Plant hormones: a fungal point of view

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SUMMARY

Most classical plant hormones are also produced by pathogenic and symbiotic fungi. The way in which these molecules favour the invasion of plant tissues and the development of fungi inside plant tissues is still largely unknown. In this review, we examine the different roles of such hormone production by pathogenic fungi. Converging evidence suggests that these fungal-derived molecules have potentially two modes of action: (i) they may perturb plant processes, either positively or negatively, to favour invasion and nutrient uptake; and (ii) they may also act as signals for the fungi themselves to engage appropriate developmental and physiological processes adapted to their environment. Indirect evidence suggests that abscisic acid, gibberellic acid and ethylene produced by fungi participate in pathogenicity. There is now evidence that auxin and cytokinins could be positive regulators required for virulence. Further research should establish whether or not fungal-derived hormones act like other fungal effectors.

Keywords: fungi, plant hormones, virulence.

INTRODUCTION

Many fungi interact with plants in a beneficial manner, as in mycorrhizal symbiosis (Sanders, 2011), or in a harmful manner, as in the case of fungal diseases (Dean et al., 2012). In order to obtain nutrients, both symbiotic and most pathogenic fungi penetrate their host without breaking the plant cell plasma membrane. The fungal membrane is protected by a cell wall composed of chitin that can be recognized by plants through membrane receptors, which then activate basal immunity. Chitin perception modulates responses during both mutualistic and pathogenic fungus–plant interactions (Gust et al., 2012). Fungi have evolved a repertoire of tools, such as protein effectors and metabolites, to impede such plant immunity and/or to establish favourable conditions for their invasion of plant tissues (Kamoun, 2007). In addition to the production of canonical effectors, fungi also produce compounds that are similar to plant hormones, such as auxins, cytokinins (CKs), gibberellic acids (GAs), ethylene (ET), abscisic acid (ABA), jasmonic acid (JA) and salicylic acid (SA). These hormones are well described to control plant development and to trigger important plant signalling events during biotic and abiotic stresses (reviewed in De Vleeschauwer et al., 2013; Peleg and Blumwald, 2011; Pozo et al., 2015; Robert-Seilaniantz et al., 2011; Spence and Bais, 2015).

There are now many examples showing that some pathogen protein effectors trigger hormone regulation to favour infection (Robert-Seilaniantz et al., 2007). By contrast, the involvement of hormonal compounds derived from microorganisms in plant–fungus interactions is poorly documented. Fungal-derived hormones were first suspected to be involved in the virulence of gall-forming pathogens (Denancé et al., 2013; Robert-Seilaniantz et al., 2007). For symbiotic fungi, such production of hormones is consistent with root modifications often required in these interactions (Hirsch et al., 1997). However, many pathogens that do not induce organ deformations can also produce and secrete plant hormones, suggesting a role of these molecules in biological processes other than organ deformation.

The role of plant-derived hormones in plant disease resistance has been reviewed extensively (De Vleeschauwer et al., 2014; Robert-Seilaniantz et al., 2011). In this review, we summarize the current knowledge on the role of fungal-derived plant hormones in plant–pathogen interactions with a focus on their putative role in virulence. When relevant, some information on plant–mycorrhiza interactions is also provided, as it often sheds some light on the role of these molecules in plant–fungus interactions.

AUXINS FROM FUNGI PLAY A POSITIVE ROLE IN PLANT–FUNGUS INTERACTIONS

Auxins are indole-derived hormones involved in plant developmental processes, such as cell division, differentiation and organ formation (Benjamins and Scheres, 2008; Oka et al., 1999; Van-neste, 2005), and senescence (Kim et al., 2011). Auxins also control biotic and abiotic stress responses in plants (Peleg and Blumwald, 2011). In bacteria, auxins are synthesized from tryptophan, which is converted into indole-3-acetamide by tryptophan-2-monoxygenase enzymes (Zhao, 2010). Indole-3-acetamide is hydrolysed to form indole-3-acetic acid (IAA), which is also the major auxin active form in plants even if it is produced through slightly different biosynthesis pathways. The bacterial genes...
Auxin involvement in plant–pathogen interactions was suspected early, and was studied when symptoms, such as organ deformation, were found to be reminiscent of responses to high auxin levels. For instance, *Agrobacterium tumefaciens* and *Pseudomonas savastanoi* are well-known plant-pathogenic bacteria that induce tumour formation in their hosts, and auxins actively contribute to the virulence of these bacteria (Glass and Kosuge, 1988). Like *Agrobacterium*, some fungi are able to induce tumours, such as the corn smut causal agent, *U. maydis*. However, fungal mutants affected in auxin production were still able to induce tumours in a similar manner to the wild-type strain, even though tumours contained a lower level of auxins (Reinke et al., 2008). This suggests that auxin production by *U. maydis* is not required for the virulence of this pathogen.

In the case of fungal pathogens not triggering organ deformation, functional evidence suggests a role for auxins. By measurement of the fungal biomass and auxins in plant tissues, it was suggested that *C. gloeosporioides* f. sp. *aeschynomene* produces auxins during the early biotrophic stages of plant colonization (Maor et al., 2004). In *F. oxysporum*, an enhanced expression of auxin biosynthetic genes (tryptophan-2-monoxygenase and indole-3-acetamide hydrolase) triggered an over-accumulation of IAA and a hypervirulent phenotype on Orobanche (Cohen et al., 2002). Consistent with these observations, the transient silencing in *Puccinia graminis* f. sp. *tritici* of a gene required for auxin biosynthesis was obtained in wheat infected leaves. The two-fold reduction of the transcript led to a decrease in pustule formation. Although auxins were not measured after silencing, these results suggest that auxins were required for full fungal pathogenicity (Yin et al., 2014). Thus, auxins seem to play a role in pathogenicity, and further functional studies with fungal mutants should help to better understand how they participate in virulence.

