

# Plant immune responses triggered by beneficial microbes

Saskia CM Van Wees, Sjoerd Van der Ent and Corné MJ Pieterse

Beneficial soil-borne microorganisms, such as plant growth promoting rhizobacteria and mycorrhizal fungi, can improve plant performance by inducing systemic defense responses that confer broad-spectrum resistance to plant pathogens and even insect herbivores. Different beneficial microbe-associated molecular patterns (MAMPs) are recognized by the plant, which results in a mild, but effective activation of the plant immune responses in systemic tissues. Evidence is accumulating that systemic resistance induced by different beneficials is regulated by similar jasmonate-dependent and ethylene-dependent signaling pathways and is associated with priming for enhanced defense.

## Address

Plant-Microbe Interactions, Institute of Environmental Biology,  
Faculty of Science, Utrecht University, P.O. Box 800.56, 3508 TB  
Utrecht, The Netherlands

Corresponding author: Pieterse, Corné MJ ([C.M.J.Pieterse@uu.nl](mailto:C.M.J.Pieterse@uu.nl))

**Current Opinion in Plant Biology** 2008, **11**:443–448

This review comes from a themed issue on  
Biotic Interactions  
Edited by Murray Grant and Sophien Kamoun

Available online 26th June 2008

1369-5266/\$ – see front matter  
© 2008 Elsevier Ltd. All rights reserved.

DOI [10.1016/j.pbi.2008.05.005](https://doi.org/10.1016/j.pbi.2008.05.005)

## Introduction

Plant roots become quickly colonized by a diverse microflora of soil-borne bacteria and fungi that may have either beneficial or deleterious effects on the plant. Classical examples of symbiotic microorganisms are mycorrhizal fungi that aid in the uptake of water and minerals, notably phosphate [1], and *Rhizobium* bacteria that fix atmospheric nitrogen for the plant [2]. Several other types of beneficial soil-borne microbes, such as plant growth promoting rhizobacteria and fungi, can stimulate plant growth by suppressing plant diseases [3–6,7] or insect herbivory [8]. This biological control activity is exerted either directly through antagonism of soil-borne pathogens or indirectly by eliciting a plant-mediated resistance response [3,9]. The mechanisms by which beneficials and parasites activate the host's immune response not only share intriguing similarities but also display crucial differences. Here, we review the recent discoveries on the molecular mechanisms involved in beneficial microbe-induced resistance.

## Resistance-inducing traits of beneficial microbes

Microbial determinants that contribute to induced resistance as triggered by beneficial microbes are best studied for fluorescent *Pseudomonas* spp. In analogy to the microbe-associated molecular patterns (MAMPs) flagellin and lipopolysaccharides (LPS) of pathogenic *Pseudomonas* spp. [10], it was found that these cell surface components of beneficial *Pseudomonas* spp. are potent inducers of the host immune response [11]. Purified flagellin and LPS of the nonpathogenic resistance-inducing strains *Pseudomonas fluorescens* WCS417 and WCS374, and *Pseudomonas putida* WCS358 have differential resistance-inducing activities on *Arabidopsis*, tomato, and bean, suggesting host specificity in the recognition of these beneficial microbe derived MAMPs. Flagellin and LPS mutants of these rhizobacterial strains are nevertheless often as effective as the wild-type strains, suggesting that multiple MAMPs are involved in the activation of the plant's immune response [11].

Under conditions of low iron availability, most aerobic and facultative anaerobic microorganisms, including fluorescent *Pseudomonas* spp., produce low molecular weight  $\text{Fe}^{3+}$ -specific chelators, so-called siderophores. Competition for iron between fluorescent *Pseudomonas* spp. and plant pathogens is often considered to be the mode of action of these siderophores in disease suppression. However, a role for siderophores in the elicitation of resistance has been reported in several systems as well [12,13]. For instance, in tomato the *P. putida* WCS358 siderophore pseudobactin358 triggers systemic resistance, but the pseudobactin358-mutant of this strain does not [12]. In bean, however, this mutant is as effective as the wild-type strain, again indicating that induced systemic resistance (ISR) is activated by multiple MAMPs in this plant–microbe interaction. Interestingly, under low iron conditions several *Pseudomonas* spp. also produce salicylic acid (SA), a signaling molecule that is known to play an important role in the regulation of pathogen-induced systemic acquired resistance (SAR) [11,14]. Indeed, SA produced by the siderophore mutant KMPCH of *P. aeruginosa* 7NSK2 was demonstrated to induce disease resistance in tomato [15]. However, in most cases, microbially produced SA does not contribute to enhanced defense, as it is directly channeled into the production of SA-containing siderophores [16].

