37°C and 200 rpm. Four hours after induction 1.2 g cells were harvested and lysed under denaturing conditions with 8 M urea, 100 mM Na<sub>2</sub>HPO<sub>4</sub> and 10 mM Tris-Cl at pH 8.0. His<sub>6</sub>XopB protein was purified from soluble cell extract with Ni-NTA agarose according to manufacturer’s instructions (Qiagen). For further purification, His<sub>6</sub>XopB was subjected to preparative polyacrylamide gel electrophoresis, and the corresponding protein band of His<sub>6</sub>XopB was eluted with an electro eluter (BioRad). For antibody production, 1.43 mg of
pure HisC:XopB solved in 25 mM Tris-HCl, 192 mM glycine and 0.1% SDS, pH 8.2 were used for immunization of rabbits (Biogenes, Berlin, Germany). The serum was further purified using affinity chromatography and used as primary antibody (dilution 1:10000) in further analyses.

For Western blot analyses, leaf discs (0.5 cm²) were homogenised in 2x Laemmli buffer containing 126 mM Tris-HCl, pH 6.8, 20% glycerol, 4% SDS and 0.02% bromophenol blue. Extracts were incubated at 95°C for 10 min and centrifuged for 1 min at RT. 10–30 μg protein were separated on 12.5% (v/v) SDS-containing polyacrylamide gels. Proteins were transferred onto nitrocellulose membranes (Porablot NCL, Macherey-Nagel, Düren, Germany), blocked for at least 1 h in 5% skim milk/TBST (20 mM Tris, 500 mM NaCl, 0.1% (v/v) Tween 20) and incubated with anti-XopB antibody for 1 h at RT. The signal was detected following incubation with secondary peroxidase-conjugated antibody using the ECL-system (Thermo Scientific) according to manufacturer’s instruction.

Quantitative RT-PCR
Quantitative real-time PCR (qPCR) was performed with cDNA and gene-specific primers. cDNA synthesis and qPCR were essentially performed as described by [79]. One μl of 1:5 or 1:10 diluted cDNA of each sample were amplified in three technical replicates on a MX3000P-Q-PCR system (Agilent Technologies) in combination with the Brilliant II SYBR Green Q-PCR Master Mix Kit (Agilent technologies). Primers for the amplification of targets were taken from Kim et al. [41] for Ph5, Mason et al. [80] for Actin or designed using Primer3plus software [81] and were as follows: Ph5 (LEU89256) forward primer 5′-ATTGC-GATTCTTGAAGTGT-3′, reverse primer 5′-AG-TAGTGGCCTTGAAGCATGATT-3′; Acre31 (SGN-U198671) forward primer 5′-AGAGCTCTGAAGATGCTGAA-3′, reverse primer 5′-TGATGAAGCTCAGCAAGCAC-3′ and Actin (AB199931) forward primer 5′-TAATCCCCAGGCGCA-GAG-3′ and reverse primer 5′-GAAAACAGCAGCTGGAGTAG-3′. For each primer pair the efficiency was determined which were 150% (r² = 0.970) for CaActin, 110% (r² = 0.971) for CaPh5 and 99.2% (r² = 0.999) for CaAcre31. A melting analysis was performed at the end of each run to ensure that unique products were formed.

Supporting Information
Figure S1 Cw-Inv activity in pepper leaves after infiltration with Xcv wild type and Xcv mutant strains at a concentration of 10⁹ cfu ml⁻¹. Values represent the mean ± SD from two different experiments each with four independent samples. Black bars: before infection. Light grey: 2 days post infection (dpi). Dark grey: 3 dpi. (TIF)

Table S1 Primers used for generation of different Xcv strains. Added restriction sites were marked by bold letters. (DOCX)

Acknowledgments
We thank U. Bonas (Martin-Luther University Halle) for providing Xcv strains and plasmids and her collaboration during the initial phase of the project. We also wish to thank Henning Tschiersch for help with chlorophyll fluorescence measurements, Melanie Rufß, Ulrike Schlereth and Stephen Reid for excellent technical assistance, and Andrea Knoppe and Sibylle Freist for plant transformation. The authors are grateful to F. Boruke for fruitful discussion.

Author Contributions
Conceived and designed the experiments: S. Sonnewald JPRP US MBM. Performed the experiments: S. Sonnewald JPRP JS EG MRH S. Siebig. Analyzed the data: S. Sonnewald JPRP US EG MH. Contributed reagents/materials/analysis tools: MBM. Wrote the paper: S. Sonnewald MBM US.

References