**CKs FROM FUNGI: A NOW CLEAR-CUT POSITIVE FUNCTION IN VIRULENCE**

CKs are diversified plant hormones derived from ATP/ADP/AMP or from the tRNA degradation pathway. CKs are well described for their role in plant developmental processes, such as root and shoot formation, through the regulation of cell cycle and cell differentiation (Barciszewski et al., 1999; Carimi et al., 2003; Fosket and Torrey, 1969; Riou-Khamlichi et al., 1999). CKs are also involved in the delay of senescence and in source–sink nutrient distribution (Peleg et al., 2011; Wingler et al., 1998). The first step in CK biosynthesis in plants involves isopentenyl transferase enzymes (IPT or tRNA-IPT), which perform the transfer of the isopentenyl chain from the methylerythritol phosphate (MEP) on the adenosine phosphate substrate, leading to the formation of the ribosylated phosphorylated CK forms (Sakakibara, 2006). Then, these CKs are activated, in part by the LONELY GUY (LOG) enzymes, into free CK active forms, such as trans-zeatin and others.
isopentenyladenine (Frébert et al., 2011; Kurakawa et al., 2007). The putative IPT and LOG genes are present in several fungal genomes, and some have been characterized recently (see below; Chanclud et al., 2016; Hinsch et al., 2015; Morrison et al., 2015b).

A large diversity of fungal species, whether saprophytic, pathogenic or symbiotic, have been shown to produce CKs (Cooper and Ashby, 1998; Murphy et al., 1997), and several studies have suggested that they could play a role in several physiological processes in fungi themselves, especially in hyphal development and nutrient uptake (LeJohn and Stevenson, 1973). For instance, CKs promote in vitro branching of ectomycorrhizal mycelia (Barker and Tagu, 2000), affect, in a dose-dependent manner, hyphal membrane viscosity, and therefore influence ion and water transport (Gogala, 1991; LeJohn and Stevenson, 1973). Pohleven et al. (1986) demonstrated that some CKs modify the content of K, Ca, P and Na in the mycelia of the basidiomycete Suillus variegatus (Gogala, 1991). The effect of CKs on hyphal growth seems to depend on the concentration and on the type of CK molecule tested (Gryndler et al., 1998). CKs could also be involved in growth optimization under adverse conditions. For instance, the inhibition of the mycelial growth of Amanita muscaria caused by aluminium is correlated significantly with a decrease in CK amount (Kovač and Žel, 1995). In a recent report, we have shown that endogenous and exogenous CKs are required for oxidative stress tolerance in the rice blast fungus Magnaporthe oryzae (Chanclud et al., 2016). In the 1960s, Lee et al. reported that CKs also affect sexual reproduction in the ascomycete N. crassa, suggesting a role in communication within fungi (Elliott, 1967; Lee, 1961).

During mycorrhizal symbiosis, CKs promote growth of the host and of the symbiont (Allen et al., 1980; Barker and Tagu, 2000; Drüge and Schönbeck, 1993). CK accumulation in the host, root and shoot has been shown in many fungal symbiotic interactions (Allen et al., 1980). A model has emerged since the early 1990s on the role of CKs in plant symbiotic interactions, proposing that plants secrete CKs which: (i) promote the growth of symbiotic microbes which are thus able to detect them; (ii) this contributes to a better absorption of nutrients through the symbiont; and (iii) leads to an increase in the photosynthetic process in the host leaves (Drüge and Schönbeck, 1993; Wollschlager and Reid, 1990). It is possible that CKs produced by mycorrhizas may initiate this whole process, but this awaits the study of CK-deficient symbiotic fungal mutants to be confirmed.

During interaction with fungal pathogens, the CK content is often affected (Devois et al., 2006; Jiang et al., 2013). As most of the necrotrophic fungi analysed do not seem to secrete CKs, in contrast with (hemi)biotrophic fungi, it has been suggested that fungal CK production and secretion could depend on the pathogen lifestyle. CKs are involved in many diseases caused by pathogens that induce tumour formation in their hosts: protists [e.g. Plasmodiophora brassicae (Siemens et al., 2006)], nematodes [e.g. Heterodera schachtii (Siddique et al., 2015)], bacteria [e.g. Pseudomonas savastanoi (Barciszewski et al., 2000), Agrobacterium sp. (Barciszewski et al., 2000), Rhodococcus fascians (Pertry et al., 2009)] and fungi [U. maydis (Mills and Van Staden, 1978), Claviceps purpurea (Hinsch et al., 2015)]. In the tumour-inducing pathogen Cl. purpurea, the deletion of two genes partially abolished CK de novo synthesis, but authors concluded that they did not affect the virulence of the fungus. By contrast, the mutants exhibited a hypersporulating phenotype, implying that CKs are environmental factors influencing fungal development (Hinsch et al., 2015). Recently, it has been shown that CK accumulation in U. maydis-infected tissues is correlated with the virulence of this pathogen, but there was no direct genetic evidence that fungal-derived CKs are required for full virulence of this pathogen (Morrison et al., 2015a).

