

# Control of cell elongation and stress responses by steroid hormones and carbon catabolic repression in plants

Klaus Salchert, Rishikesh Bhalerao, Zsuzsanna Koncz-Kálmán and Csaba Koncz\*

Max-Planck Institut für Züchtungsforschung, Carl-von-Linné-Weg 10, D-50829 Köln, Germany

Molecular analysis of *Arabidopsis* mutants displaying hypocotyl elongation defects in both the dark and light revealed recently that steroids play an essential role as hormones in plants. Deficiencies in brassinosteroid biosynthesis and signalling permit photomorphogenic development and light-regulated gene expression in the dark, and result in severe dwarfism, male sterility and de-repression of stress-induced genes in the light. A cytochrome P450 steroid hydroxylase (CYP90) controls a rate limiting step in brassinosteroid biosynthesis and appears to function as a signalling factor in stress responses. Another key step in steroid biosynthesis is controlled by the *Arabidopsis* SNF1 kinases that phosphorylate the 3-hydroxy-3methylglutaryl-CoA reductase. The activity of SNF1 kinases is regulated by PRL1, an evolutionarily conserved  $\alpha$ -importin-binding nuclear WD-protein. The *prl1* mutation results in cell elongation defects, de-repression of numerous stress-induced genes, and augments the sensitivity of plants to glucose, cold stress and several hormones, including cytokinin, ethylene, auxin, and abscisic acid.

**Keywords:** brassinosteroids; glucose repression; CYP90; PLR1; SNF1 kinase; control of transcription

## 1. REGULATION OF CELL ELONGATION BY LIGHT AND BRASSINOSTEROIDS

Hypocotyl elongation of seedlings during skotomorphogenesis in the dark is inhibited by light signals perceived by the photoreceptor phytochrome A (phyA) controlling the onset of photomorphogenesis and de-etiolation (Mustilli & Bowler 1997). As for light signals, ethylene also inhibits hypocotyl elongation in the dark, but prevents the opening of apical hook of cotyledons (Ecker 1995). Induction of photomorphogenesis by phyA-activation is repressed by glucose signalling (Barnes *et al.* 1996) involving the functions of, as yet, unknown *SUN* genes (Dijkwel *et al.* 1997). Mutations in the *DET* (de-etiolated) and *COP* (constitutive photomorphogenesis) genes induce photomorphogenesis in the dark (Chory *et al.* 1996). The *DET* and *COP* functions act downstream of the photoreceptors and their absence results in the activation of light-induced genes, as well as genes involved in general stress responses (von Armin & Deng 1996; Mayer *et al.* 1996). The *DET*-*COP* functions also seem to affect cytokinin signalling. For example, cytokinin signalling enhances, synergistically, the light-induced onset of photomorphogenesis, and cytokinins phenocopy the *det1* mutation (Chory *et al.* 1994). In the dark, the *COP1* WD-protein and *DET1* are located in the nucleus and probably function as general repressors of light-regulated genes. *COP1* and *DET1* act in concert with elements of the *COP9* complex that shows a similarity to chromatin remodelling modulator complexes of RNA polymerase II (Chamovitz *et al.* 1996; Wilson *et al.* 1996).

