Development 140, 1147-1151 (2013) doi:10.1242/dev.087650

Gibberellin signaling in plants

Jean-Michel Davière and Patrick Achard*

Summary

The plant hormone gibberellin (GA) regulates major aspects of plant growth and development. The role of GA in determining plant stature had major impacts on agriculture in the 1960s, and the development of semi-dwarf varieties that show altered GA responses contributed to a huge increase in grain yields during the 'green revolution'. The past decade has brought great progress in understanding the molecular basis of GA action, with the cloning and characterization of GA signaling components. Here, we review the molecular basis of the GA signaling pathway, from the perception of GA to the regulation of downstream genes.

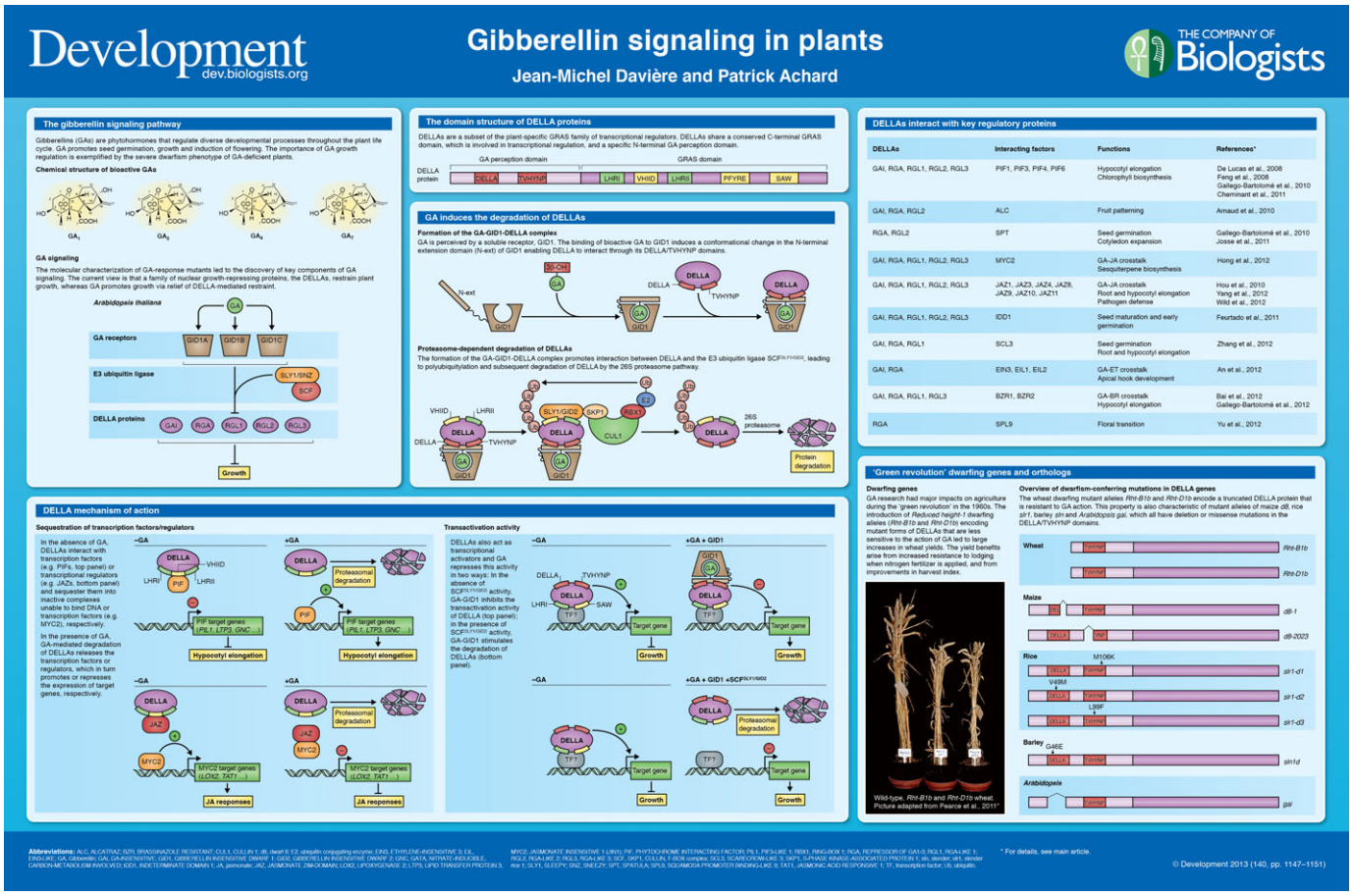
Key words: GA signaling, GID1, DELLA, $SCF^{SLY1/GID2}$, plant growth

Institut de Biologie Moléculaire des Plantes, Centre National de la Recherche Scientifique, Unité Propre de Recherche 2357, Conventionné avec l'Université de Strasbourg, 67084 Strasbourg, France.

