CONTROL OF PIERCE'S DISEASE BY METHODS INVOLVING PATHOGEN CONFUSION

Principal Investigator:
Steven E. Lindow
Dept. Plant & Microbial Biol.
University of California
Berkeley, CA 94720
icelab@berkeley.edu

Cooperators:
Michael Ionescu
Dept. Plant & Microbial Biol.
University of California
Berkeley, CA 94720

Clelia Baccari
Dept. Plant & Microbial Biol.
University of California
Berkeley, CA 94720

Alessandra Souza
Dept. Plant & Microbial Biol.
University of California
Berkeley, CA 94720

Reporting Period: The results reported here are from work conducted October 2008 to October 2009.

ABSTRACT
Xylella fastidiosa (Xf) produces an unsaturated fatty acid signal molecule called diffusible signal factor (DSF) that modulates gene expression in cells as they reach high numbers in plants. By increasing the expression of a variety of afimbrial adhesins while decreasing the expression of pili involved in twitching motility as well as extracellular enzyme involved in degrading pit membranes, DSF accumulation suppresses virulence of *Xf* in grape. We thus are exploring different ways to elevate DSF levels in plants to achieve "pathogen confusion." Plants expressing *rpfF* from *Xf* produce low levels of DSF and are highly resistant to Pierce's disease (PD). Chloroplast targeting of RpfF substantially increased DSF production in grape; these plants are currently being tested for disease resistance. *Xf* moved much less rapidly in *rpfF*-transformed grape, colonized many fewer xylem vessels, and achieved a much lower population size indicating that elevated DSF levels suppressed movement within the plant. Topical applications of DSF-containing bacterial extracts also reduced the severity of PD suggesting that DSF is relatively mobile within the plant and that exogenous sources of DSF might also be applied in various ways to achieve suppression of pathogen mobility and hence virulence. Some reduction in disease severity was observed in grape scions grafted to DSF-producing rootstocks suggesting that DSF produced by rootstocks can somewhat move to scions and confer disease control' the control of disease was substantially less than that seen in transformed scions however. While certain bacteria such as *Rhizobium etli* can produce DFS when transformed with *rpfF* from *Xf*, and to colonize grape slowly after inoculation, modest levels of disease control are conferred by pre-treatment of grape suggesting that a more rapidly multiplying and internally mobile endophytic bacterium might be superior for disease control as a surrogate DSF producer. As studies of pathogen confusion will be greatly facilitated by having an improved bioassay for the DSF produced by *Xf*, we have been developing several immunological and biochemical means to assay for the presence of DSF using *Xf* itself as a bioindicator.

LAYPERSON SUMMARY:
Xylella fastidiosa (Xf) produces an unsaturated fatty acid signal molecule called diffusible signal factor (DSF) that changes its gene expression in cells as they reach high numbers in plants. Accumulation of DSF in *Xf* cells, which presumably normally occurs as cells become numerous within xylem vessels, causes a change in many genes in *Xf*, but the overall effect is to suppress the virulence of *Xf* in plants. We have investigated DSF-mediated cell-cell signaling in *Xf* with the aim of developing cell-cell signaling disruption (pathogen confusion) as a means of controlling Pierce's disease (PD). We have investigated both the role of DFS-production by *Xf* on its behavior within plants, the manner in which other bacterial strains affect such cell signaling, the extent to which other endophytes could modulate density-dependent behaviors and virulence in *Xf* by interfering with cell-cell signaling, performed genetic transformation of grape to express DSF, and explored other means to alter DSF abundance in plants to achieve PD control. Elevating DSF levels in plants should reduce movement of *Xf* in the plant. We have produced bacterial endophyte strains that can produce large amounts of DSF and, by moving within plants apparently they can alter the abundance of DSF sufficiently to reduce the virulence of *Xf*. Given that DSF overabundance appears to mediate an attenuation of virulence in *Xf* we have transformed grape with the *rpfF* gene of *Xf* to enable DSF production in plants; such grape plants produce at least some DSF and are much less susceptible to disease. Higher levels of expression of DSF have been obtained in plants by targeting the biosynthetic enzymes to the chloroplast. Some reduction in disease severity was observed in grape scions grafted to DSF-producing rootstocks suggesting that DSF produced by rootstocks can somewhat move to scions and confer disease control.