Whereas the *DET1* and *COP* functions are needed for safe-guarding the light- and stress-regulated pathways in the dark, the *DET2*, *CPD1* (constitutive photomorphogenic dwarf), *DIM1* (diminuto), and *BR11* (brassinosteroid insensitivity) genes are required for positive control of skotomorphogenesis. *DET2*, *DIM1*, and *CPD1* code for enzymes involved in the biosynthesis of plant steroid hormones, termed brassinosteroids (BRs) (Sakurai & Fujioka 1997; Yokota 1997), whereas *BR11* is required for BR-perception (Li & Chory 1997). Mutations affecting BR biosynthesis and signalling result in the inhibition of hypocotyl elongation in the dark, and cause severe dwarfism in light-grown plants. *DET2* is a  $5\alpha$ -steroid reductase that is required for the production of campestanol by catalysing the synthesis of (24*R*)-24-methyl-5 $\alpha$ -cholestan-3-one from (24*R*)-24-methylcholestan-4-en-3-one. *DET2* mediates also the conversion of progesterone, teasterone, and androstendione to their 5 $\alpha$ -reduced forms in animal cells. Similarly, animal 5 $\alpha$ -steroid reductases can complement the *Arabidopsis det2* mutation, indicating a remarkable conservation of functions in plant and animal steroid biosynthesis (Li *et al.* 1997). Our studies show that the *CPD* gene codes for a cytochrome P450 enzyme (CYP90) involved in C23-hydroxylation of cathasterone to teasterone, whereas *DIM1* is probably involved in the biosynthesis of typhasterol (Szekeres *et al.* 1996).

## 2. SIGNALLING FUNCTION OF CYP90 IN BRASSINOSTEROID BIOSYNTHESIS

Complete loss of the *CPD* function results in the de-repression of light regulated-genes (e.g. *RBCS* and

\*Author for correspondence (koncz@mpiz-koeln.mpg.de).

*CAB*) in the dark, as well as activation of a set of stress-regulated genes (e.g. chalcone synthase, lipoxygenase, alcohol dehydrogenase and so on) in the light. This indicates that brassinosteroids are not only required for stimulation of cell elongation by controlling the activity of genes involved in cell wall biosynthesis (Clouse 1996), but also exert a negative control over several pathways regulated by stress and hormonal stimuli. Overexpression of the CYP90 steroid hydroxylase in transgenic plants induces the expression of pathogenesis-related genes independently of BR production. This suggests that CYP90 may also perform a signalling function. Recent data demonstrate that expression of the *CPD* gene is feedback regulated by BRs at the level of transcription. The fact that protein synthesis inhibitors, such as cycloheximide, prevent down-regulation of the *CPD* gene by BRs indicates that BR-mediated signalling requires *de novo* synthesis of a repressor (Mathur *et al.* 1998). Feedback regulation of the *CPD* gene by BRs shows a remarkable analogy to oxysterol signalling in mammals. Oxysterols are hydroxylated cholesterol derivatives that, by analogy to BRs, down-regulate the transcription of steroid hydroxylase genes in mammals (Honda *et al.* 1993; Janowski *et al.* 1996; Lala *et al.* 1997). Oxysterols inhibit the proteolytic processing of membrane-bound sterol regulatory element-binding factors (SREBPs) controlling the transcription of genes involved in steroid biosynthesis, including the 3-hydroxy-3-methylglutaryl-CoA reductase (HMGR) (Brown & Goldstein 1997). It is therefore intriguing that CYP90 has been found to interact in the yeast two-hybrid system with a sterol-binding protein, as well as with RING-finger factors showing homology to protease inhibitors (Z. Koncz-Kálmán, unpublished data).

### 3. THE *CPD* GENE IS REGULATED BY *PRL1* IN *ARABIDOPSIS*

By characterizing the regulation of the *CPD* gene in diverse *Arabidopsis* mutants, we have found that, as in BRs, a mutation in *pleiotropic regulatory locus-1* (*PRL1*) down-regulates transcription of the *CPD* gene in light-grown *Arabidopsis* plants. The *PRL1* gene codes for a WD-protein that, by analogy to COP1, functions as a negative regulator of a set of light-, hormone-, and stress-regulated genes (Németh *et al.* 1998). Mutation of *PLR1* results in complex phenotypic defects, including the inhibition of hypocotyl elongation in the dark. Intriguingly, whereas the *det1* mutation is phenocopied by cytokinin in the dark, the phenotype of the *prll* mutation is mimicked by cytokinin treatment of wild-type plants only in the light. The *prll* mutation results in hypersensitivity to glucose and sucrose, as well as transcriptional de-repression of genes that are positively or negatively regulated by glucose, or cytokinin, or both. The *prll* mutation also augments the sensitivity of seedlings to auxin, ethylene, abscisic acid, and cold temperature. As a result of these regulatory alterations, root elongation of the *prll* mutant is inhibited in both the dark and light. In addition, *prll* roots produce ectopic root hairs and show de-repressed initiation of side-root development.