Fungal pathogens that do not induce tumours also produce CK compounds, and their role in virulence is still poorly understood (see, for instance, Jiang et al., 2013; Murphy et al., 1997). CKs are probably involved in ‘green island’ formation, a photosynthetically active zone often found around lesions caused by biotrophic fungi (Angra and Mandahar, 1991; Choi et al., 2011). In plants, CK production is thought to occur in the roots (Rani Debi et al., 2005), and experiments with detached leaves could indirectly address the question of the origin of CKs in green islands. Using this assay in wheat and maize leaves infected with Pyrenophora teres and Dreschlera maydis, respectively, the increase in CK content was attributed to the pathogen. The increase in CK levels in susceptible hosts was also correlated with increased metabolite contents around infection sites (Angra-Sharma and Sharma, 1999). CK secretion was shown by immunodetection in plant tissues in the case of Puccinia recondita f. sp. tritici during wheat infection (Hu and Rijkenberg, 1998), but, as for most hormones found during infection, it is not possible to unambiguously assign this accumulation to the plant or to the pathogen without characterization of the mutants impaired in CK production or perception. A recent study has reported that CK production by fungi, especially the cissimaein form (which seems to be the main form produced by filamentous fungi), could involve tRNA-IPT enzymes that perform modification of tRNA, which then releases free CKs after degradation (Morrison et al., 2015b). Among the non-tumour-inducing fungal pathogens, M. oryzae produces and secretes CKs (Jiang et al., 2013). Knock-out mutants impaired in the only tRNA-IPT gene identified in M. oryzae were also impaired in CK production, thus confirming the hypothesis of Morrison et al. (2015b) that tRNA-IPT enzymes are involved in fungal CK production (Chanclud et al., 2016). The interaction between rice and the CK-deficient strain of M. oryzae has been characterized. This analysis demonstrated that M. oryzae-derived CKs are required for full virulence by affecting rice defences, nutrient distribution and fungal oxidative stress tolerance (Chanclud et al., 2016). As the tRNA-IPT gene...
identified in *M. oryzae* is well conserved, this mutation could be studied in other fungi as a potential tool to distinguish fungal CKs from plant CKs in other plant–fungus interactions. Recently, the deletion of a *tRNA-IPT* gene has also been performed in the nematode *H. schachtii*, confirming the conservation of the role of this enzyme in CK production among different organisms (Siddique *et al.*, 2015).

**ANCIENT BUT LIMITED DIRECT EVIDENCE FOR A ROLE OF GAs OF FUNGAL ORIGIN**

GAs are terpenoid hormonal compounds identified for the first time as being produced by *Gibberella fujikuroi*. This fungus is the causal agent of the 'bakanae' or 'foolish seedlings' disease of rice, in which infected plants are abnormally tall. Following this discovery, the role of GAs in plant physiology was studied. GAs are involved in the control of germination, flowering, cell division and internode elongation (Brian and Elson, 1954; Pimenta Lange and Lange, 2006; Swain and Singh, 2005). The first steps of GA biosynthesis pathways identified in fungi are almost identical with those known in plants. The complex GA biosynthesis pathways have been well described by Tuzynski (2005). GA production has been found in several fungal species, but its effects on fungal biology are not well described.

In liquid culture, GAs have been shown to increase conidial germination and to improve the growth of young hyphae of the ascomycete fungus *N. crassa* (Nakamura *et al.*, 1978; Tomita *et al.*, 1984). These effects are additive with the effects of auxins, suggesting that these two hormones could act independently to affect *Neurospora* germination and growth (Tomita *et al.*, 1984).

Few studies have reported the role of GAs during interaction between fungi and plants (Tsavkelova *et al.*, 2006). In mycorrhizal interaction, the GA content is increased in plants (Barker and Tagu, 2000). Blee and Anderson (1998) have suggested a model in which the production of fungal GAs is possibly required to initiate a signal leading to enhanced carbon sink activity of the infected cell (probably combined with CKs and auxins).

In plant–pathogen interactions, the role of GAs has been less well studied compared with the role of other plant hormonal pathways. Different strains of *G. fujikuroi* were analysed for their production of GAs, and a correlation was found between the quantity of GAs produced and the virulence of the strain (Desjardins *et al.*, 2000). However, in another study, there was no clear link between the production of GAs and the pathogenicity of *Fusarium* (Marika, 1980). *Gibberella fujikuroi* mutated for two histone deacetylases showed a reduction in GA production. Plants infected with the double deletion mutant resembled the uninfected control plants, suggesting that GA production is required for bakanae disease on rice (Studt *et al.*, 2013). However, the possibility that the introduced mutations affected other virulence factors cannot be ruled out.

**ABA: CONVERGING EVIDENCE FOR ABA USED AS A VIRULENCE FACTOR**

In plants, ABA is well known to induce stomatal closure and thus to contribute to plant drought tolerance (Beardsell and Cohen, 1975). ABA is the key hormone for plant abiotic stress responses (Peleg and Blumwald, 2011) and it is also involved in seed dormancy by acting antagonistically with the GA pathway (Debajoung and Koornneef, 2000). In plants, ABA is synthesized from both the MEP and mevalonate pathway (Nambara and Marion-Poll, 2005).

In fungi, it is thought that the mevalonate pathway is mainly involved and that different ABA precursors can be used (Morrison *et al.*, 2015b; Oritani and Kyotai, 2003). Fungal production of ABA was first shown in *Cercospora risicola* (Norman *et al.*, 1983). Since then, many fungi with different lifestyles (saprophytic, symbiotic and pathogenic) have been described as producing ABA (Crocoli *et al.*, 1991; Esch *et al.*, 1994; Jiang *et al.*, 2010; Morrison *et al.*, 2015b). There are only two reports of ABA affecting mycelium growth. In *Ceratocystis fimbriata*, exogenous application of ABA showed a slight promotion of fungal growth. In *M. oryzae*, ABA increased germination and the formation of appressoria, a specialized infection structure differentiating for breaking down the plant cell wall and allowing invasion (Spence and Bais, 2015, and references therein).