Antibiotics, which are produced by some beneficial microorganisms, can also function as MAMPs in triggering the immune response. An example is 2,4-diacetylphloroglucinol (DAPG) that is produced by many

fluorescent *Pseudomonas* spp. [17]. In Arabidopsis, DAPG produced by *P. fluorescens* CHA0 was demonstrated to induce resistance, while DAPG-mutants lost this ability [18]. Recently, the biosurfactant massetolide A from *P. fluorescens* SS101 was shown to trigger systemic resistance in tomato against *Phytophthora infestans*, while the *massA*-mutant was significantly less effective in controlling the disease than the wild-type strain [19<sup>•</sup>]. A similar role in the activation of host defense was demonstrated for surfactin, a lipoprotein produced by *Bacillus subtilis* [20]. Other rhizobacterially produced compounds implicated in eliciting host defense are *N*-alkylated benzylamine [21] and *N*-acyl-L-homoserine lactone [22]. Interestingly, the volatile organic compound (VOC) 2,3-butanediol produced by two *Bacillus* spp. was shown to induce resistance in Arabidopsis as well [23], demonstrating the diversity of MAMPs produced by beneficial rhizobacteria that are recognized by the plant.

MAMPs involved in systemic resistance triggered by beneficial fungi are not well studied. The nonenzymatic activity of *Trichoderma* spp.-produced cellulose and xylanase is known to elicit resistance in plants [24]. Djonović *et al.* [25<sup>•</sup>] recently demonstrated that the hydrophobin-like elicitor Sm1 of the beneficial soil-borne fungus *Trichoderma virens* induces systemic resistance in maize. Maize plants grown with *SM1*-deletion strains or *SM1*-overexpressing strains displayed decreased or enhanced levels of systemic disease protection, respectively, demonstrating its role in triggering host defense. The fungal determinants that elicit mycorrhiza-induced resistance are currently unknown [9]. However, the recently published genome sequence of the mycorrhizal fungus *Laccaria bicolor* [26<sup>••</sup>] may provide clues for the discovery of MAMPs involved in the induction of systemic resistance by these beneficials.

### Induced defense signaling pathways

It is probable that MAMPs of beneficial microbes and pathogens are recognized in a largely similar manner, ultimately resulting in an enhanced defensive capacity of the plant. However, in plant–beneficial microbe interactions, MAMP-triggered immunity does not ward off the interacting beneficial as it remains accommodated by the plant. This suggests a high degree of coordination and a continuous molecular dialog between the plant and the beneficial organism. The local and systemic defense responses that are triggered by beneficial and parasitic microorganisms are controlled by a signaling network in which the plant hormones SA, jasmonic acid (JA), and ethylene (ET) play important roles [27]. There is ample evidence that SA, JA, and ET pathways crosscommunicate, allowing the plant to finely tune its defense response depending on the invader encountered [28<sup>•</sup>]. Well-studied examples of systemically induced resistance are SAR, which is triggered upon infection by necrosis-inducing pathogens and is dependent on SA signaling [14],

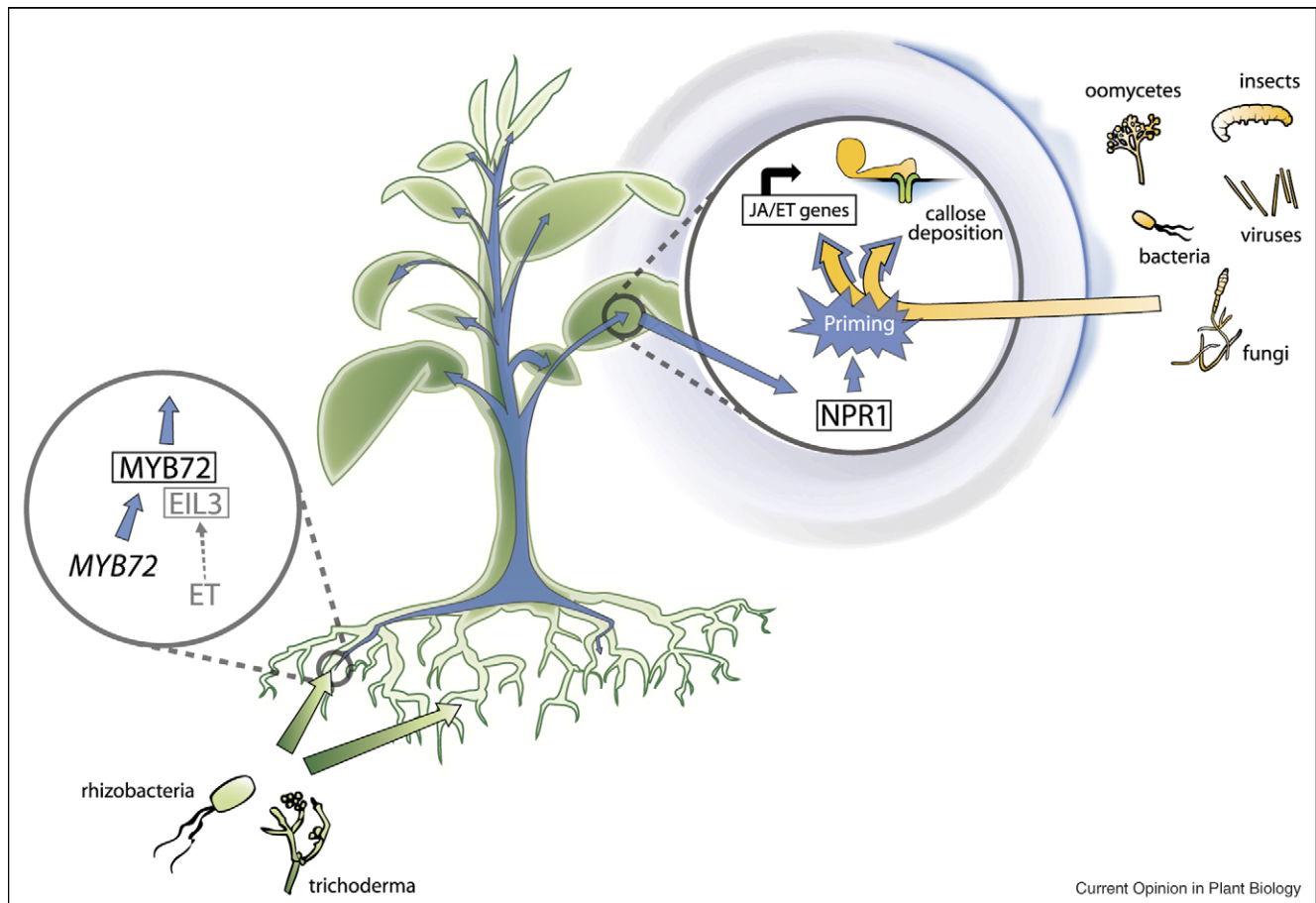
and ISR, which is triggered by beneficial rhizobacteria, such as *P. fluorescens* WCS417 and requires components of the JA and ET signaling pathway [29]. Both pathogen-induced SAR and *P. fluorescens* WCS417-triggered ISR are controlled by the transcriptional regulator NPR1 ([30]; Figure 1). Because SAR is associated with NPR1-dependent *PR* gene expression [31], and ISR is not, NPR1 must differentially regulate gene expression, depending on the signaling pathway that is activated upstream of it. Hence, the NPR1 protein is integrating and responding to different hormone-dependent defense pathways [32]. Not only several other rhizobacterial strains but also some beneficial fungi have been shown to induce systemic resistance in a JA-dependent, ET-dependent, and/or NPR1-dependent manner [7<sup>•</sup>,18,19<sup>•</sup>,25<sup>•</sup>,33<sup>•</sup>,34–36] (S Van der Ent, PhD thesis, Utrecht University, 2008), while there are also some reports about dependency on SA signaling [15,37], or requirement of both ISR and SAR components [38<sup>•</sup>].