### 4. *PRL1* IS A CONSERVED $\alpha$ -IMPORTIN-BINDING NUCLEAR PROTEIN THAT FUNCTIONS AS A REGULATOR OF *ARABIDOPSIS* SNF1 KINASES

*PRL1* encodes a basically charged protein of 54 kDa that is found in both a free cytoplasmic form and in association with microsomal (endoplasmic reticulum and nuclear) membranes. Immunolocalization studies show that a proportion of *PRL1* protein is located in the nucleus in *Arabidopsis*. *PRL1* carries seven WD-40 repeats that share over 60% identity with *PRL1* orthologues found in yeast, *Caenorhabditis*, *Drosophila*, and mouse. Recently, a *PRL1* homologue (GenBank AF044333) was located on human chromosome 4q31.2. Functional conservation of *PRL1* orthologues in mammals is indicated by the observation that *PRL1* is also imported into the nucleus when expressed in human cells. *PRL1* functions as a receptor for activated human protein kinase C *in vitro* (i.e. RACK, Ron & Mochly-Rosen 1995). Specific binding of *PRL1* to activated protein kinase C- $\beta$ II, but not to PKC- $\beta$ I, suggests that *PRL1* orthologues may regulate glucose signalling in mammals where differential splicing, expression, and nuclear transport of PKC- $\beta$ II are induced by insulin signalling (Chalfant *et al.* 1995).

Genetic screening for *PRL1* interacting proteins in the yeast two-hybrid system revealed that *PRL1* specifically binds a novel  $\alpha$ -importin, ATHKAP2 (Németh *et al.* 1998). ATHKAP2 does not bind to proteins containing monopartite and bipartite nuclear localization signals (NLS). Thus, although a variant of the SV40-type NLS is carried by the C-terminus of *PLR1*, binding of ATHKAP2 to *PRL1* in the yeast two-hybrid system is probably not owing to a recognition of *PRL1*-NLS, but rather reflects a regulatory interaction. *PRL1*-binding to human PKC- $\beta$ II also suggests that *PRL1* may in fact serve as a protein kinase-targeting subunit involved in the control of nuclear import by either phosphorylation of NLS sequences or  $\alpha$ -importin.

Homologues of the yeast Ser-Thr protein kinase SNF1p have also been identified as *PRL1*-binding proteins in the yeast two-hybrid system. In yeast, SNF1p is a master kinase in glucose signalling and its function is required for de-repression of glucose-repressible genes (reviewed by Ronne (1995)). Yeast SNF1p controls the phosphorylation, and thereby nuclear localization, of MIG1p that acts as a repressor of glucose-regulated genes by recruiting the general transcriptional repressor complex TUP1-SSN6 (Tzamarias & Struhl 1995). Although TUP1 is a prototype of WD-protein repressors showing functional analogy to *PRL1*, the *tup1* mutations cannot be complemented by the *Arabidopsis PRL1* cDNA. Binding of *PRL1* to yeast and *Arabidopsis* SNF1 kinases is regulated by glucose. *PRL1*, as the yeast SNF1-activator SNF4, shows an enhanced binding to SNF1p in the absence of glucose, whereas the *PRL1*-SNF1 interaction is inhibited when yeast is grown in the presence of glucose. The fact that *Arabidopsis* SNF1 homologues can functionally complement the yeast *snf1* mutation and suppress the *snf4* deficiency demonstrates the conservation of SNF1 and *PRL1* functions between yeast and plants.