The arbuscular-mycorrhizal (AM) fungus *Glomus* sp. produces ABA, and ABA concentration in the xylem sap is different between mycorrhizal and non-mycorrhizal plants. However, the origin of this increase in ABA has not yet been established (Esch *et al.*, 1994).

In several plant–pathogen interactions, ABA has been described to affect plant disease resistance in a positive or negative manner, depending on the host–pathogen interaction studied (De Vleeschauwer *et al.*, 2010; Jiang *et al.*, 2010; Xu *et al.*, 2013). Kettner and Dorffling (1995) inoculated tomato plants with two strains of *Botrytis cinerea* presenting differences in ABA production, and showed that the increase in ABA was higher in leaves inoculated with the higher ABA-producing strain than with the lower ABA-producing strain. This suggests that ABA accumulation in the host during infection could result from or be initiated by this pathogenic fungus. Similarly, ABA was accumulated during the early stages of infection by *U. maydis* and this accumulation could be correlated with the virulence of the fungus (Morrison *et al.*, 2015a). Although exogenous ABA triggered a faster development of necrotic lesions, the role of fungal ABA in virulence was not described until recently. Knocking out one gene homologous to the *B. cinerea* *ABA4* gene responsible for ABA biosynthesis reduced, by two-fold, ABA levels in *M. oryzae* (Siewers *et al.*, 2006; Spence *et al.*, 2015). Appressorium formation *in vitro* was severely reduced in the *M. oryzae* Δaba4 mutant, a phenotype that could be reversed by the exogenous application of ABA. The virulence of the Δaba4 mutant was also strongly compromised, suggesting that ABA contributes to the virulence of this fungus.
One may then speculate that the production of ABA by *M. oryzae* inhibits the SA-dependent defence response (Jiang et al., 2010), as observed in many other biological situations (Ton et al., 2009). However, as the Δaba4 mutant did not form appressoria and infect plants at all, it is difficult to draw conclusions on the role of fungal-produced ABA on the plant itself.

**ET: A GASEOUS HORMONE INVOLVED IN PLANT PHYSIOLOGY AND DEFENCE WHICH ALSO AFFECTS FUNGAL DEVELOPMENT**

ET is a gaseous compound first discovered for its role in fruit maturation (Bleecker and Kende, 2000; Payton et al., 1996). ET was later shown to be involved in senescence, germination, flowering and the inhibition of root and shoot growth (Bleecker and Kende, 2000; Grbic and Bleecker, 1995). In *Arabidopsis*, ET has been described to contribute, with JA, to the induction of defences against necrotrophic pathogens. However, this dichotomy of responses, to biotrophic and necrotrophic pathogens, is not always clear in other plants, such as in rice, in which hormonal regulation of defences is slightly different (De Vleesschauwer et al., 2013, 2014). In plants and fungi, ET biosynthesis occurs from methionine, which is transformed into 1-aminocyclopropane-1-carboxylic acid (ACC) via ACC-synthase enzymes (Esser et al., 2002). Moreover, fungi also produce ET from 2-keto-4-methylthiobutyric acid, derived from methionine, and/or from 2-oxoglutarate, therefore requiring ET-forming enzymes (Bockhaven et al., 2015; Hottiger and Boyle, 1991, and references therein). Altogether, studies on fungal ET production show that it is strongly dependent on the growth medium, and confirm that several pathways exist among fungi (Esser et al., 2002; Strzeczyk et al., 1994). Since the first report of ET production by *Penicillium digitatum* in 1940, ET production has been measured in many fungal species, in both hyphae and spores (Dasilva et al., 1974). These fungi belong to different phyla, have different lifestyles and range from pathogenic fungi, such as *B. cinerea*, to symbiotic fungi, such as *F. oxysporum* f. sp. *pini* (Arshad and Frankenberger, 1991; Dasilva et al., 1974; Graham and Linderman, 1980). Several *in vitro* experiments have demonstrated that ET and certain precursors (etephon and ACC) affect spore germination and hyphal growth of the pathogenic filamentous fungi, *Alternaria alternata* and *B. cinerea*, and the symbiotic fungi, *Gigaspora ramisporangora* and *G. mosseae* (Chagué et al., 2006; Kępczyńska, 1994). The effects of ET on fungal development seem to be dose dependent, with a promising effect observed at concentrations below 1 mM and a negative effect at or higher than 1 mM (Ishii et al., 1996).

In the case of mycorrhiza, the role of ET depends on the type of symbiotic interaction. A low content of ET was measured in mycorrhizal roots (McArthur and Knowles, 1992) and an exogenous supply of ET suppressed AM development (Geil et al., 2001; Zsoög et al., 2008). Therefore, it was suggested that a repression of the ET pathway by AM fungi is required to allow the establishment of symbiosis. Indeed, the AM fungus *Glomus intraradices* secretes a protein (SP7: secreted protein 7) which interacts with an ET response factor to suppress ET signalling (Kloppholz et al., 2011). In contrast, ET seems to promote ectomycorrhizal symbiosis. Two species of truffle (*Tuber melanosporum* and *Tuber borchii*) have been shown to produce ET (and auxin) for the manipulation of these hormonal pathways in the host and for the induction of root morphological modifications, a plant developmental process in which these hormones are involved (Spiválová et al., 2009). Given the roles of ET in plant defence, this fungal ET production by symbionts could also be required to counteract the establishment of host immunity.