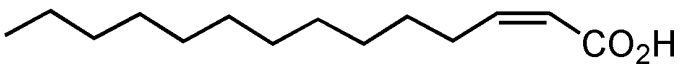


Figure 1

INTRODUCTION
We have found that the virulence of *Xylella fastidiosa (Xf)* is strongly regulated in a cell density-dependent fashion by accumulation of a signal molecule called diffusible signal factor (DSF) encoded by *rpfF* and involving signal transduction that requires other *rpf* genes. We now have shown that *Xf* makes a DSF molecule that is recognized by *Xanthomonas campestris pv. campestris (Xcc*) but slightly different than the DSF of *Xcc* (**Figure 1**). In striking contrast to that of Xcc, *rpfF*- mutants of *Xf* blocked in production of DSF, exhibit dramatically increased virulence to plants, however, they are unable to be spread from plant to plant by their insect vectors since they do not form a biofilm within the insect. These

observations of increased virulence of DFS-deficient mutants of *Xf* are consistent with the role of this density-dependent signaling system as suppressing virulence of *Xf* at high cell densities. Our observations of colonization of grapevines by *gfp*-tagged *Xf* are consistent with such a model. We found that *Xf* normally colonizes grapevine xylem extensively (many vessels colonized but with only a few cells in each vessel), and only a minority of vessels are blocked by *Xf*. Importantly, rpfF-mutants of *Xf* plug many more vessels than the wild-type strain. We thus believe that *Xf* has evolved as an endophyte that colonizes the xylem; blockage of xylem would reduce its ability to multiply since xylem sap flow would cease and thus the DSF-mediated virulence system in *Xf* constrains virulence. That is, *Xf* would benefit from extensive movement throughout the plant where it would partially colonize xylem vessels but would have evolved not to grow to excessively within a vessel, thereby plugging it and hence blocking the flow of necessary nutrients in the xylem sap. Given that the DSF signal molecule greatly influences the behavior of Xf we are investigating various ways by which this pathogen can be "confused" by altering the local concentration of the signal molecule in plants to disrupt disease and/or transmission. We thus are further exploring how DSF-mediated signaling occurs in the bacterium as well as ways to alter DSF levels in the plant. Our work has shown that the targets of Rpf regulation are genes encoding extracellular polysaccharides, cellulases, proteases and pectinases necessary for colonizing the xylem and spreading from vessel to vessel as well as adhesins that modulate movement. Our earlier work revealed that several other bacterial species can both positively and negatively interact with the DSF-mediated cell-cell signaling in *Xf*. In this period we have extensively investigated both the role of DFS-production by *Xf* on its behavior within plants, the patterns of gene regulation mediated by DSF, the extent to which other endophytes can modulate density-dependent behaviors and virulence in *Xf* by interfering with cell-cell signaling, obtained genetic transformation of grape and other hosts of *Xf* to express DSF, and explored other means to alter DSF abundance in plants to achieve Pierce's disease (PD) control.

OBJECTIVES

1. Evaluate plants with enhanced production of DSF for disease control
2. Determine if DSF is transferable within plants – eg. whether DSF production in rootstocks can confer resistance to PD in the scion
3. Evaluate enhanced DSF-producing endophytic bacteria for control of PD
4. Investigate DSF-overproducing strains of *Xf* as biocontrol agents for PD and whether *Xf* strains previously identified with biocontrol potential exhibit an elevated production of DSF
5. Determine if resistance to PD is associated with low rates of degradation of DSF by plants
6. Determine those plant factors that confer induction of virulence genes in *Xf* and whether susceptibility to PD is due to differences in induction of virulence factors in the pathogen by the plant

RESULTS AND DISCUSSION

Objective 1. Production of DSF in transgenic plants for disease control.

We have expressed the *rpfF* gene in several different plant species to investigate whether DSF excess can lead to reduced disease caused by *Xf*. In addition to grape, we have transformed genes conferring DSF production into tobacco since this species is colonized by *Xf* and disease symptoms can be produced. Because transformation of tobacco is much quicker than grape, we have used studies of *Xf* infection of tobacco as a surrogate for studies in grape to speed our assessment of different ways to produce DSF in grape. The various mutants of *Xf* that are hyper and hypo virulence on grape yield similar reactions on SR1 tobacco.

Further tests of SR1tobacco as a surrogate host to evaluate transgenic expression of *rpfF* as a means to increase DSF abundance in plants were performed. SR1 tobacco which had been transformed with the untargeted *rpfF* genes from either *Xf* or *Xcc* were inoculated with *Xf* ; the incidence of disease was dramatically reduced in *rpfF*-expressing SR1 compared to untransformed tobacco

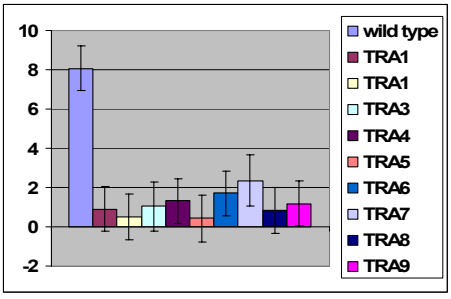


Figure 2. Disease severity (# symptomatic leaves/plant) on Freedom grape transformed with the r*pfF* gene encoding DSF production and inoculated with *Xf*.