*Arabidopsis* SNF1 homologues Akin10 and Akin11, similarly to other plant SNF1-kinases, are capable of phosphorylating proteins carrying the SAMS peptide motif,

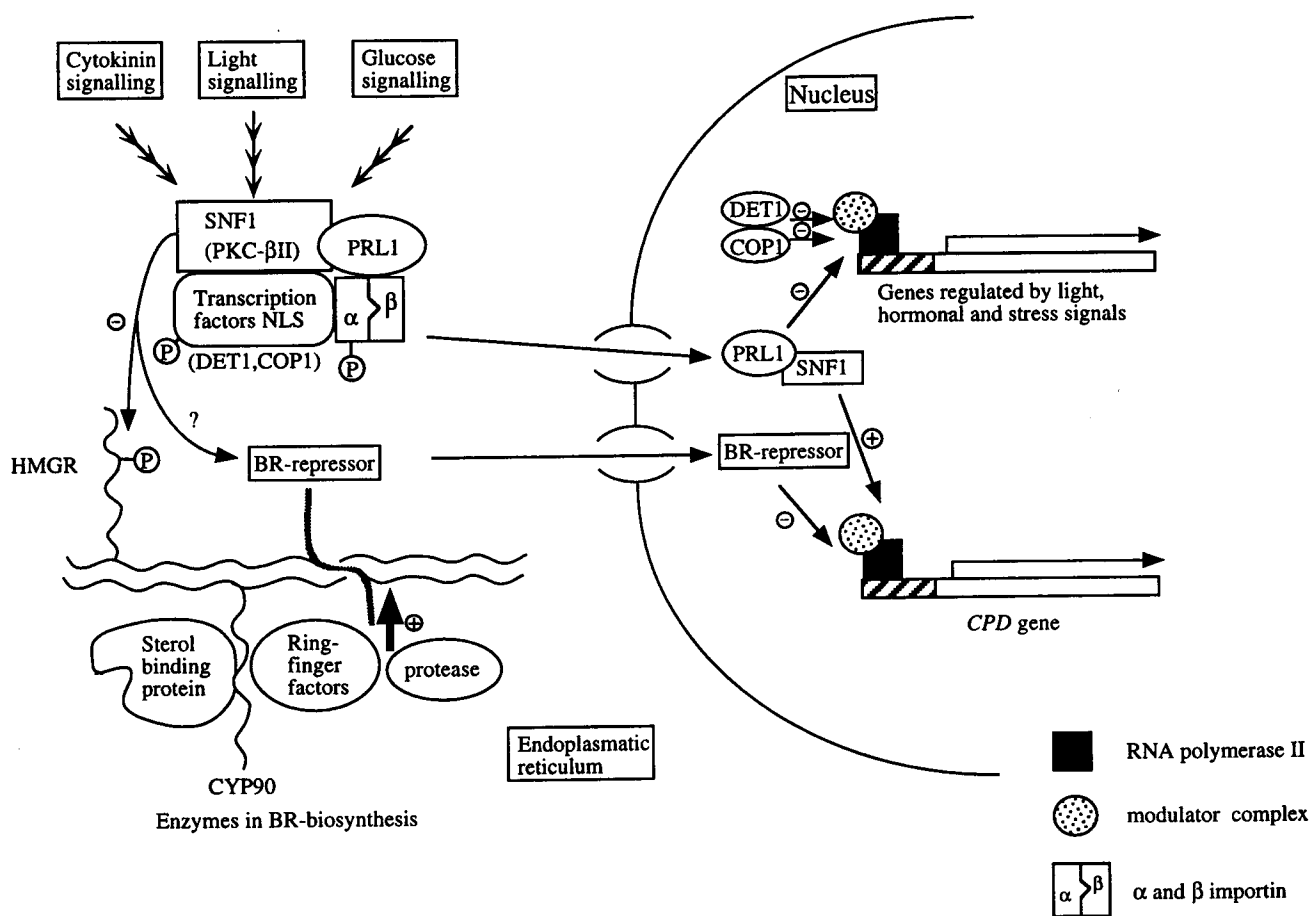


Figure 1. Regulatory connections between glucose and steroid signalling: a model. As outlined in the text, the  $\alpha$ -importin-binding PRL1 protein is a regulator of the SNF1 kinase, and functions as a specific receptor for human protein kinase C- $\beta$ II *in vitro*. PRL1 may target protein kinases to complexes of  $\alpha$  and  $\beta$  importins and affect the regulation of nuclear import by phosphorylation of nuclear localization sequences (NLS) of transcription regulatory proteins or  $\alpha$ -importins. The *CPD* gene controls a rate-limiting step in BR biosynthesis. Negative feedback regulation of *CPD* expression by BRs requires the synthesis of a BR-repressor. The *CPD* gene is down-regulated in the *prll* mutant, suggesting that PRL1 controls the transcription of *CPD*. The PRL1 controlled SNF1 kinase down-regulates the activity of HMGR by phosphorylation and thereby may modulate the first committed step in steroid biosynthesis. The *CPD* gene product, CYP90, interacts in the yeast two-hybrid system with an oxysterol-binding protein and signalling factors carrying RING-finger motives of protease inhibitors. CYP90 may thus be part of a mechanism that, by analogy to oxysterol signalling in mammals (Brown & Goldstein 1997), controls the activity of a membrane-bound steroid regulatory factor by, for example, proteolytic processing or phosphorylation.