During plant–fungus pathogen interactions, the ET content often increases at the beginning of the interaction (Broekhert et al., 2006). However, its origin, from plants or fungi, is still unclear. In the case of the *Colletotrichum* sp. pathogens, ET is required for the formation of appressoria (Flashman and Kolattukudy, 1994). Indeed, appressoria formed on ripening tomato, whereas none formed in plant mutants affected in ET production. An exogenous supply of ET restored appressorium formation on these plant mutants, suggesting that ET produced by fruits during ripening is perceived by the pathogen and is beneficial to initiate the development of specialized structures required for penetration and thus for full virulence. Furthermore, ET production by fungi could be required to disturb host defence induction by affecting plant hormonal homeostasis, essential for the establishment of plant immunity (Broekaert et al., 2006). This hypothesis was recently investigated in the interaction between rice and the necrotrophic pathogen *Cochliobolus miyabeanus*, in which ET increases rice susceptibility (Bockhaven et al., 2015). In this study, the authors used a specific inhibitor of fungal ET biosynthesis (2,2-bipyriddyl), which abolishes fungal ET production and leads to a greater resistance of the host (or a lack of virulence of the fungus). Combined with other results showing that *C. miyabeanus* affects the 2-oxoglutarate (an ET precursor for microbes) pool in rice, the authors suggested that ET accumulation is mainly initiated and caused by the fungus and contributes to symptom development (Bockhaven et al., 2015). However, exogenous supplies of hormonal production inhibitors or signalling inhibitors could have side-effects on the host and on the fungus; therefore, the study of fungal mutants affected in ET perception or production is still lacking for an understanding of the different roles of ET in plant–fungus interactions.

**PATHOGENIC FUNGI ALSO PRODUCE THE DEFENCE-RELATED HORMONES SA AND JA**

In most plants, SA and JA trigger defences against fungal biotrophic and necrotrophic pathogens, respectively, in an antagonistic manner (Bari and Jones, 2009; Robert-Seilaniantz et al., 2011). Some fungal pathogens may produce one hormone in order to
inhibit the defence pathway which is the most detrimental to their growth. In plants, SA is synthesized from chorismate. The fungal pathogen *U. maydis* targets the corresponding pathway by secreting a chorismate mutase, which channels chorismate into the phenyl propanoid pathway, preventing SA accumulation during infection and contributing to its virulence (Djamei et al., 2011). However, the chorismate pathways identified in fungi do not lead to SA biosynthesis. Thus, although SA (or SA derivatives) production has been measured in different species, to date this pathway is still unknown in fungi (Packter and Steward, 1967).

Some pathogens produce both SA and JA, such as, for example, *Moniliophthora perniciosa*, which causes witches’ broom disease of cocoa. In this case, the production of these hormones could: (i) contribute to manipulate the hormonal pathways involved in the host defence responses throughout its invasion, i.e. causing abnormal shoot development and necrosis; and (ii) have a direct effect on this fungus as both SA and JA promote *in vitro* growth (Chaves and Gianfagna, 2006; Kilaru et al., 2007). Several other studies have reported the effects of SA or JA on fungal physiological processes. SA has a moderate suppressive effect on the spore germination and colony growth rate of *Harpophora maydis* (Degani et al., 2015). In *Aspergillus flavus*, the results obtained from *in vitro* experiments show that SA reduces hyphal growth significantly at all concentrations tested (Panahirad et al., 2014).

Several studies have reported the production of JA by pathogenic fungi, such as *G. fujikuroi* and *Botryodiplodia theobromae* (Miersch et al., 1991, 1992). JAs are derived from lipid peroxidation, and thus belong to the oxylipins. Some fungal oxylipin biosynthesis pathways have been identified and characterized. JA and the other oxylipins can affect both host and fungal physiological processes (Tsitsigiannis and Keller, 2007). The *in vitro* application on *F. oxysporum* f. sp. *lycopersici* of methyl jasmonate reduced spore germination and mycelium growth (Kröl et al., 2015). Recently, *M. oryzae* has been shown to affect JA homeostasis by both producing JA derivatives and secreting a monoxygenase that converts rice endogenous JA into hydroxylated JA (12OHCJA). This 12OHCJA may then inhibit JA signalling and thus impair JA-dependent host defences and resistance (Patkar et al., 2015).

Although the number of pathogenic fungi characterized for the production of SA and/or JA has increased, there is no direct evidence that fungal SA or JA is required for their virulence.

**CONCLUSIONS**

Thus far, most fungi have been shown to produce almost all plant-like hormones *in vitro*. It is noteworthy that certain growth media used in many studies are prepared from potato dextrose agar and/or yeast extract, two compounds that already contain some plant-derived hormones, including auxins, CKs, ABA and others, in unknown concentrations. Thus, some confusion exists between the ability of fungi to produce plant hormones *de novo* and their ability to metabolize them from the growth medium. This should be carefully addressed in future studies conducted *in vitro*. The sequencing of many genomes may also help to shed light on the presence of the hormonal biosynthesis pathways already described in some fungal species (Esser et al., 2002).

This overview shows that most known plant hormonal compounds are produced and perceived by fungi. To date, the involvement of fungal hormonal compounds, and the way in which they are secreted and act in the plant cell, is still poorly understood. Although most of the biosynthesis pathways of hormones in fungi are well described (reviewed in Esser et al., 2002), studies on fungal mutants affected in hormonal production are strikingly lacking to confirm the involvement of fungal-derived plant hormones in such interactions. In particular, the origin of hormones in colonized tissues is unclear and needs to be established to understand the complex relationships between fungal-derived and plant-derived hormones.

Some plant hormones have been shown to affect fungal development, nutrition and reproduction processes, suggesting that these molecules trigger certain signals in fungi (Elliott, 1967; Esch et al., 1994; Gryndler et al., 1998; Kepczyńska, 1989; LeJohn and Stevenson, 1973; Nakamura et al., 1978, 1982). Figure 1 provides a non-exhaustive summary of the main effects of the hormones known to date on fungal biology. However, the perception
systems of hormones by fungi, as well as the signalling pathways triggered and the physiological responses induced, still remain to be discovered.