*Author for correspondence (patrick.achard@ibmp-cnrs.unistra.fr)

Introduction

Gibberellins (GAs) are plant hormones that are essential for many developmental processes in plants, including seed germination, stem elongation, leaf expansion, trichome development, pollen maturation and the induction of flowering (Achard and Genschik, 2009). Hence, mutant plants that are deficient in GA exhibit a dwarf and late-flowering phenotype, and treating these plants with GA restores normal growth. Historically, GA was first identified in the pathogenic fungus *Gibberella fujikuroi*, the causal agent of the 'foolish-seedling' disease of rice, causing excessive elongation of infected plants (Yabuta and Sumiki, 1938). Since its original discovery, >130 GAs have been identified in plants, fungi and bacteria, although only a few GAs have biological activity (Yamaguchi, 2008); many non-bioactive GAs exist in plants, and these act as precursors for the bioactive forms or are de-activated metabolites. The major bioactive GAs, which include GA_1, GA_3, GA_4 and GA_7, are derived from a basic diterpenoid carboxylic acid skeleton, and commonly have a C3-hydroxyl group (Yamaguchi, 2008). During the past decade, most of the components of the GA signaling pathway have been identified from genetic screens in rice and *Arabidopsis*. Key components



(See poster insert)

include the GA receptor GIBBERELLIN INSENSITIVE DWARF1 (GID1), the DELLA growth inhibitors (DELLAs) and the F-box proteins SLEEPY1 (SLY1) and SNEEZY (SNZ) in *Arabidopsis* and GIBBERELLIN INSENSITIVE DWARF2 (GID2) in rice (Achard and Genschik, 2009). The current model of GA action proposes that DELLA proteins restrain plant growth whereas the GA signal promotes growth by overcoming DELLA-mediated growth restraint (Harberd, 2003; Achard and Genschik, 2009). Here, and in the accompanying poster, we provide an overview of the GA signaling cascade, highlighting the molecular events occurring from GA perception through to the activation of transcriptional networks that regulate plant development.

GA-response mutant categories

Physiological and biochemical analyses of GA response mutants with altered stem heights played a crucial role in the identification of early GA signaling components (Harberd et al., 2009). In contrast to GA-deficient mutants that have led to considerable insights into GA biosynthetic routes, GA-response mutants display altered response to GA and include mutants with alterations in both GA perception and GA signal transduction. Hence, GA-insensitive mutants display a similar dwarf phenotype to GA-deficient mutants, except that they fail to respond to exogenous GA. By contrast, mutants with constitutively active GA responses have taller stems, paler green leaves and lower fertility than do wild-type plants, irrespective of bioactive GA content. Genetic analysis of the GA-response mutant categories led to the current model that GA acts as an 'inhibitor of an inhibitor' (Harberd et al., 2009).