### Local immune responses triggered by beneficial microbes

Only few plant–beneficial microbe interactions leading to enhanced systemic resistance have been studied for locally induced changes in plant gene expression or metabolism. In most cases only weak, transient, or strictly localized defense-associated responses were elicited, which differs greatly from the massive induction of defense responses triggered during plant–pathogen interactions [39–41,42<sup>••</sup>]. Transcriptome analysis of Arabidopsis expressing WCS417-ISR revealed a set of 94 genes that were differentially expressed locally in the roots [39]. Knockout mutant analysis of a subset of these WCS417-responsive genes showed that the transcription factor (TF) MYB72 is required in early signaling steps of ISR [43<sup>••</sup>]. Arabidopsis *myb72* mutants were incapable of mounting ISR against both SA-controlled and JA-controlled pathogens, indicating that MYB72 is essential to establish broad-spectrum ISR. Overexpression of MYB72 was not sufficient for the expression of ISR. Hence, MYB72 was assumed to act in concert with another signaling component. MYB72 interacted with the EIN3-like TF EIL3 *in vitro*, making EIL3 a potential candidate in this respect [43<sup>••</sup>]. The interaction with EIL3 links MYB72 function to the ET response pathway involved in ISR, which was previously demonstrated to orchestrate ISR in the roots ([44]; Figure 1). Interestingly, resistance induced in Arabidopsis by the beneficial fungus *Trichoderma asperellum* T34 also appeared to be dependent on MYB72 (S Van der Ent, PhD thesis, Utrecht University, 2008), suggesting that MYB72 functions as a node of convergence in induced defense triggered by soil-borne beneficial microorganisms.

In the case of plant–mycorrhizal symbiosis, significantly more local changes take place. For instance, defense-related compounds like chitinases and glucanases have

Figure 1



Model for the ISR signaling pathway. Recognition of MAMPs of beneficial rhizosphere-colonizing microorganisms, such as *Pseudomonas fluorescens* WCS417 or *Trichoderma asperellum* T34, leads to a local activation of the transcription factor gene *MYB72* in the roots. Subsequently, *MYB72* putatively interacts with the transcription factor *EIL3*. Downstream of, or in parallel with *MYB72/EIL3*, a so far unidentified ET signaling component is required in the roots for the onset of ISR in the leaves. The ISR signal transduction cascade requires *NPR1*, probably in the systemic tissue. Systemically, induction of ISR is associated with priming for enhanced expression of a set of JA-responsive and/or ET-responsive genes and increased formation of callose-containing papillae at the site of attempted pathogen entry. Attack by pathogens or insects, as depicted on the right side of the figure, activates defense responses in the plant (yellow arrows), which is accelerated in ISR-primed plants (combined blue and yellow arrows). Artwork: Wouter Boog.