including HMGR (Dale *et al.* 1995). Phosphorylation by SNF1 inhibits the activity of HMGR catalysing the first committed step in steroid biosynthesis. As in yeast, the activity of Akin10 and Akin11 SNF1-kinases is negatively regulated in *Arabidopsis* by glucose in the dark. In contrast, glucose increases the activity of SNF1 kinases in light-grown *Arabidopsis* seedlings, indicating a connection with light signalling. In the light, the activity of SNF1 kinases is three- to fivefold higher in *prll* than in wild-type plants, showing that PRL1 is a negative regulator of SNF1 kinases in light-grown plants. Abnormal activation of the SNF1 kinases thus correlates well with cell elongation defects and down-regulation of the *CPD* gene observed in the *prll* mutant. In the dark, the SNF1 kinase activity is lower in *prll* than in wild-type plants indicating that PRL1 is a positive modulator of SNF1 kinase in dark-grown plants (Bhalerao *et al.* 1998). PRL1 inhibits *in vitro* the phosphorylation of SAMS peptide by both *Arabidopsis* Akin10 and Akin11 SNF1 kinases. Therefore, it is likely that *in vivo* regulation of SNF1 kinases by PRL1 involves

light-, and glucose-dependent post-translational modifications, such as phosphorylation by activating kinases, and dephosphorylation by protein phosphatases. This conclusion is supported by data showing that the levels of protein phosphatase type 1 and 2a are significantly reduced in the light-grown *prll* mutant, as well as that PRL1 has been found to interact also with a specific  $\text{Ca}^{2+}$ -dependent kinase.

## 5. CONCLUSIONS

In this review, we aimed to give a brief insight into recent studies of novel signalling functions coordinating plant responses to metabolic, hormonal and environmental stimuli. In particular, regulatory relations (see figure 1) between two seemingly unrelated signalling proteins, CYP90 in steroid biosynthesis and PRL1 in the control of glucose repression, have been discussed. Research in progress shows that the fragmentary relations described here will be soon supplemented by many more