DELLA proteins: central repressors of GA-dependent processes

DELLAs, a subset of the plant-specific GRAS family of putative transcription regulators, are key intracellular repressors of GA responses (Peng et al., 1997; Silverstone et al., 1998; Ogawa et al., 2000; Ikeda et al., 2001; Chandler et al., 2002). DELLAs repress seed germination, growth and almost all known GA-dependent processes, whereas GA relieves their repressive activity (Achard and Genschik, 2009). Hence, lack of DELLA function confers complete suppression of GA-deficient phenotypes (Dill and Sun, 2001; King et al., 2001; Lee et al., 2002; Cheng et al., 2004; Tyler et al., 2004). Like all GRAS proteins, DELLAs share a conserved C-terminal GRAS domain that is involved in transcriptional regulation and is characterized by two leucine heptad repeats (LHRI and LHRII) and three conserved motifs, VHIID, PFYRE and SAW (Bolle, 2004). DELLAs are distinguished from the rest of the GRAS family by a specific N-terminal sequence containing two conserved domains: the DELLA domain (which gives them their name) and the TVHYNP domain. DELLAs are highly conserved among different species, including *Arabidopsis*, wheat, maize, rice and barley (Peng et al., 1997; Peng et al., 1999; Ikeda et al., 2001; Chandler et al., 2002). The *Arabidopsis* genome encodes five DELLAs (GA-INSENSITIVE, GAI; REPRESSOR OF GA1-3, RGA; RGA-LIKE1, RGL1; RGL2 and RGL3) that play distinct but also overlapping functions in repressing GA responses (Peng et al., 1997; Ikeda et al., 2001; Silverstone et al., 2001; Lee et al., 2002; Wen and Chang, 2002; Tyler et al., 2004). Hence, RGA and GAI repress vegetative growth and floral induction (Dill and Sun, 2001; King et al., 2001), RGL2 inhibits seed germination (Lee et al., 2002), RGA, RGL1 and RGL2 together modulate floral development (Cheng et al., 2004; Tyler et al., 2004), and RGL3 contributes to plant fitness during environmental stress (Achard et al., 2008; Wild et al., 2012).

Perception of the GA signal: formation of the GA-GID1-DELLA complex

Previous biochemical studies on oat aleurone cells suggested that the GA signal was perceived by a plasma membrane receptor (Lovegrove et al., 1998). More recently, the characterization of the GA-insensitive dwarfism *gid1-1* mutant allele in rice led to the discovery of the GA receptor, GID1 (Ueguchi-Tanaka et al., 2005). Unexpectedly, GID1 encodes a soluble nuclear GA receptor with homology to human hormone-sensitive lipases (Ueguchi-Tanaka et al., 2005). Whereas the rice genome contains a single *GID1* gene, there are three orthologs in *Arabidopsis* (*GID1A*, *GID1B* and *GID1C*) that display some overlapping functions (Nakajima et al., 2006). Crystal structure data revealed that GID1 contains a GA-binding pocket and a flexible N-terminal extension (Murase et al., 2008; Shimada et al., 2008). Upon the binding of bioactive GA, the C3-hydroxyl group of the GA molecule becomes hydrogen-bound to the Tyr31 residue of GID1, inducing a conformational change in the N-terminal extension to cover the GA pocket (Murase et al., 2008; Shimada et al., 2008). Once the pocket is closed, the upper surface of the lid binds with the DELLA and TVHYNP regions of DELLAs to form the GA-GID1-DELLA complex (Griffiths et al., 2006; Ueguchi-Tanaka et al., 2007; Willige et al., 2007). It is noteworthy that DELLA and TVHYNP regions are essential for the interaction because their deletion results in an inability of DELLAs to interact with GID1, despite the presence of GA (Griffiths et al., 2006; Willige et al., 2007).

GA promotes proteasome-dependent degradation of DELLAs

As discussed above, GA binding to GID1 stimulates the formation of the GA-GID1-DELLA complex. How then does GA suppress the repressive activity of DELLAs? A major breakthrough came from the discovery that GA stimulates the disappearance of DELLAs (Silverstone et al., 2001). Whereas in absence of GA, DELLAs accumulate and repress GA responses, the formation of the GA-GID1-DELLA complex stimulates the degradation of the DELLAs. The second step in furthering our understanding of GA signaling was the characterization of the rice GID2 and *Arabidopsis* SLY1 F-box proteins, based on analysis of the GA-insensitive dwarf phenotype of the loss-of-function mutants *gid2-1* and *sly1-10*, respectively (Sasaki et al., 2003; McGinnis et al., 2003). F-box proteins are components of the SCF (SKP1, CULLIN, F-BOX) E3 ubiquitin-ligase complexes, which catalyze the attachment of polyubiquitin chains to target proteins for their subsequent degradation by the 26S proteasome (Lechner et al., 2006). Based on yeast-interaction assays, the formation of the GA-GID1-DELLA complex has been proposed to induce conformational changes in the GRAS domain of DELLA that enhance recognition between the VHIID and LHRII motifs of DELLA and the F-box protein SLY1/GID2 (Hirano et al., 2010). In turn, the $SCF^{SLY1/GID2}$ complex promotes the ubiquitylation and subsequent destruction of DELLAs by the 26S proteasome, thereby relieving their growth-restraining effects (McGinnis et al., 2003; Sasaki et al., 2003; Dill et al., 2004; Fu et al., 2004). Thus, GA promotes growth by mediating the proteasome-dependent destabilization of DELLA proteins. Interestingly, recent evidence indicates that GA-mediated removal of DELLA proteins is required in a cell type-specific manner to ensure normal organ growth. For example, endodermis represents the primary GA-responsive tissue in roots (Ubeda-Tomás et al., 2008).