These plant hormone compounds are also produced, and very probably perceived, by other microbes, including bacteria and nematodes (Denanç et al., 2013; Kisiala et al., 2013; Siddique et al., 2015). Moreover, some of these compounds have effects on animal cells (Ishii et al., 2003; Jiang et al., 2002; Slaugenheup et al., 2004), suggesting that ‘plant’ hormones not only participate in the plant–microbe dialogue, but might also contribute to communication in other host–microbe interactions involving widely different organisms (animals, plants and all types of pathogenic, saprophytic and symbiotic microbes). However, to date, there has been no report on the involvement of such compounds in these interactions.

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REFERENCES

Allen, M.F., Moore, Jr. T.S. and Christensen, M. (1980) Phytochrome changes in Botryolus gracilis infected by vesicular-arbuscular mycorrhizae: I. Cytokinin increases in the host plant. Can. J. Bot. 58, 371–374.

Angra, R. and Mandal, C.L. (1991) Pathogenesis of barley leaves by Helminthosporium oryzae: green island formation and the possible involvement of cytokinins. Mycopathologia, 114, 21–27.

Angra-Sharma, R. and Sharma, D.K. (1998) Cytokinin in pathogenesis and disease resistance of Pyrenophora teres—barley and Deschlera maydis—maize interactions during early stages of infection. Mycopathologia, 148, 87–95.

Arshad, M. and Frankenberger, W.T. (1991) Microbial production of plant hormones. Plant Soil, 133, 1–8.

Barciszewski, J., Rattan, S.I.S., Siboska, G. and Clark, B.F.C. (1999) Kinetin — 45 years on. Plant Sci, 148, 37–45.

Barciszewski, J., Siboska, G., Rattan, S.I.S. and Clark, B.F.C. (2000) Occurrence, biosynthesis and properties of kinetin (N6-furfuryladine) Plant Growth Regul. 26, 257–265.

Barker, D.R. and Jones, J.D.G. (2009) Role of plant hormones in plant defence responses. Plant Mol. Biol. 69, 473–488.

Barker, S. and Tagu, D. (2000) The roles of auxins and cytokinins in mycorrhizal symbioses. J. Plant Growth Regul. 19, 144–154.

Beardsell, M.F. and Cohen, D. (1975) Relationships between leaf water status, abscisic acid levels, and stomatal resistance in maize and sorghum. Plant Physiol. 56, 207–212.

Benjamin, R. and Scheres, B. (2008) Auxin: the looping star in plant development. Annu. Rev. Plant Biol. 59, 443–465.

Blee, K.A. and Anderson, A.J. (1998) Regulation of arbuscule formation by carbon in the plant. Plant J. 16, 523–530.

Bleecker, A.B. and Kende, H. (2000) Ethylene: a gaseous signal molecule in plants. Annu. Rev. Cell Dev. Biol. 16, 1–18.

Brian, P. and Elson, G. (1954) The plant-growth-promoting properties of gibberellic acid, a metabolite product of the fungus Gibberella fujikuroi. J. Sci. Food Agric. 5, 602–612.

Broekaert, W.F., Delaere, S.L., De Bolle, M.F.C. and Cammue, B.P.A (2006) The role of ethylene in host–pathogen interactions. Annu. Rev. Phytopathol. 44, 393–416.

Carimi, F., Zottini, M., Formentin, E., Terzi, M. and Lo Schiavo, F. (2003) Cytokinins: new apoptotic inducers in plants. Planta. 216, 413–421.

Chaguet, V., Dant, L.V., Sievers, V., Schulze-Gronover, C., Tuzdysynki, P., Tuzdysynki, B. and Sharon, A. (2006) Ethylene sensing and gene activation in Botrytis cinerea: a missing link in ethylene regulation of fungus–plant interactions? Mol. Plant–Microbe Interact. 19, 33–42.
Fosket, D.E. and Torrey, J.G. (1969) Hormonal control of cell proliferation and xylem differentiation in cultured tissues of Glycine max var. Biloxi. Plant Physiol. 44, 871–880.

Freibort, I., Kowalska, M., Hlusa, T., Freibortova, J. and Galuszkova, P. (2011) Evolution of cytokinin biosynthesis and degradation. J. Exp. Bot. 62, 2431–2452.

Fukuzawa, T., Koga, I., Adachi, T., Kishi, K. and Sono, Y. (2006) Efficient conversion of L-tryptophan to indole-3-acetic acid and/or tryptophol by some species of Rhizoctonia. Plant Cell Physiol. 37, 899–905.

Gay, G., Normand, L., Marmesse, R., Sotta, B. and Debaud, J.C. (1988) Role of indoleacetic acid lyse synthase in regulation of indoleacetic-acid pool size and virulence of Pseudomonas-syringae subsp savastani. J. Bacteriol. 170, 2367–2373.

Gogala, N. (1991) Regulation of mycorrhizal infection by hormonal factors produced by hosts and fungi. Experientia, 47, 331–340.

Graham, J.H. and Linderman, R.G. (1991) Ethylene biosynthesis in Fusarium oxysporum f. sp. lycopersici in tomato via 12-oxo-phytodienoic acid, salicylic acid, and flavonol accumulation. J. Plant Physiol. 179, 122–132.

Gust, A.A., Willmann, R., Debaud, J. and Nuber, I., Kowalska, M., Hluska, T., Fr.