Grape has been transformed at the Ralph M. Parsons Foundation Plant Transformation Facility at the University of California at Davis with a non-targeted *rpfF* construct. These plants produced only very low levels of DSF but are MUCH less susceptible to PD (**Figure 2**). While *Xf* spread throughout non-transformed plants causing disease on petioles located great distances from the point of inoculation, disease was observed only very close to the point of inoculation in *rpfF*-expressing plants. We measured the movement of Xf in these plants by measuring both the population size of *Xf* in stems and petioles at different distances from the point of inoculation, as well as to observe the fraction of vessels to which a gfp-marked strain of *Xf* had moved using fluorescence microscopy (**Figure 3**). *Xf* was greatly limited in its movement in plants producing DSF as evidenced by both a lower population size at sites distal to the point of inoculation and a lower incidence of vessel colonization at all points; both would contribute to low disease severity.

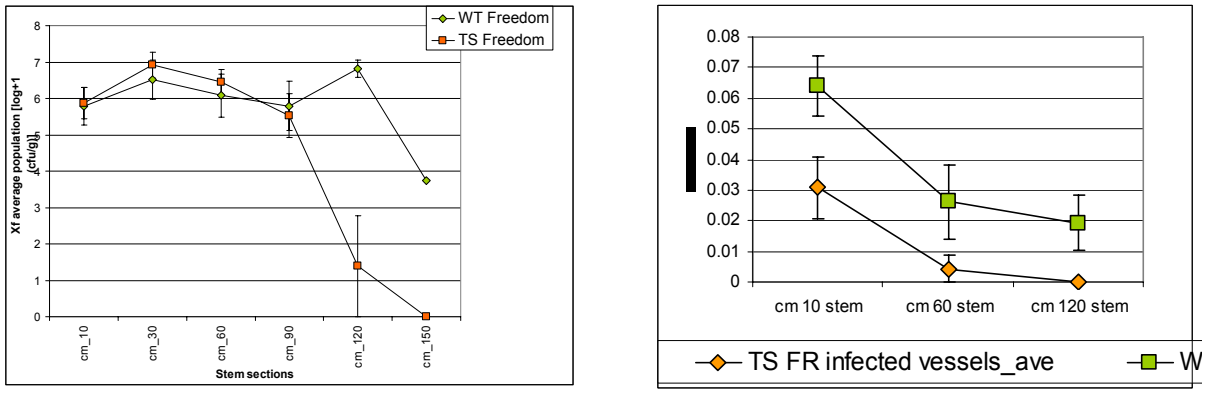


Figure 3. (Left) Population size of *Xf* in 1 cm stem segments at different distances from the point of inoculation on non-transformed Freedom grape (green) and in *rpfF*-transformed Freedom (red). The vertical bars represent the standard error of mean log population size. (Right). Proportion of xylem vessels in stems of transformed Freedom grape (green) and in *rpfF*-transformed Freedom (orange) colonized with a gfp-marked strain of *Xf* at different distances from the point of inoculation.

We have recently transformed tobacco, *Arabidopsis*, tomato, and grape with an *rpfF* gene that has been modified to direct the protein product to the chloroplast where fatty acid synthesis (and DSF synthesis) should be much enhanced compared to its production in the cytosol, the presumed location of RpfF in the current transformed plants. Assay of DSF in transgenic SRI tobacco plants-where the RpfF is targeted to the chloroplast, indicated that the DSF levels as well as expression of *rpfF* are much higher as compared to the plants in which the RpfF is expressed in the cytosol. Further tests of the efficacy of chloroplast targeting of rpfF implants were preformed by evaluating DSF production in transgenic Moneymaker tomato. Substantial levels of DSF could be detected in the chloroplast-targeted tomato and sufficient amounts of DSF were present to alter the behavior of *Xanthomonas campestris pv. vesicatoria* (*Xcv*) that was inoculated onto leaves. While an average of 323 lesions formed when *Xcv* was inoculated onto normal tomato, 570 lesions formed per leaf on the DSF-producing plants, a finding expected if DSF was present since virulence of *Xcv* is enhanced by DSF. We obtained the chloroplast-targeted grape in June, 2009 and have very recently produced enough vegetative clones of these grapes and have initated pathogenicity studies; results are expected by November, 2009. We also have inoculated the chloroplast-targeted rpfF plants with a gfp-marked strain of *Xf* to assess differences in its movement within the DSF-producing and normal Thompson seedless grape using fluorescence microscopy.