been shown to accumulate locally in mycorrhizal roots of tomato [9]. In rice, 40% of the mycorrhiza-responsive genes were also responsive to infection by fungal pathogens, indicating that the responses to beneficial and pathogenic fungi partly overlap [45]. Interestingly, some of the initial responses of *Medicago truncatula* to the mycorrhizal fungus *Glomus mosseae* and to the beneficial rhizobacterium *P. fluorescens* C7R12 have been shown to be overlapping as well [46]. Both beneficial microbes failed to elicit these shared responses in the symbiosis-defective mutant *dmi3*, which is affected in the calcium-dependent and calmodulin-dependent protein kinase DMI3 [46]. Again, this suggests that the signaling pathways triggered by very different beneficial microbes converge.

### Priming for enhanced defense

In contrast to the systemic immune responses that are triggered upon pathogen attack, systemic resistance conferred by beneficial microorganisms is generally not associated with substantial reprogramming of the transcriptome. Instead, the systemic changes in gene expression are either relatively mild [42<sup>•</sup>,47,48<sup>•</sup>] or not detectable at all [39]. However, a common feature of ISR responses induced by beneficial microorganisms is priming for enhanced defense. In primed plants, defense responses are not activated directly, but are accelerated upon pathogen or insect attack, resulting in enhanced resistance to the attacker encountered [49<sup>•</sup>,50]. In *Arabidopsis*, rhizobacteria-mediated ISR is often associated with priming for enhanced expression of JA/ET-respon-

sive genes and increased deposition of callose at the site of pathogen entry [8\*,33\*,39,43\*\*,51,52] (Figure 1). Both priming phenomena were abolished in the ISR mutants *myb72* and *npr1* [43\*\*], demonstrating the key role of priming in ISR. Some beneficial rhizobacteria, such as *Paenibacillus alvei* K165 prime for enhanced SA-dependent defenses [37], while others, such as selected endophytic actinobacteria, are able to prime both the SA and the JA/ET pathway [38\*].

Like beneficial rhizobacteria, certain plant growth promoting fungi have also been reported to induce priming in plants. Cucumber plants preinoculated with the beneficial fungus *T. asperellum* T203 developed a JA/ET-dependent systemic resistance that was associated with potentiated PR gene expression in response to pathogen challenge [35]. A similar observation was noted in Arabidopsis following colonization of the roots by a beneficial *Penicillium* sp. [7\*]. The endophytic fungus *Piriformospora indica* induced systemic resistance in barley without priming for JA-mediated, ET-mediated, or SA-mediated defenses, but was associated with the activation of the glutathione–ascorbate cycle, indicating an increased antioxidative capacity [5]. In some cases, shoots of mycorrhizal plants showed changes in defense-related gene expression in the absence of a pathogen [42\*\*], but in other cases priming seems to be the dominant mechanism involved in mycorrhiza-induced systemic resistance [9]. For instance, colonization of tomato roots by mycorrhizal fungi systemically provided protection against *Phytophthora parasitica* infection without direct accumulation of PR proteins. However, upon pathogen attack, mycorrhized plants significantly accumulated more PR proteins than nonmycorrhized plants [53]. Although JA emerged as an important regulator of mycorrhization [54], it remains to be elucidated whether JA serves as the endogenous signal in the mycorrhiza-induced primed state.

## Conclusions

Progress in research on plant immune responses that are triggered by beneficial microorganisms shows that the establishment of mutualistic associations usually involves mutual recognition and a high degree of coordination between the plant and the beneficial organism. Various MAMPs from beneficial microbes have been identified that, in analogy to MAMPs of pathogens, play crucial roles in the onset of the plant's immune response. There seems to be considerable redundancy in the ability of MAMPs from beneficials to induce resistance, which is also common to MAMPs of pathogens [55]. Recognition of different pathogen-derived MAMPs has been shown to elicit similar cellular responses, suggesting an early point of convergence in the corresponding signaling pathways. Recently, the receptor-like kinase BAK1 (brassinosteroid-associated kinase 1) was identified as a potentially important regulator in this signaling convergence [56\*\*].

It is tempting to speculate that redundancy in MAMP recognition guarantees robustness of induced immune response.

The signaling networks that are activated by the plant in response to parasitic and beneficial organisms overlap; this indicates that the regulation of the adaptive response of the plant is finely balanced between protection against aggressors and acquisition of benefits. In the roots, the TF MYB72 and the protein kinase DMI3 have emerged as signaling nodes in which defense signaling pathways triggered by different types of beneficial microorganisms converge. Systemic resistance induced by beneficial microorganisms appears to be predominantly regulated by the JA/ET pathway based on priming for enhanced defense, rather than on direct activation of defense. This is not illogical, because activation of inducible defenses involves major costs that affect plant growth and reproduction [57], and this is inconsistent with the beneficial nature of these plant–microbe interactions. Through the study of the costs and benefits of priming in Arabidopsis, it was recently shown that the fitness costs of priming are lower than those of constitutively activated defenses, such as those expressed in the constitutive SAR-expressing mutant *cpr1* [58\*\*]. Intriguingly, the fitness benefits of priming outweighed its costs under pathogen pressure, which suggests that priming functions as an ecological adaptation of the plant to respond faster to its hostile environment.