DELLAs interact with key regulatory proteins to modulate plant development

The mechanism by which DELLAs repress GA responses remained unclear until recently. An important function of DELLAs relies on their ability to interact with diverse classes of regulatory proteins. For example, DELLAs regulate hypocotyl elongation by interacting with PHYTOCHROME INTERACTING FACTORS (PIFs) (de Lucas et al., 2008; Feng et al., 2008; Gallego-Bartolomé et al., 2010) and BRASSINAZOLE RESISTANT1 (BZR1) (Bai et al., 2012; Gallego-Bartolomé et al., 2012), they control floral transition and fruit patterning by respectively interacting with SQUAMOSA PROMOTER BINDING-LIKE (SPL) and ALCATRAZ (ALC) factors (Yu et al., 2012; Arnaud et al., 2010), and they contribute to plant defense by interacting with JASMONATE ZIM-DOMAIN (JAZ) proteins (Hou et al., 2010; Yang et al., 2012; Wild et al., 2012). Through these interactions, DELLAs block the DNA-binding capacity of transcription factors (such as with PIFs) (de Lucas et al., 2008; Feng et al., 2008) or inhibit the activity of transcriptional regulators (such as with JAZs) (Hou et al., 2010). Meanwhile, GA relieves the repression of the DELLAs by promoting their degradation via the 26S proteasome pathway. More recently, DELLAs have been shown to interact with and inhibit the activity of numerous transcription regulators (Cheminant et al., 2011; Feurtado et al., 2011; Josse et al., 2011; Hong et al., 2012; An et al., 2012; Zhang et al., 2011). By doing so, GA signaling controls the expression of a multitude of target genes functioning in distinct pathways.

DELLAs can also function as transactivation factors

DELLAs are nuclear-localized repressors and are also likely to function as transcription factors (Ogawa et al., 2000). This is consistent with recent findings of RGA being able to associate with DNA (Zentella et al., 2007; Zhang et al., 2011). However, the moderate enrichment of promoter targets determined by chromatin immunoprecipitation and the lack of typical DNA-binding domains in DELLAs suggest that the association of DELLAs with gene promoters might involve additional factors. Further advances in understanding how DELLAs exert their transcriptional activity came from recent studies in rice. First, expression of the rice DELLA protein SLR1 fused to the activation domain of the herpes simplex virus protein VP16 severely compromises plant growth (but not when SLR1 is fused to a repressor domain), thus suggesting that DELLAs repress GA responses by also directly activating the transcription of downstream genes (Hirano et al., 2012). Second, experiments in yeast and rice revealed that GID1-SLR1 interaction suppresses the transactivation activity of SLR1 (Hirano et al., 2012). This observation is consistent with previous data showing that DELLA activity may be regulated by a proteolysis-independent mechanism, involving protein interaction with GA-GID1 (Ariizumi et al., 2008; Ueguchi-Tanaka et al., 2008). Third, mutations in the LHRI and SAW motifs alter the repressive effects of SLR1 without affecting its transactivation activity (Hirano et al., 2012), thus suggesting that the LHRI/SAW motifs might be involved in direct association with gene promoters or, most likely, with other transcription factors bound to DNA. Altogether, these results indicate that DELLA proteins function as transactivation factors and that GA represses their activity by a dual mechanism: in the absence of $SCF^{SLY1/GID2}$ activity, the GA-GID1 complex bound to DELLAs suppresses their transcriptional activity, whereas the presence of $SCF^{SLY1/GID2}$ stimulates the degradation of DELLAs.