Although RpfB is not required for DSF synthesis in *Xf*, it presumably aids in DSF synthesis by encoding long chain fatty acyl CoA ligase which might increase availably of the appropriate substrates for DSF synthesis by RpfF. We expected that co-expression of RpfB and RpfF in the chloroplast will further enhance the DSF levels in plants. We have produced transgenic *Arabidopsis* plants with such a construct and find evidence of high levels of DSF production. Pathogenicity assays with the *rpfF* mutant of *Xcc* indicated that the transgenic plants expressing both *rpfB* and *rpfF* transgenic plants can better complement the virulence of the non pathogenic *rpfF* mutant of *Xcc*. We thus are preparing genetic constructs to transform grape with these two genes to further enhance DSF production.

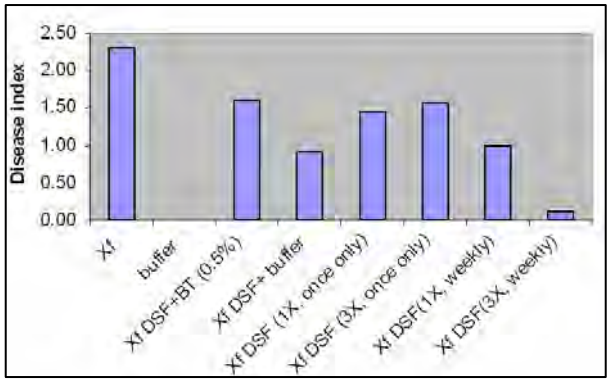
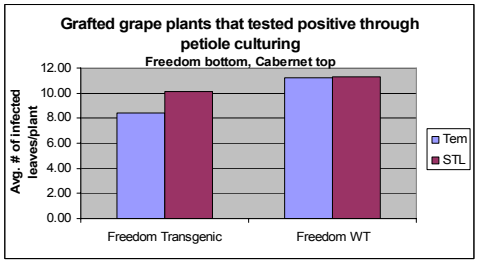


Figure 4. Disease incidence-severity relation (disease index) for grape inoculated with *Xf* and to which DSF was topically applied or introduced into the stem.

Direct application of DSF to non-transgenic grape can also confer disease control. While we have very recently tentatively determined the chemical structure and have synthesized the putative DSF of *Xf,,* for these studies we used crude ethyl acetate extracts of a DSF-producing *E. herbicola* strain as a source of DSF. The DSF was either topically applied as well as needle inoculated into the stems of grape either once a day before inoculation with *Xf* or weekly. While a single needle application of DSF reduces disease index, a weekly application of DSF into the stem of the plant was much more effective (**Figure 4**). These results are exciting in that they suggest that disease control from external applications of DSF might be a practical means of disease control. We are currently repeating these studies using DSF extracted from various surrogate hosts as well as from an rpfC mutant of *Xf* to compare the efficacy of these various sources of DSF to determine whether the amount and chemical identity of DSF from these sources are the same. This will be very helpful in our continuing efforts to

unambiguously determine the chemical structure of DSF and to justify the synthesis of large amounts of DSF for plant experiments.

Objective 2. Graft transmissibility of DSF. To test whether DSF is mobile within the plant we are performing grafting experiments in which DSF-producing tobacco and grape transformed with the rpfF of *Xf* are used as rootstocks to which normal SR1 tobacco or grape is grafted as a scion. These plants have been inoculated with *Xf* to test whether normal scions on DSF-producing rootstocks have a lower susceptibility to *Xf* colonization. The average disease severity rating on the normal SR1 tobacco grafted onto the rpfF-expressing rootstock was 0.97 compared to a rating of 0.84 on SR1 grafted onto normal SR1 rootstocks (control); these ratings did not differ significantly. However, the average disease rating on *rpfF*-expressing SR1 tobacco scion grafted onto an *rpfF*-expressing rootstock was only 0.24, which was significantly lower than that of a normal scion grafted onto an *rpfF*-expressing rootstock or onto a normal rootstock. These preliminary results suggest that putative DSF production in the scion is much more effective on reducing the movement and growth of *Xf* in the scion than that of the rootstock. This work is being repeated.



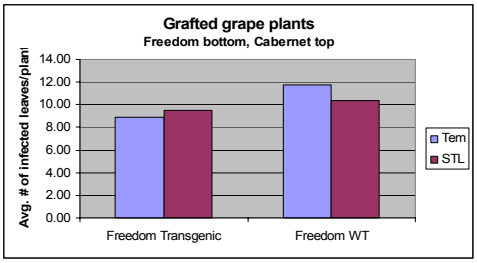


Figure 5. Severity of PD (left box) or number of leaves per vine infested with *Xf* (right box) of Freedom grape having a Cabernet sauvignon grape scion grafted onto the rootstock noted on the abscissa. Plants were inoculated with either *Xf* strain Temecula (blue) or strain STL.