partners and regulatory connections. Thus, genetic analyses suggest that the *prll* mutation is exacerbated by the *ampl* function regulating cytokinin production and cell division of meristems (Chaudhury *et al.* 1993). In addition, the *ein2* mutation that confers cytokinin resistance and ethylene insensitivity (Ecker 1995) appears to be epistatic to *prll* in the dark, but this epistatic relation is reversed in the light (Németh *et al.* 1998). Biochemical and genetic data demonstrate that PRL1 is a regulator of many diverse genes, including *CPD* in BR biosynthesis. *CPD* may also specify a signalling function, because its overexpression activates a set of pathogenesis-related genes, and because its product, the CYP90 C23-steroid hydroxylase, interacts with novel signalling proteins. Thus, CYP90 may, in fact, control a pathway of stress signalling in addition to being essential for the biosynthesis of BR hormones. PRL1 is a regulator of SNF1 kinases that control the expression of glucose-, and cytokinin-responsive genes by overcoming the regulation of these genes by other signals. Analysis of the PRL1 function not only supports the notion that light, glucose, and cytokinin signalling are tightly cross-connected (Chory *et al.* 1996; von Armin & Deng 1996), but also suggests a considerable conservation of eukaryotic regulatory mechanisms modulating nuclear import by protein kinases and their targeting subunits, and cross-talk between glucose and steroid signalling.