The ‘green revolution’ dwarfing genes

The introduction of dwarfing genes into cereal crops was a major factor in breeding higher-yielding varieties during the ‘green revolution’, as they allowed more nitrogen fertilizer to be applied without leading to excessive stem elongation and subsequent lodging (Hedden, 2003). For example, the introduction of wheat mutant dwarfing alleles at *Reduced height-1* (*Rht-B1* and *Rht-D1*) loci led to large increases in worldwide grain yields during the 1960s, owing to improvements in both harvest index and lodging resistance (Hedden, 2003). Since then, *Rht-1* dwarfing alleles are still widely used in modern wheat cultivars. The wheat *Rht-B1b* and *Rht-D1b* alleles encode a mutant DELLA protein that confers semi-dominant GA-insensitive dwarfism (Peng et al., 1999). As with the *Arabidopsis gai* mutation (Peng et al., 1997), the GA-insensitivity of these mutants is conferred by the expression of a functional DELLA protein that lacks the DELLA-domain involved in the DELLA-GID1 interaction, resulting in a more stable DELLA protein (Peng et al., 1999; Dill et al., 2001; Griffiths et al., 2006; Ueguchi-Tanaka et al., 2007; Willige et al., 2007; Pearce et al., 2011). The importance of this trait was further emphasized by the identification of a wild array of GA-insensitive dwarf mutants in maize, rice and barley, all exhibiting a deletion or a missense mutation in the conserved N-terminus of DELLA or TVHYNP regions of DELLA, rendering the protein resistant to GA-induced degradation (Peng et al., 1999; Chandler et al., 2002; Asano et al., 2009).

Perspectives

Our knowledge of the GA signaling pathway has been considerably improved during this past decade, although a number of questions remain to be answered. In particular, previous studies have suggested the existence of additional GA-independent factors modulating the function of DELLAs. One such factor is the *O*-Linked *N*-acetylglucosaminyltransferase (OGT) encoded by *SPYNDLY* (*SPY*) (Jacobsen and Olszewski, 1993; Silverstone et al., 2007). OGTs catalyze *O*-linked *N*-acetylglucosamine (*O*-GlcNac) modification of target Ser/Thr residues of regulatory proteins. Loss-of-function *spy* alleles partially suppress the dwarf phenotype of GA-deficient mutants despite the accumulation of DELLAs (Shimada et al., 2006; Silverstone et al., 2007). Although it has not been demonstrated at the biochemical level, one plausible explanation for this phenotype is that *O*-GlcNac modification directly increases DELLA activity. Other studies have suggested that phosphorylation/dephosphorylation mechanisms might also play a crucial role in the regulation of DELLA protein activity and/or turnover (Fu et al., 2002; Sasaki et al., 2003; Gomi et al., 2004; Itoh et al., 2005; Hussain et al., 2005; Hussain et al., 2007). Recently, the casein kinase EARLY FLOWERING1 (EL1) was shown to phosphorylate SLR1 and to negatively regulate gibberellin signaling in rice (Dai and Xue, 2010). Although it becomes clear that post-translational modifications on DELLAs are important, the effects of *O*-GlcNAc activity and phosphorylation on DELLA function will require further investigation. Furthermore, using mathematical models, two recent studies revealed the importance of the transcriptional feedback in GA signaling and of the GA dilution mechanism for the dynamics of root cell elongation (Band et al., 2012; Middleton et al., 2012). Additional biochemical and system biology approaches will undoubtedly be crucial for gaining clearer insights into the GA signaling network.

Acknowledgements

The authors apologize to all colleagues whose relevant work could not be cited because of space limitations. The authors wish to thank Steve Thomas, Michael Wild and Thomas Regnault for their comments on the manuscript.

Funding
This work was supported by the Centre National de la Recherche Scientifique and the Agence Nationale de la Recherche [Grant 07-JCJC-0118].

Competing interests statement
The authors declare no competing financial interests.

Development at a Glance
A high-resolution version of the poster is available for downloading in the online version of this article at http://dev.biologists.org/content/140/6/1147.full