Non-chloroplast targeted RpfF-expressing transgenic Freedom grape were also sued as a rootstock for green-grafted Cabernet Sauvignon scions. Initial estimates of disease severity indicate that there were about 30% less symptomatic leaves of the normal Cabernet scion when grafted onto a *rpfF*-expressing rootstock compared with plants on a normal Freedom rootstock (**Figure 5**). Thus, like in the studies of the *rpf*F-expressing tobacco, it appears that DSF production in the scion is more efficacious for disease control than is the expression of *rpfF* in the rootstock. We are repeating these experiments and will be inoculating the plants in a variety of ways to determine the efficiency of disease control from rootstock modification.

Objectives 3 and 4. Disease control with endophytic bacteria**.** We have been successful in producing large quantities of DSF in endophytes like *Erwinia herbicola* and also in lab strains of *E. coli*). We recently were able to transform a putative efficient endophyte of plants, *Rizobium etili* G12 with both the *Xcc* and *Xf rpfF* (DSF biosynthetic gene) and have obtained production of DSF in this strain. This DSF-producing endophyte has been inoculated into grape to determine both its ability to move and multiply within grape as well as its ability to interfere with the disease process. The *R. etli* strain G12 was found to move within grape tissue after inoculation into either the stem or the leaves. When measured four weeks after inoculation by puncture inoculation into one site in the stem measurable populations of *R. etli* were seen as far as 50 cm away from the point of inoculation. While the population size away from the point of inoculation were relatively low in this short time interval since inoculation, this strain clearly has the ability to move within grape; we are excited about this result since no other of several bacterial strains that we have investigated for the ability to move within grape has ever exhibited any ability to move beyond the point of inoculation. Further studies are underway to determine the population sizes to which *R. etli* will grow given more time after inoculation. *R. etli* also has the ability to move within grape leaves and multiply to high population sizes. When applied as a point source to leaves using a penetrating surfactant, cells of *R. etli* could be found up to 3 cm away within one week, and population sizes of this strain increased 100-fold within three weeks after inoculation. Studies are continuing to determine the maximum population size that this strain can achieve in grape leaves. The evidence, however, suggests that the bacteria move relatively slowly in grape, and thus such strains would have to be inoculated into grape substantially in advance of the pathogen in order to achieve high levels of disease control. We thus are exploring the possibilities of introducing these bacteria throughout the plant by various means as a way to rapidly increase their population size in the plant, and thus their ability to elevate the DSF levels within the plant. As the use of surfactants to introduce the bacteria into the plant sometimes resulted in some phytotoxicity to leaves, we are exploring an experimental strategy of forcing the bacteria physically into leaves using either pressure or a vacuum in order to achieve leaves that have high levels of bacteria but without any leaf damage that will complicate the interpretation of disease control by such bacteria.

Various DSF-producing bacteria were tested for their ability to control PD when applied to grape in different ways. DSF-producing *R. etli* were both needle inoculated one or more times at sites near where *Xf* was subsequently inoculated, as well as co-inoculated with *Xf* into grape stems and sprayed onto leaves with 0.5% of the penetrating surfactant Breakthru 1 week before *Xf* was inoculated into stems. The co-inoculation of *R. etli* with *Xf* greatly decreased the incidence of colonization of grape petioles compared to control plants inoculated with *Xf* alone (**Figure 6**) while topical application or injection elsewhere in the stem provided little control. We presume that the relatively slow movement of *R. etli* in the stems of plants and explains why co-inoculation was most effective. *R. etli* was somewhat susceptible to damage from Breakthru and its population sizes were reduced during application with this detergent. We will continue to test different ways in which *R. etli* can be introduced into plants to determine its ability to control PD. We expect that introduction of *R. etli* into stems far in advance of *Xf* will provide much better disease control. RpfC- mutants of *Xf* greatly over-produce DSF so we tested them for their ability to control PD when applied in various ways as discussed above for *R. etli*. The incidence of colonization of grape petioles with *Xf* was greatly reduced when plants were needle inoculated into grape either two weeks before plants were inoculated with *Xf* or when co-inoculated with the pathogen (**Figure 7**). While the RpfC mutant does not move as well within grape as the wild-type *Xf*, its presence locally in plants can suppress the movement of wild-type *Xf* and thus lead to control of PD. These studies are promising and are being repeated.

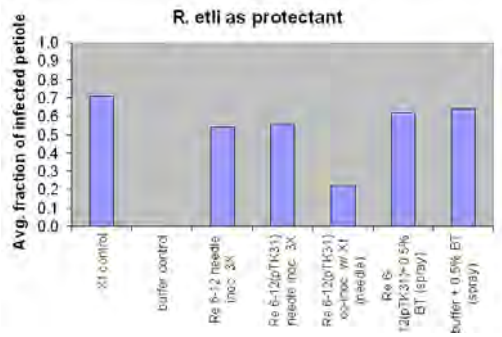


Figure 6 Incidence of colonization of petiols of grape by *Xf* when plants were treated with DSF-producing *R. etli* in various ways.