## Acknowledgements

We thank Peter Bakker for valuable discussions. This work was supported in part by the Earth and Life Sciences Foundation (grant no. 865.04.002), and the Centre for BioSystems Genomics (grant no. CBSG A4), which is part of the Netherlands Genomics Initiative/Netherlands Organisation for Scientific Research. We apologize to those researchers whose work we were unable to discuss because of space limitations.

## References and recommended reading

Papers of particular interest, published within the period of the review, have been highlighted as:

- of special interest
- of outstanding interest

1. Harrison MJ: **Signaling in the arbuscular mycorrhizal symbiosis.** *Annu Rev Microbiol* 2005, **59**:19–42.
2. Spaink HP: **Root nodulation and infection factors produced by rhizobial bacteria.** *Annu Rev Microbiol* 2000, **54**:257–288.
3. Van Loon LC, Bakker PAHM, Pieterse CMJ: **Systemic resistance induced by rhizosphere bacteria.** *Annu Rev Phytopathol* 1998, **36**:453–483.
4. Kloepper JW, Ryu C-M, Zhang SA: **Induced systemic resistance and promotion of plant growth by *Bacillus* spp.** *Phytopathology* 2004, **94**:1259–1266.
5. Waller F, Achatz B, Baltruschat H, Fodor J, Becker K, Fischer M, Heier T, Huckelhoven R, Neumann C, von Wettstein D *et al.*: **The endophytic fungus *Piriformospora indica* reprograms barley to salt-stress tolerance, disease resistance, and higher yield.** *Proc Natl Acad Sci U S A* 2005, **102**:13386–13391.
6. Harman GE, Howell CR, Viterbo A, Chet I, Lorito M: ***Trichoderma* species—opportunistic, avirulent plant symbionts.** *Nat Rev Microbiol* 2004, **2**:43–56.