References
Achard, P. and Genschik, P. (2009). Releasing the brakes of plant growth: how GAs shutdown DELLA proteins. *J. Exp. Bot.* **60**, 1085-1092.
Achard, P., Gong, F., Cheminant, S., Alioua, M., Hedden, P. and Genschik, P. (2008). The cold-inducible CBF1 factor-dependent signaling pathway modulates the accumulation of the growth-repressing DELLA proteins via its effect on gibberellin metabolism. *Plant Cell* **20**, 2117-2129.
An, F., Zhang, X., Zhu, Z., Ji, Y., He, W., Jiang, Z., Li, M. and Guo, H. (2012). Coordinated regulation of apical hook development by gibberellins and ethylene in etiolated Arabidopsis seedlings. *Cell Res.* **22**, 915-927.
Ariizumi, T., Murase, K., Sun, T. P. and Steber, C. M. (2008). Proteolysis-independent downregulation of DELLA repression in Arabidopsis by the gibberellin receptor Gibberellin Insensitive DWARF1. *Plant Cell* **20**, 2447-2459.
Arnaud, N., Girin, T., Sorefan, K., Fuentes, S., Wood, T. A., Lawrenson, T., Sablowski, R. and Østergaard, L. (2010). Gibberellins control fruit patterning in Arabidopsis thaliana. *Genes Dev.* **24**, 2127-2132.
Asano, K., Hirano, K., Ueguchi-Tanaka, M., Angeles-Shim, R. B., Komura, T., Satoh, H., Kitano, H., Matsuoka, M. and Ashikari, M. (2009). Isolation and characterization of dominant dwarf mutants, Slr1 day, in rice. *Mol. Gen. Genomics* **281**, 223-231.
Bai, M. Y., Shang, J. X., Oh, E., Fan, M., Bai, Y., Zentella, R., Sun, T. P. and Wang, Z. Y. (2012). Brassinosteroid, gibberellin and phytochrome impinge on a common transcription module in Arabidopsis. *Nat. Cell Biol.* **14**, 810-817.
Band, L. R., Úbeda-Tomás, S., Dyson, R. J., Middleton, A. M., Hodgman, T. C., Owen, M. R., Jensen, O. E., Bennett, M. J. and King, J. R. (2012). Growth-induced hormone dilution can explain the dynamics of plant root cell elongation. *Proc. Natl. Acad. Sci. USA* **109**, 7577-7582.
Bolle, C. (2004). The role of GRAS proteins in plant signal transduction and development. *Planta* **218**, 683-692.
Chandler, P. M., Marion-Poll, A., Ellis, M. and Gubler, F. (2002). Mutants at the Slender1 locus of barley cv Himalaya. Molecular and physiological characterization. *Plant Physiol.* **129**, 181-190.
Cheminant, S., Wild, M., Bouvier, F., Pelletier, S., Renou, J. P., Erhardt, M., Hayes, S., Terry, M. J., Genschik, P. and Achard, P. (2011). DELLAs regulate chlorophyll and carotenoid biosynthesis to prevent photooxidative damage during seedling deetiolation in Arabidopsis. *Plant Cell* **23**, 1849-1860.
Cheng, H., Qin, L., Lee, S., Fu, X., Richards, D. E., Cao, D., Luo, D., Harberd, N. P. and Peng, J. (2004). Gibberellin regulates Arabidopsis floral development via suppression of DELLA protein function. *Development* **131**, 1055-1064.
Dai, C. and Xue, H. W. (2010). Rice early flowering1, a CKI, phosphorylates DELLA protein SLR1 to negatively regulate gibberellin signalling. *EMBO J.* **29**, 1916-1927.
de Lucas, M., Davière, J. M., Rodríguez-Falcón, M., Pontin, M., Iglesias-Pedraz, J. M., Lorrain, S., Fankhauser, C., Blázquez, M. A., Titarenko, E. and Prat, S. (2008). A molecular framework for light and gibberellin control of cell elongation. *Nature* **451**, 480-484.
Dill, A. and Sun, T. (2001). Synergistic derepression of gibberellin signaling by removing RGA and GAI function in Arabidopsis thaliana. *Genetics* **159**, 777-785.
Dill, A., Jung, H. S. and Sun, T. P. (2001). The DELLA motif is essential for gibberellin-induced degradation of RGA. *Proc. Natl. Acad. Sci. USA* **98**, 14162-14167.
Dill, A., Thomas, S. G., Hu, J., Steber, C. M. and Sun, T. P. (2004). The Arabidopsis F-box protein SLEEPY1 targets gibberellin signaling repressors for gibberellin-induced degradation. *Plant Cell* **16**, 1392-1405.