## REFERENCES

- Barnes, S. A., Nishizawa, N. K., Quaggio, R. B., Whitelam, G. C. & Chua, N.-H. 1996 Far-red light blocks greening of *Arabidopsis* seedlings via a phytochrome A-mediated change in plastid development. *Pl. Cell* **8**, 601–615.
- Bhalerao, R., Salchert, K., Bakó, L., Murakana, T., Maschida, Y., Ökrész, L., Schell, J. & Koncz, C. 1998 PRL1-binding regulates the activity of glucose responsive plant SNF1 protein kinase homologs. (In the press.)
- Brown, M. S. & Goldstein, J. L. 1997 The SREBP pathways: regulation of cholesterol metabolism by proteolysis of a membrane-bound transcription factor. *Cell* **89**, 331–340.
- Chalfant, C. E., Mischak, H., Watson, J. E., Winkler, B. C., Goodnight, J., Farese, R. V. & Cooper, D. R. 1995 Regulation of alternative splicing of protein kinase C- $\beta$  by insulin. *J. Biol. Chem.* **270**, 13 326–13 332.
- Chamovitz, D. A., Wei, N., Osterlund, M. T., von Arnim, A. G., Staub, M. T., Matsui, M. & Deng, X.-W. 1996 The COP9 complex, a novel multisubunit nuclear regulator involved in light control of a plant developmental switch. *Cell* **86**, 115–121.
- Chaudhury, A. M., Letham, S., Craig, S. & Dennis, E. S. 1993 *ampl*—a mutant with high cytokinin levels and altered embryonic pattern, faster vegetative growth, constitutive photomorphogenesis and precocious flowering. *Plant J.* **4**, 907–916.
- Chory, J., Reinecke, D., Sim, S., Washburn, T. & Brenner, M. 1994 A role for cytokinins in de-etiolation in *Arabidopsis*. *Pl. Physiol.* **104**, 339–347.
- Chory, J. (and 11 others) 1996 From seed germination to flowering, light controls plant development via the pigment phytochrome. *Proc. Natn. Acad. Sci. USA* **93**, 12 066–12 071.
- Clouse, S. D. 1996 Molecular genetic studies confirm the role of brassinosteroids in plant growth and development. *Plant J.* **10**, 1–8.
- Dale, S., Arró, M., Becerra, B., Morrice, N. G., Boronat, A., Hardie, D. G. & Ferrer, A. 1995 Bacterial expression of the catalytic domain of 3-hydroxy-3-methylglutaryl-CoA reductase (isoform HMGR1) from *Arabidopsis thaliana*, and its inactivation by phosphorylation at Ser577 by *Brassica oleracea* 3-hydroxy-3-methylglutaryl-CoA reductase kinase. *Eur. J. Biochem.* **233**, 506–513.
- Dijkwel, P. P., Huijser, C., Weisbeek, P. J., Chua, N.-H. & Smeekens, S. C. M. 1997 Sucrose control of phytochrome A signaling in *Arabidopsis*. *Pl. Cell* **9**, 583–595.
- Ecker, J. 1995 The ethylene signal transduction pathway in plants. *Science* **268**, 667–675.
- Honda, S., Morohashi, K., Nomura, M., Takeya, H., Kitajama, M. & Omura, T. 1993 Ad4BP regulating steroidogenic P450-gene is a member of steroid hormone receptor superfamily. *J. Biol. Chem.* **268**, 7494–7502.
- Janowski, B. A., Willy, P. J., Devi, T. R., Falck, J. R. & Mangelsdorf, D. J. 1996 An oxysterol signalling pathway mediated by the nuclear receptor LXR $\alpha$ . *Nature* **383**, 728–731.
- Lala, D., Syka, P. M., Lazarchik, S. B., Mangelsdorf, D. J., Parker, K. L. & Heyman, R. A. 1997 Activation of the orphan nuclear receptor steroidogenic factor 1 by oxysterols. *Proc. Natn. Acad. Sci. USA* **94**, 4895–4900.
- Li, J. & Chory, J. 1997 A putative leucine-rich repeat receptor kinase involved in brassinosteroid signal transduction. *Cell* **90**, 929–938.
- Li, J., Biswas, M. G., Chao, A., Russel, D. W. & Chory, J. 1997 Conservation of function between mammalian and plant steroid 5 $\alpha$ -reductases. *Proc. Natn. Acad. Sci. USA* **94**, 3554–3559.
- Mathur, J. (and 11 others) 1998 Transcription of the *Arabidopsis CPD* gene, encoding a steroidogenic P450, is negatively regulated by brassinosteroids. *Plant J.* **14**, 593–602.
- Mayer, R., Raventos, D. & Chua, C.-H. 1996 *det1*, *cop1*, and *cop9* mutations cause inappropriate expression of several gene sets. *Pl. Cell* **8**, 1951–1959.
- Mustilli, A. C. & Bowler, C. 1997 Tuning in to the signals controlling photoregulated gene expression in plants. *EMBO J.* **16**, 5801–5806.
- Németh, K. (and 14 others) 1998 Pleiotropic control of glucose and hormone responses by PRL1, a nuclear WD-protein, in *Arabidopsis*. (In the press.)
- Ron, D. & Mochly-Rosen, D. 1995 An autoregulatory region of protein kinase C: the pseudoanchoring site. *Proc. Natn. Acad. Sci. USA* **92**, 492–496.
- Ronne, H. 1995 Glucose repression in fungi. *Trends Genet.* **11**, 12–17.
- Sakurai, A. & Fujioka, S. 1997 Studies on biosynthesis of brassinosteroids. *Biosci. Biotech. Biochem.* **61**, 757–762.
- Szekeres, M., Németh, K., Koncz-Kálmán, Z., Mathur, J., Kauschmann, A., Altmann, T., Rédei, G. P., Nagy, F., Schell, J. & Koncz, C. 1997 Brassinosteroids rescue the deficiency of CYP90, a cytochrome P450, controlling cell elongation and de-etiolation in *Arabidopsis*. *Cell* **85**, 171–182.
- Tzamarias, D. & Struhl, K. 1995 Distinct TPR motifs of Cyc8 are involved in recruiting the Cyc8-Tup1 corepressor complex to differentially regulated promoters. *Genes Dev.* **9**, 821–831.
- von Arnim, A. & Deng, X.-W. 1996 Light control of seedling development. *A. Rev. Pl. Physiol. Pl. Molec. Biol.* **47**, 215–243.
- Wilson, C. J., Chao, D. M., Imbalzano, A. N., Schnitzler, G. R., Kingston, R. E. & Young, R. A. 1996 RNA polymerase II holoenzyme contains SWI/SNF regulators involved in chromatin remodeling. *Cell* **84**, 235–244.
- Yokota, T. 1997 The structure, biosynthesis and function of brassinosteroids. *Trends Pl. Sci.* **2**, 137–143.