7. Hossain MM, Sultana F, Kubota M, Hyakumachi M: **Differential inducible defense mechanisms against bacterial speck pathogen in *Arabidopsis thaliana* by plant-growth-promoting-fungus *Penicillium* sp. GP16-2 and its cell free filtrate.** *Plant Soil* 2008, **304**:227-239.  
This study reports that a nonpathogenic strain of the fungus *Penicillium* induces ISR against *P. syringae* in *Arabidopsis* via a JA-dependent, ET-dependent, and NPR1-dependent pathway and is associated with priming for JA/ET-inducible gene expression.
8. Van Oosten VR, Bodenhausen N, Reymond P, Van Pelt JA, Van Loon LC, Dicke M, Pieterse CMJ: **Differential effectiveness of microbially induced resistance against herbivorous insects in *Arabidopsis*.** *Mol Plant Microbe Interact* 2008, **21**:919-930.  
This study shows that microbially induced resistance is effective against the generalist insect herbivore *Spodoptera exigua*, but not against the specialist herbivore *Pieris rapae*. The induced resistance response is associated with priming for enhanced insect-induced expression of several defense-related genes.
9. Pozo MJ, Azcon-Aguilar C: **Unraveling mycorrhiza-induced resistance.** *Curr Opin Plant Biol* 2007, **10**:393-398.
10. Nürnberger T, Brunner F, Kemmerling B, Piater L: **Innate immunity in plants and animals: striking similarities and obvious differences.** *Immunol Rev* 2004, **198**:249-266.
11. Bakker PAHM, Pieterse CMJ, Van Loon LC: **Induced systemic resistance by fluorescent *Pseudomonas* spp.** *Phytopathology* 2007, **97**:239-243.
12. Meziane H, Van der Sluis I, Van Loon LC, Höfte M, Bakker PAHM: **Determinants of *Pseudomonas putida* WCS358 involved in inducing systemic resistance in plants.** *Mol Plant Pathol* 2005, **6**:177-185.
13. Ran LX, Li ZN, Wu GJ, Van Loon LC, Bakker PAHM: **Induction of systemic resistance against bacterial wilt in *Eucalyptus urophylla* by fluorescent *Pseudomonas* spp.** *Eur J Plant Pathol* 2005, **113**:59-70.
14. Durrant WE, Dong X: **Systemic acquired resistance.** *Annu Rev Phytopathol* 2004, **42**:185-209.
15. Audenaert K, Pattery T, Cornelis P, Höfte M: **Induction of systemic resistance to *Botrytis cinerea* in tomato by *Pseudomonas aeruginosa* 7NSK2: role of salicylic acid, pyochelin, and pyocyanin.** *Mol Plant Microbe Interact* 2002, **15**:1147-1156.
16. Mercado-Blanco J, Bakker PAHM: **Interactions between plants and beneficial *Pseudomonas* spp.: exploiting bacterial traits for crop protection.** *Antonie van Leeuwenhoek* 2007, **92**:367-389.
17. Weller DM, Raaijmakers JM, McSpadden Gardener BB, Thomashow LS: **Microbial populations responsible for specific soil suppressiveness to pathogens.** *Annu Rev Phytopathol* 2002, **40**:309-348.
18. Iavicoli A, Boutet E, Buchala A, Métraux J-P: **Induced systemic resistance in *Arabidopsis thaliana* in response to root inoculation with *Pseudomonas fluorescens* CHA0.** *Mol Plant Microbe Interact* 2003, **16**:851-858.
19. Tran H, Ficke A, Asimwe T, Höfte M, Raaijmakers JM: **Role of the cyclic lipopeptide massetolide A in biological control of *Phytophthora infestans* and in colonization of tomato plants by *Pseudomonas fluorescens*.** *New Phytol* 2007, **175**:731-742.  
This study describes the biosurfactant massetolide A as a novel MAMP for rhizobacteria-induced ISR. This compound is required for the ISR triggering capacity of *P. fluorescens* SS101 in tomato against tomato late blight. Assays with NahG plants indicate that the induced resistance response is independent of SA.
20. Ongena M, Jourdan E, Adam A, Paquot M, Brans A, Joris B, Arpigny JL, Thonart P: **Surfactin and fengycin lipopeptides of *Bacillus subtilis* as elicitors of induced systemic resistance in plants.** *Environ Microbiol* 2007, **9**:1084-1090.
21. Ongena M, Jourdan E, Schäfer M, Kech C, Budzikiewicz H, Luxen A, Thonart P: **Isolation of an *N*-alkylated benzylamine derivative from *Pseudomonas putida* BTP1 as elicitor of induced systemic resistance in bean.** *Mol Plant Microbe Interact* 2005, **18**:562-569.
22. Schuegger R, Ihring A, Gantner S, Bahnweg G, Knappe C, Hartmann A, Langebartels C: **Induction of systemic resistance in tomato by *N*-acyl-L-homoserine lactone-producing rhizosphere bacteria.** *Plant Cell Environ* 2006, **29**:909-918.