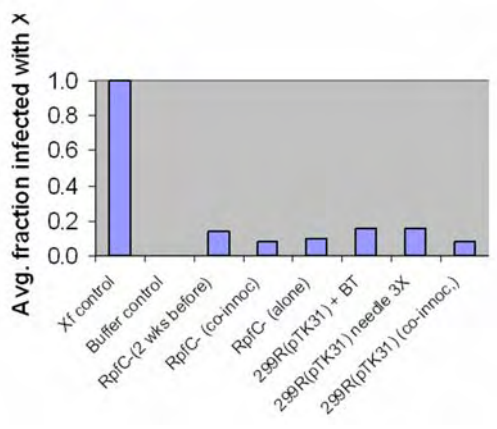


Figure 7 Incidence of colonization of petioles of grape by *Xf* when plants were treated with RpfC mutants of *Xf* in various ways.

Objective 5. Degradation of DSF by plants**.** Development of an *Xcc* biosensor efficient in detecting *Xylella* DSF. For many of the objectives of this project, in addition to the study of DSF degradation in plants, an improved bioindicator for DSF would be very valuable. We are presently using an *Xcc*-based biosensor in which the endoglucanase gene is linked to a GFP reporter gene. Previous studies have shown that this biosensor is able to detect the DFS made by *Xf* but that it detects *Xf* DSF with a much lower efficiency then the *Xanthomonas* DSF since the two molecules apparently differ slightly. Elsewhere have described another project in which we are developing a surrogate *Xcc* biosensor system which will express all the components of DSF signal transduction of *Xf*. This should give rise to a system which is close to DSF signal transduction system in *Xcc* but which will be most responsive to DSF from *Xf*. We have made much effort in this reporting period to developing methods to use *Xf* itself to detect DSF**.** Among the several genes that we know to be most strongly regulated by DSF include *pil* genes involved in twitching motility, several genes such as *fimA* and *hxfA* and *HxfB* which are involved in cell-surface adhesion, and gum genes involved in production of EPS. We thus have examined the phenotypes of an *rpfF*- mutant and WT strain of *Xf* exposed to different amounts of DSF to determine if it can be used to bioassay for the presence of DSF. Initial results are encouraging. For example, cells of the *rpfF*- mutant which are not adherent, and thus which do not form cell-cell aggregations became much more adherent to each other when DSF was added to shaken broth cultures. The increased adherence is readily visualized as an enhanced ring of cell-cell aggregates that forms at the liquid-air interface of shaken cultures (**Figure 8**). Thus it appears that we may be able to assess the concentration of DSF in samples using a cell adhesion assay using *Xf* cells, although both assays are time consuming and somewhat qualitative.

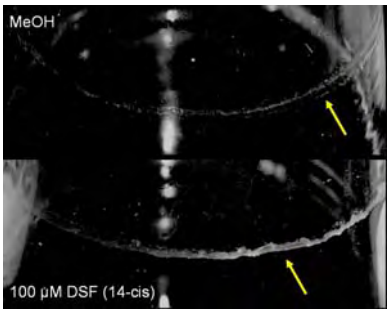


Figure 8. Cellular aggregations that formed at the air-liquid interface in broth cultures of a *rpfF*- mutant of *Xf* grown in XFM minimal medium without added DSF (top) or with 100 uM of added C14-cis enoic acid, the presumptive DSF produced by grape strains of *Xf*. The yellow arrows note the presence of the ring of adhered cells.

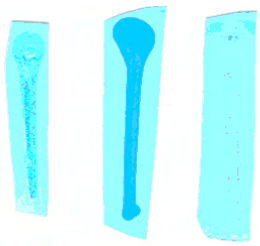


Figure 9. Staining of colony lifts of streaks of WT Xf (left), a GGDEF mutant (center) and a GGDEF mutant in which gene PD 0279 has been over-expressed in trans (right) with Alcian Blue.

We are also exploring several other methods of assessing the presence of DSF using *Xf* itself as a bioindicator. We are taking advantage of the fact that we now know what genes in *Xf* are induced in the presence of DSF. For example, we now know that *gumJ*, involved in extracellular polysaccharide (EPS) biosynthesis is strongly induced in the presence of DSF from *Xf* and that DSF-deficient strains produce noticeably less EPS in culture. We are fusing this gene to a *gfp* reporter gene that has been optimized for expression in E. coli (and thus hopefully will also have higher levels of expression in *Xf* – see progress report for project 08-0170 for more details) and will introduce it into the genome of *Xf* by homologous recombination to yield cells of *Xf* that will become green fluorescent in the presence of DSF. Likewise, we have cloned the gene encoding alkaline phosphatase from *Xf* and are determining if it can be used in in vitro bioassays when fused to DSF-responsive genes in an alkaline phosphatase-deficient background in *Xf*. Such cells should be much more responsive to *Xf* DSF and be useful in assaying biochemical fractions for DSF in the purification processes below and in assaying DSF analogs.