Hebeloma cylindrosporum overproducer mutants of Moniliophthora perniciosa produces hormones and alters endogenous auxin and salicylic acid in infected coca leaves. FEMS Microbiol. Lett. 274, 238–244.

Kim, J.I., Murphy, A.S., Baek, D., Lee, S.W., Yun, D.J., Bressan, R.A. and Narasimhan, M.L. (2011) YUCCA6 over-expression demonstrates auxin function in delaying leaf senescence in Arabidopsis thaliana. J. Exp. Bot. 62, 3981–3992.

Kisiala, A., Laffont, C., Emery, R.J.N. and Frugier, F. (2013) Bioactive cytokinins are selectively secreted by Sinorhizobium meliloti modulating and nonmodulating strains. Mol. Plant–Microbe Interact. 26, 1225–1231.

Kloppholz, S., Kuhn, H. and Requena, N. (2011) A secreted fungal effector of Glium inadarticus promotes symbiotic biotrophy. Curr. Biol. 21, 1204–1209.

Kovač, M. and Zel, J. (1995) The effect of aluminum on cytokinins in the mycelia of Amanita muscaria. J. Plant Growth Regul. 14, 117–120.

Krol, P., Igielski, R., Pollmann, S. and Kępczyńska, E. (2015) Priming of seeds with methyl jasmonate induced resistance to hemi-biotrophic Fusarium oxysporum f.sp. lycopersici in tomato via 12-oxo-phytodienoic acid, salicylic acid, and flavonol accumulation. J. Plant Physiol. 179, 122–132.

Kulkarni, G.B., Sanjeev Kumar, S., Kirankumar, B., Santoshkumar, M. and Karegoudar, T.B. (2013) Indole-3-acetic acid biosynthesis in Fusarium delphinoidei strain GFP, a causal agent of wilt in chickpea. Appl. Biochem. Biotechnol. 169, 1292–1305.

Kunzawa, T., Ueda, N., Maekawa, M., Kobayashi, K., Kojima, M., Nagato, Y., Sakakibara, H. and Koyuzka, J. (2007) Direct control of shoot meristem activity by a cytokinin-activating enzyme. Nature, 445, 652–655.

Laurans, F., Pepin, R. and Gay, G. (2001) Fungal auxin overexpression affects the anatomy of Hebeloma cylindrosporum–Pinus pinaster ectomycorrhizas. Tree Physiol. 21, 533–540.

Lee, B.O. (1961) Effect of kinetin on the fertility of some strains of Neurospora crassa. Nature, 192, 288–289.

Lejohn, H.B. and Stevenson, R.M. (1973) Cytokinins and magnesium ions may control the flow of metabolites and calcium ions through fungal cell membranes. Biochim. Biophys. Acta, 324, 275–293.

Mills, L.J. and Van Staden, J. (1991) Hydroxylated jasmonic acid by hosts and fungi. Can. J. Microbiol. 37, 243–250.

Morrison, E.N., Knowles, S., Hayward, A., Thorn, R.G., Saville, B.J. and Emery, P. (2010) Analysis of cytokinin responses in the pathosystem: relationships between abscisic acid and cytokinin levels and xylem virulence in infected cobe tissue. PLoS One, 10, e0130945.

Morrison, E.N., Knowles, S., Hayward, A., Thorn, R.G., Saville, B.J. and Emery, R.J.N. (2010) Detection of phytohormones in temperate forest fungi predicts conditional infection and density dependence of pather Zooydiploid theaeome. Phytochemistry, 30, 4049–4051.

Miersch, O., Neider, G. and Sembdner, G. (1991) Hydroxylated jasmonic acid and related compounds from Botryodiplodia theaeome. Phytochemistry, 30, 3815–3817.

Mitsi, L.S. and Van Staden, J. (1978) Extraction of cytokinins from maize, smut tumors of maize and Ustilago maydis cultures. Physiol. Plant Pathol. 13, 73–80.

Nakamura, T., Kawanabe, Y., Takiyama, E., Takahashi, N. and Murayama, Y. (1978) Effects of auxin and gibberelin on conidial germination in Neurospora crassa. Plant Cell Physiol. 19, 705–709.

Nakamura, T., Tomita, K., Kawanabe, Y. and Murayama, Y. (1978) Effects of auxin and gibberelin on conidial germination in Neurospora crassa II: "conidial density effect" and auxin. Plant Cell Physiol. 23, 1363–1369.

Kępczyńska, E. (1994) Involvement of ethylene in spore germination and mycelial growth of Alternaria alternata. Mycol. Res. 98, 118–120.

Kettner, J. and Dorfling, K. (1995) Biosynthesis and metabolism of abscisic-acid in tomato leaves infected with Botrytis cinerea. Planta, 196, 627–634.

Kilaru, A., Bailey, B.A. and Hasenstein, K.H. (2007) Moniliosphaera perniciosa produces hormones and alters endogenous auxin and salicylic acid in infected coca leaves. FEMS Microbiol. Lett. 274, 238–244.
Nambara, E. and Marion-Poll, A. (2005) Abscisic acid biosynthesis and catabolism. Annu. Rev. Plant Biol. 56, 165–185.

Norman, S.M., Bennett, R.D., Maier, V.P. and Poling, S.M. (1983) Cytokinins inhibit abscisic acid biosynthesis in Cercospora rosicola. Plant Sci. Lett. 28, 255–263.

Ok, M., Miyamom ov après le virus. Pl. J. Microbiol. 53, 111–116.