23. Ryu C-M, Farag MA, Hu CH, Reddy MS, Kloepper JW, Paré PW: **Bacterial volatiles induce systemic resistance in *Arabidopsis*.** *Plant Physiol* 2004, **134**:1017-1026.
24. Rotblat B, Enshell-Seijffers D, Gershoni JM, Schuster S, Avni A: **Identification of an essential component of the elicitation active site of the EIX protein elicitor.** *Plant J* 2002, **32**:1049-1055.
25. Djonović S, Vargas WA, Kolomiets MV, Horndeski M, Wiest A, Kenerley CM: **A proteinaceous elicitor Sm1 from the beneficial fungus *Trichoderma virens* is required for induced systemic resistance in maize.** *Plant Physiol* 2007, **145**:875-889.  
Genetic evidence is provided for the involvement of a hydrophobin-like elicitor named Sm1 in the induction of systemic resistance in maize. SM1-deletion strains of *T. virens* did not protect maize plants and, conversely, SM1-overexpression strains elicited enhanced protection compared to wild type. *T. virens*-induced systemic resistance in maize is modulated through JA-regulated pathways and green leaf volatiles rather than SA-regulated pathways.
26. Martin F, Aerts A, Ahren D, Brun A, Danchin EGJ, Duchaussoy F, Gibon J, Kohler A, Lindquist E, Pereda V et al.: **The genome of *Laccaria bicolor* provides insights into mycorrhizal symbiosis.** *Nature* 2008, **452**:88-92.  
The genome sequence of the mycorrhizal fungus *L. bicolor* opens new avenues for studying the processes by which symbionts interact with plants. A battery of effector-type small secreted proteins was detected, several of which are expressed only in symbiotic tissue, where they may have a decisive role in the establishment and maintenance of the symbiosis.
27. Glazebrook J: **Contrasting mechanisms of defense against biotrophic and necrotrophic pathogens.** *Annu Rev Phytopathol* 2005, **43**:205-227.
28. Koornneef A, Pieterse CMJ: **Cross-talk in defense signaling.** *Plant Physiol* 2008, **146**:839-844.  
An informative overview of molecular mechanisms involved in crosstalk between defense signaling pathways.
29. Pieterse CMJ, Van Wees SCM, Van Pelt JA, Knoester M, Laan R, Gerrits H, Weisbeek PJ, Van Loon LC: **A novel signaling pathway controlling induced systemic resistance in *Arabidopsis*.** *Plant Cell* 1998, **10**:1571-1580.
30. Pieterse CMJ, Van Loon LC: **NPR1: the spider in the web of induced resistance signaling pathways.** *Curr Opin Plant Biol* 2004, **7**:456-464.
31. Van Loon LC, Rep M, Pieterse CMJ: **Significance of inducible defense-related proteins in infected plants.** *Annu Rev Phytopathol* 2006, **44**:135-162.
32. Van Wees SCM, De Swart EAM, Van Pelt JA, Van Loon LC, Pieterse CMJ: **Enhancement of induced disease resistance by simultaneous activation of salicylate- and jasmonate-dependent defense pathways in *Arabidopsis thaliana*.** *Proc Natl Acad Sci U S A* 2000, **97**:8711-8716.
33. Ahn I-P, Lee S-W, Suh S-C: **Rhizobacteria-induced priming in *Arabidopsis* is dependent on ethylene, jasmonic acid, and NPR1.** *Mol Plant Microbe Interact* 2007, **20**:759-768.  
ISR induced by rhizobacterium *P. putida* LSW17S in *Arabidopsis* is demonstrated to be compromised in mutants *etr1*, *jar1*, and *npr1*, but not in NahG plants. LSW17S-induced ISR is associated with priming for enhanced *PR-1*, *PR-2*, *PR-5*, and *PDF1.2* expression, hydrogen peroxide accumulation, and callose deposition. Priming for all these responses is abolished in the non-ISR expressing mutants.
34. Ryu C-M, Murphy JF, Mysore KS, Kloepper JW: **Plant growth-promoting rhizobacteria systemically protect *Arabidopsis thaliana* against Cucumber mosaic virus by a salicylic acid and NPR1-independent and jasmonic acid-dependent signaling pathway.** *Plant J* 2004, **39**:381-392.
35. Shores M, Yedidia I, Chet I: **Involvement of jasmonic acid/ethylene signaling pathway in the systemic resistance induced in cucumber by *Trichoderma asperellum* T203.** *Phytopathology* 2005, **95**:76-84.
36. Van Wees SCM, Pieterse CMJ, Trijsenaar A, Van't Westende YAM, Hartog F, Van Loon LC: **Differential induction of**