In addition to estimating the transcriptional expression of genes known to be regulated in response to accumulation of DSF, we are also exploring ways of measuring the amounts of gene products (proteins) or EPS that are made in response to the presence of DSF. For example, we are exploring whether we can detect EPS production by *Xf* both in culture and in plants by use of antibodies that recognize the EPS of *Xf*. Such antibodies have recently been described by the group of Bruce Kirkpatrick. Our initial results suggest that DSF-deficient RpfF- mutants of *Xf* exhibit little or no EPS production as monitored by use of fluorescently-labeled antibodies directed against EPS. A gfp-marked RpfF- strain of *Xf* could be used as a DSF detector both in culture and *in planta* by examining co-localization of constitutive GFP fluorescence and red fluorescence when a red-fluorophore-labeled anti-EPS antibody is applied to a sample; GFP fluorescent cells that were not also labeled with the antibody stain would indicate lack of DSF availability while cells that were both GFP and red fluorescent would indicate the presence of DSF.

We are also exploring the use of a simple staining procedure to estimate the abundance of EPS produced by *Xf*. For example, our work on the mechanism by which DSF mediates changes in gene expression in *Xf* has uncovered the important role of cyclic di-GMP as a so-called second messenger within cells. We have made mutants in gene PD 0279 which encodes a GGDEF domain protein the apparently functions in the synthesis of cyclic di-GMP. The GGDEF mutant produces much more EPS ion culture as apparent from observing colonies, and this difference in EPS can be readily visualized by staining of colony lifts on nitrocellulose filters by staining with Alcian Blue; the GGDEF mutant stains a much darker blue than the wild type, which the over-expression of this GGDEF proteins stains much less intensely (**Figure 9**). This Alcian blue staining method thus is being pursued as a means to estimate DSF-mediated changes in EPS production in an *rpfF* mutant of *Xf* exposed to different amounts of DSF.

We have also explored the use of immunofluorescence to detect other DSF-regulated proteins in *Xf*. This work is very promising. Antibodies to XadA were provided by Dr. Alessandra Souza who had developed this tool to detect a homologous protein in CVC strains of *Xf*. The antibodies cross-reacted strongly to the XadA from grape strains of *Xf*. In preliminary experiments we find that cells of an *rpfF* mutant of *Xf* harbor very little XadA when grown on XFM minimal medium without added DSF, but that significant amounts of XadA is detected with the antibody when DFS-containing extracts from an rpfC mutant of *Xf* were added (**Figure 10**). These are very exciting results in that it suggests that such a biosensor would be very useful within plants to monitor the temporal and spatial patterns of DSF production within plants, as well as allow us to monitor the dispersal and stability of DSF that has been applied to plants, or of DSF which has been produced by

transgenic plants themselves. We also observed a very curious effect of DSF on XadA; while some of this protein is cell-associated, a much lower proportion of this protein is released to the outside of the cell when cells are exposed to DSF (**Figure 11**). This phenomenon also should provide a useful means to estimate DSF abundance in vitro. We are exploring the use of other antibodies such as those directed against PilC as well for such studies.

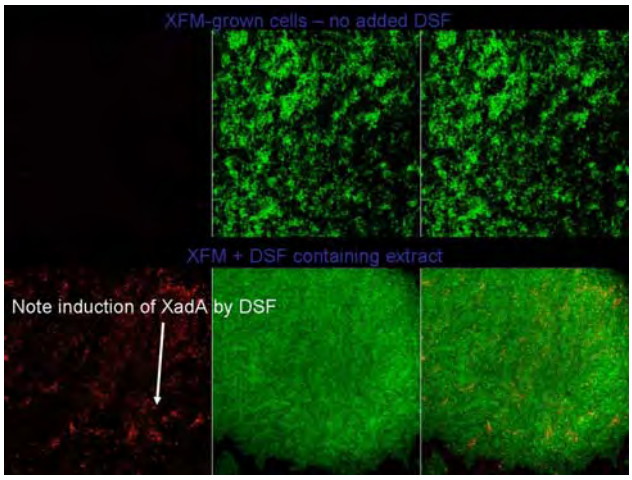


Figure 10 Cells of rpfF- mutant of *Xf* grown on a minimal medium and then stained with Syto-9 (green) and probed with rhodamine-labeled anti-XadA antibody (red). Cells were grown in XFM minimal medium without added DSF extract (top) or with added DSF-containing cell culture extract (Bottom).