Siddique, S., Radakovits, Z.S., De La Torre, C.M., Chronis, D., Novak, O., Ramireddy, E., Holbein, J., Matera, C., Hutten, M., Gutzbrod, P., Anjam, M.S., Rozanska, E., Habash, S., Elshar, A., Sobczak, M., Kakimoto, T., Strnad, M., Schmulling, T., Mitch, M.G. and Gruler, F.M. (2015) A parasitic nemadote releases cytokinin that controls cell division and orchestrates feeding site formation in host plants. Proc. Natl. Acad. Sci. USA 112, 2669–12674.

Siemens, J., Keller, I., Sarz, J., Kunz, S., Schuller, A., Nagel, W., Schmulling, T., Parmiske, M. and Ludwig-Müller, J. (2008) Transcriptome analysis of Arabidopsis. Stubsroot indicates a key role for cytokinins in disease development. Mol. Plant–Microbe Interact. 19, 480–494.

Sievers, V., Kokkelink, L., Smedsgaard, J. and Tardlinsky, P. (2006) Identification of an assic acid gene cluster in the grey mold Botrytis cinerea. Appl. Environ. Microbiol. 72, 4619–4626.

Slaugenhaup, S.A., Mill, J., Leune, M., Cuajungco, M.P., Gill, S.P., Hima, M., Quintero, F., Axelrod, F.B. and Gussella, J.F. (2004) Rescue of a human mRNA splicing defect by the plant cytokinin kinetin. Hum. Mol. Genet. 13, 429–436.

Spence, C. and Bais, H. (2015) Role of plant growth regulators as chemical signals in plant–microbe interactions: a double edged sword. Curr. Opin. Plant Biol. 27, 52–58.

Spence, C.A., Lakshmanan, V., Donofrio, N. and Bais, H.P. (2015) Crucial roles of abscisic acid biogenesis in virulence of rice blast fungus Magnaporthe oryzae. Plant. Sci. 6, 1–13.

Spilvallo, R., Fischer, U., Gobel, C., Feussner, I. and Karlowsky, P. (2009) Truffles regulate plant root morphogenesis via the production of auxin and ethylene. Plant Physiol. 150, 2018–2029.

Strzelczuk, E., Kampert, M. and Pacщlewski, R. (1994) The influence of pH and temperature on ethylene production by mycorrhizal fungi of pine. Mycorrhiza, 4, 193–196.

Stuft, L., Schmidt, F.J., John, L., Sieber, C.M., Connolly, L.R., Niehaus, E.-M., Freitag, M., Humph, H.-U. and Tardlinsky, B. (2013) Two histone deacetylases, FIH4a1 and FIH4a2, are important for Fusarium fujikuri secondary metabolism and virulence. Appl. Environ. Microbiol. 79, 2719–2734.

Swain, S.M. and Singh, D.P. (2005) Tall tales from sly dwarves: novel functions of gibberellins in plant development. Trends Plant Sci. 10, 123–129.

Tomita, K., Murayama, T. and Nakamura, T. (1984) Effects of auxin and gibberellin on elongation of young hyphae in Neurospora crassa. Mycol. Sci. 25, 355–358.

Ton, J., Flors, V. and Mauch-Mani, B. (2009) The multifaceted role of ABA in disease resistance. Trends Plant Sci. 14, 310–317.

Tsvakelova, E.A., Klimova, S.V., Cherynevitska, T.A. and Netrusov, A.I. (2006) Microbial producers of plant growth stimulants and their practical use: a review. Appl. Biochem. Microbiol. 42, 117–126.

Tsvakelova, E., Oser, E., Oren-Young, L., Israeli, M., Sasso, Y., Tidzynsky, B. and Sharon, A. (2012) Identification and functional characterization of indole-3-acetic acid-mediated IAA biosynthesis in plant-associated Fusarium species. Fungal Genet. Bioinf. 49, 48–57.

Tsigissionis, D.I. and Keller, N.P. (2007) Oxylipins as developmental and host–fungal communication signals. Trends Microbiol. 15, 109–118.

Tidzynsky, B. (2005) Gibberellin biosynthesis in fungi: genes, enzymes, evolution, and impact on biotechnology. Appl. Microbiol. Biotechnol. 66, 597–611.

Ulrich, C. (1960) Auxin production by mycorrhizal fungi. Physiol. Plant. 13, 429–443.

Van Bockhaven, J., Spence, C.A., Lakshmanan, V., Donofrio, N., Strnad, M., Azano, T., Kikuchi, S., Hofte, M. and De Vleesschauwer, D. (2015) Silicon induces resistance to the brown spot fungus Cochliobolus miyabeanus by preventing the pathogen from hijacking the rice ethylene pathway. New Phytol. 206, 761–773.

Vanneste, S. (2005) Auxin coordinates cell division and cell fate specification during lateral root initiation. Plant Physiol. 132, 139–146.

Wingler, A., Leegood, R.C., Lea, P.J. and Quick, W.P. (1998) Regulation of leaf senescence by cytokinin, sugars, and light. Plant Physiol. 116, 329–333.

Wullschleger, S. and Reid, C.P.P. (1990) Implication of ectomycorrhizal fungi in the cytokinin relations of Loblolly pine (Pinus-taeda). Plant Physiol. 94, 6–4.

Yanagishima, N. (1965) Role of gibberellic acid in the growth response of yeast cells (Saccharomycyces cerevisae). Sci. in Curr. Opin. Plant Biol. 10, 372–379.

Zhang, X., Xu, M., Wang, C., Wang, X., Li, X., Zhang, H. and Guo, X. (2010) Auxin biosynthesis and its role in plant development. Annu. Rev. Plant Biol. 61, 49–64.

Zsagov, A., Lambais, M.R., Benedito, V.A., Figueira, A.V.D.O. and Peres, L.E.P. (2008) Reduced arbuscular mycorrhizal colonization in tomato ethylene mutants. Sci. Agri. 65, 259–267.