- systemic resistance in *Arabidopsis* by biocontrol bacteria.** *Mol Plant Microbe Interact* 1997, **10**:716-724.
37. Tjamos SE, Flemetakis E, Paplomatas EJ, Katinakis P: **Induction of resistance to *Verticillium dahliae* in *Arabidopsis thaliana* by the biocontrol agent K-165 and pathogenesis-related proteins gene expression.** *Mol Plant Microbe Interact* 2005, **18**:555-561.
  38. Conn VM, Walker AR, Franco CMM: **Endophytic actinobacteria induce defense pathways in *Arabidopsis thaliana*.** *Mol Plant Microbe Interact* 2008, **21**:208-218.
- The authors report that selected strains of endophytic bacteria induce a low expression level of SA-regulated or JA/ET-regulated genes in *Arabidopsis*, which suggests that they are detected as minor pathogens. The endophytes prime for both SA-pathway and JA/ET-pathway, resulting in enhanced activation of genes in either pathway, which is shown to depend on the challenging pathogen.
39. Verhagen BWM, Glazebrook J, Zhu T, Chang H-S, Van Loon LC, Pieterse CMJ: **The transcriptome of rhizobacteria-induced systemic resistance in *Arabidopsis*.** *Mol Plant Microbe Interact* 2004, **17**:895-908.
  40. De Vos M, Van Oosten VR, Van Poecke RMP, Van Pelt JA, Pozo MJ, Mueller MJ, Buchala AJ, Métraux JP, Van Loon LC, Dicke M *et al.*: **Signal signature and transcriptome changes of *Arabidopsis* during pathogen and insect attack.** *Mol Plant Microbe Interact* 2005, **18**:923-937.
  41. Gianinazzi-Pearson V: **Plant cell responses to arbuscular mycorrhizal fungi: getting to the roots of the symbiosis.** *Plant Cell* 1996, **8**:1871-1883.
  42. Liu J, Maldonado-Mendoza I, Lopez-Meyer M, Cheung F, Town CD, Harrison MJ: **Arbuscular mycorrhizal symbiosis is accompanied by local and systemic alterations in gene expression and an increase in disease resistance in the shoots.** *Plant J* 2007, **50**:529-544.
- Transcript profiles of shoots of mycorrhizal *Medicago* plants indicated systemic induction of a set of stress-related and defense-related genes. In addition, the resistance to the leaf bacterial pathogen *Xanthomonas campestris* was increased in these plants.
43. Van der Ent S, Verhagen BWM, Van Doorn R, Bakker D, Verlaan MG, Pel MJC, Joosten RG, Proveniers MCG, Van Loon LC, Ton J *et al.*: **MYB72 is required in early signaling steps of rhizobacteria-induced systemic resistance in *Arabidopsis*.** *Plant Physiol* 2008, **146**:1293-1304.
- This paper describes the MYB72 TF as a new player in rhizobacteria-mediated ISR. MYB72 is induced locally in the roots after the colonization of the rhizosphere by *P. fluorescens* WCS417 and is required for systemic resistance to a variety of pathogens, indicating that MYB72 is essential for the establishment of broad-spectrum ISR.
44. Knoester M, Pieterse CMJ, Bol JF, Van Loon LC: **Systemic resistance in *Arabidopsis* induced by rhizobacteria requires ethylene-dependent signaling at the site of application.** *Mol Plant Microbe Interact* 1999, **12**:720-727.
  45. Güimil S, Chang HS, Zhu T, Sesma A, Osbourn A, Roux C, Ionnidis V, Oakeley EJ, Docquier M, Descombes P *et al.*: **Comparative transcriptomics of rice reveals an ancient pattern of response to microbial colonization.** *Proc Natl Acad Sci U S A* 2005, **102**:8066-8070.
  46. Sanchez L, Weidmann S, Arnould C, Bernard AR, Gianinazzi S, Gianinazzi-Pearson V: ***Pseudomonas fluorescens* and *Glomus mosseae* trigger DMI3-dependent activation of genes related to a signal transduction pathway in roots of *Medicago truncatula*.** *Plant Physiol* 2005, **139**:1065-1077.
  47. Wang YQ, Ohara Y, Nakayashiki H, Tosa Y, Mayama S: **Microarray analysis of the gene expression profile induced by the endophytic plant growth-promoting rhizobacteria, *Pseudomonas fluorescens* FPT9601-T5 in *Arabidopsis*.** *Mol Plant Microbe Interact* 2005, **18**:385-396.
  48. Alfano G, Ivey MLL, Cakir C, Bos JIB, Miller SA, Madden LV, Kamoun S, Hoitink HAJ: **Systemic modulation of gene expression in tomato by *Trichoderma hamatum* 382.** *Phytopathology* 2007, **97**:429-437.
- Using a high-density oligonucleotide microarray, the authors found that 45 genes were differentially expressed in tomato leaves after the colonization of a few cell layers in the roots by the resistance-inducing fungus *Trichoderma hamatum* 382. These genes did not encode defense-related markers, but a remarkably high number of them function in RNA, DNA, and protein metabolism.
49. Conrath U, Beckers GJM, Flors V, García-Agustín P, Jakab G, Mauch F, Newman M-A, Pieterse CMJ, Poinssot B, Pozo MJ *et al.*: **Priming: getting ready for battle.** *Mol Plant Microbe Interact* 2006, **19**:1062-1071.
- This paper reviews different (biotic and abiotic) inducers of priming, the responses that are primed, and the effectiveness of priming.
50. Frost CJ, Mescher MC, Carlson JE, De Moraes CM: **Plant defense priming against herbivores: getting ready for a different battle.** *Plant Physiol* 2008, **146**:818-824.
  51. Cartieaux F, Contesto C, Gallou A, Desbrosses G, Kopka J, Taconnat L, Renou JP, Touraine B: **Simultaneous interaction of *Arabidopsis thaliana* with *Bradyrhizobium* sp. strain ORS278 and *Pseudomonas syringae* pv. tomato DC3000 leads to complex transcriptome changes.** *Mol Plant Microbe Interact* 2008, **21**:244-259.
  52. Van Wees SCM, Luijendijk M, Smoorenburg I, Van Loon LC, Pieterse CMJ: **Rhizobacteria-mediated induced systemic resistance (ISR) in *Arabidopsis* is not associated with a direct effect on expression of known defense-related genes but stimulates the expression of the jasmonate-inducible gene *Atvsp* upon challenge.** *Plant Mol Biol* 1999, **41**:537-549.
  53. Pozo MJ, Cordier C, Dumas-Gaudot E, Gianinazzi S, Barea JM, Azcón-Aguilar C: **Localized vs systemic effect of arbuscular mycorrhizal fungi on defence responses to *Phytophthora* infection in tomato plants.** *J Exp Bot* 2002, **53**:525-534.
  54. Hause B, Mrosk C, Isayenkova S, Strack D: **Jasmonates in arbuscular mycorrhizal interactions.** *Phytochemistry* 2007, **68**:101-110.
  55. Bittel P, Robatzek S: **Microbe-associated molecular patterns (MAMPs) probe plant immunity.** *Curr Opin Plant Biol* 2007, **10**:335-341.
  56. Heese A, Hann DR, Gimenez-Ibanez S, Jones AME, He K, Li J, Schroeder JI, Peck SC, Rathjen JP: **The receptor-like kinase SERK3/BAK1 is a central regulator of innate immunity in plants.** *Proc Natl Acad Sci U S A* 2007, **104**:12217-12222.
- This report describes that BAK1, which was in previous studies identified as brassinosteroid-associated kinase 1, is a common component linking perception of different unrelated MAMPs with subsequent signal transduction leading to immunity. *bak1*-silenced *Nicotiana benthamiana* is comprised in resistance to *P. syringae* and *H. parasitica*. BAK1 forms a complex with flg22 and its receptor FLS2, which resembles the interaction of BAK1 with brassinosteroid (BR) and its receptor BRI1, implicating BAK1 in both plant immunity and BR signaling.
57. Heil M: **Ecological costs of induced resistance.** *Curr Opin Plant Biol* 2002, **5**:345-350.
  58. Van Hulten M, Pelser M, Van Loon LC, Pieterse CMJ, Ton J: **Costs and benefits of priming for defense in *Arabidopsis*.** *Proc Natl Acad Sci U S A* 2006, **103**:5602-5607.
- This study shows that priming for enhanced defense entails less fitness costs than direct induction of defense.