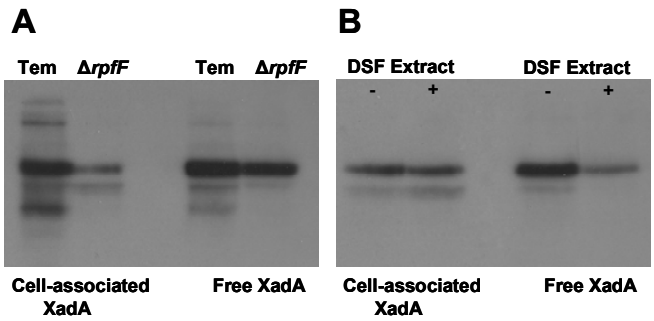


Figure 11. (**A**) Western blot analysis of cell-associated and cell-free XadA in *Xf* Tem and Δ*rpf*F after 14 days of growth on minimal media (XFM) supplemented with pectin. (B) Effect of *Xf* Δ*rpfC* DSF extract on XadA level in Δ*rpf*F.

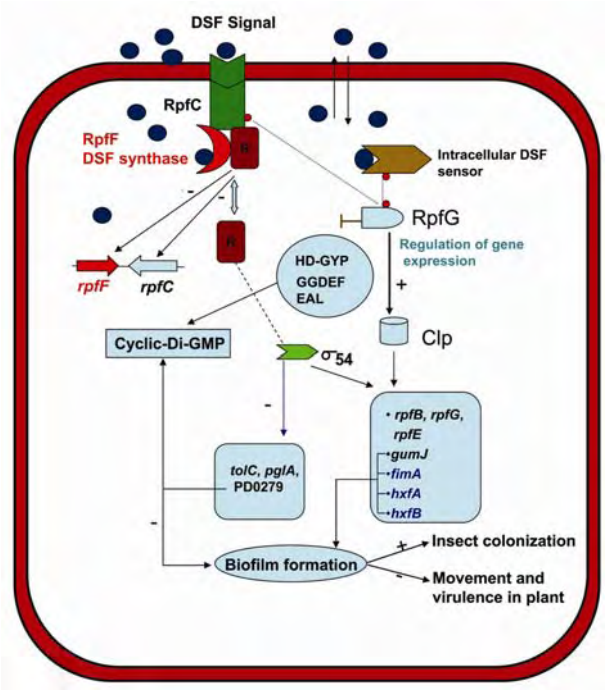


Figure 12. A proposed model for DSF-mediated cell-cell signaling regulation in *Xylella fastidiosa*.

Objective 5. Plant regulation of *Xf* virulence factors. Before investigating the effects of plant extracts on gene expression in *Xf* we have further examined the complex pattern of gene regulation in *Xf* that is DSF dependent to better understand which virulence genes might be most informative to examine. Analysis of the genome sequence of *Xf* revealed that several genes

encoding proteins potentially involved in intracellular signaling are present. Gene expression of several genes was thus examined in both a *rpfF* and *rpfC* mutant background as well as a double mutant. The results have enabled the production of a more complete model of DSF-dependent gene expression in *Xf* (**Figure 12**). A central role for modulation of cyclic d-GMP in altering expression of cell surface features central to virulence of *Xf* has been noted (**see Figure 9**). The several genes identified here will be examined by RT-PCR in cultures of *Xf* to which plant extracts have been applied as proposed.

CONCLUSIONS

Since we have shown that DSF accumulation within plants is a major signal used by *Xf* to change its gene expression patterns and since DFS-mediated changes all lead to a reduction in virulence in this pathogen we have shown proof of principle that disease control can be achieved by a process of "pathogen confusion". Several methods of altering DSF levels in plants, including direct introduction of DSF producing bacteria into plants, topical application of such bacteria to plants with surfactants, and direct application of DSF itself to plants appear promising as means to reduce PD. Transgenic DSF-producing plants appear particularly promising and studies indicates that such plants provide at least partial protection when serving as a rootstock instead of a scion. Based on work done on other plant species in which a chloroplast-targeted DFS synthase has provided much higher levels of DSF production, we are hopeful that such a construct in grape will provide even higher levels of PD control in our current studies. While the principle of disease control by altering DSF levels has been demonstrated, this work addresses the feasibility of how achieve this goal, and what are the most practical means to achieve disease control by pathogen confusion. Our continuing work will address which method is both most practical and efficacious.

FUNDING AGENCIES

Funding for this project was provided by the CDFA Pierce's Disease and Glassy-winged Sharpshooter Board.