Feng, S., Martinez, C., Gusmaroli, G., Wang, Y., Zhou, J., Wang, F., Chen, L., Yu, L., Iglesias-Pedraz, J. M., Kircher, S. et al. (2008). Coordinated regulation of Arabidopsis thaliana development by light and gibberellins. *Nature* **451**, 475-479.
Feurtado, J. A., Huang, D., Wicki-Stordeur, L., Hemstock, L. E., Potentier, M. S., Tsang, E. W. and Cutler, A. J. (2011). The Arabidopsis C2H2 zinc finger INDETERMINATE DOMAIN1/ENHYDROUS promotes the transition to germination by regulating light and hormonal signaling during seed maturation. *Plant Cell* **23**, 1772-1794.
Fu, X., Richards, D. E., Ait-Ali, T., Hynes, L. W., Ougham, H., Peng, J. and Harberd, N. P. (2002). Gibberellin-mediated proteasome-dependent degradation of the barley DELLA protein SLN1 repressor. *Plant Cell* **14**, 3191-3200.
Fu, X., Richards, D. E., Fleck, B., Xie, D., Burton, N. and Harberd, N. P. (2004). The Arabidopsis mutant sleepy1gar2-1 protein promotes plant growth by increasing the affinity of the SCFSLY1 E3 ubiquitin ligase for DELLA protein substrates. *Plant Cell* **16**, 1406-1418.
Gallego-Bartolomé, J., Minguet, E. G., Marín, J. A., Prat, S., Blázquez, M. A. and Alabadí, D. (2010). Transcriptional diversification and functional conservation between DELLA proteins in Arabidopsis. *Mol. Biol. Evol.* **27**, 1247-1256.
Gallego-Bartolomé, J., Minguet, E. G., Grau-Enguix, F., Abbas, M., Locascio, A., Thomas, S. G., Alabadí, D. and Blázquez, M. A. (2012). Molecular mechanism for the interaction between gibberellin and brassinosteroid signaling pathways in Arabidopsis. *Proc. Natl. Acad. Sci. USA* **109**, 13446-13451.
Gomi, K., Sasaki, A., Itoh, H., Ueguchi-Tanaka, M., Ashikari, M., Kitano, H. and Matsuoka, M. (2004). GID2, an F-box subunit of the SCF E3 complex, specifically interacts with phosphorylated SLR1 protein and regulates the gibberellin-dependent degradation of SLR1 in rice. *Plant J.* **37**, 626-634.
Griffiths, J., Murase, K., Rieu, I., Zentella, R., Zhang, Z. L., Powers, S. J., Gong, F., Phillips, A. L., Hedden, P., Sun, T. P. et al. (2006). Genetic characterization and functional analysis of the GID1 gibberellin receptors in Arabidopsis. *Plant Cell* **18**, 3399-3414.
Harberd, N. P. (2003). Botany. Relieving DELLA restraint. *Science* **299**, 1853-1854.
Harberd, N. P., Belfield, E. and Yasumura, Y. (2009). The angiosperm gibberellin-GID1-DELLA growth regulatory mechanism: how an "inhibitor of an inhibitor" enables flexible response to fluctuating environments. *Plant Cell* **21**, 1328-1339.
Hedden, P. (2003). The genes of the Green Revolution. *Trends Genet.* **19**, 5-9.
Hirano, K., Asano, K., Tsuji, H., Kawamura, M., Mori, H., Kitano, H., Ueguchi-Tanaka, M. and Matsuoka, M. (2010). Characterization of the molecular mechanism underlying gibberellin perception complex formation in rice. *Plant Cell* **22**, 2680-2696.
Hirano, K., Kouketu, E., Katoh, H., Aya, K., Ueguchi-Tanaka, M. and Matsuoka, M. (2012). The suppressive function of the rice DELLA protein SLR1 is dependent on its transcriptional activation activity. *Plant J.* **71**, 443-453.
Hong, G. J., Xue, X. Y., Mao, Y. B., Wang, L. J. and Chen, X. Y. (2012). Arabidopsis MYC2 interacts with DELLA proteins in regulating sesquiterpene synthase gene expression. *Plant Cell* **24**, 2635-2648.
Hou, X., Lee, L. Y., Xia, K., Yan, Y. and Yu, H. (2010). DELLAs modulate jasmonate signaling via competitive binding to JAZs. *Dev. Cell* **19**, 884-894.
Hussain, A., Cao, D., Cheng, H., Wen, Z. and Peng, J. (2005). Identification of the conserved serine/threonine residues important for gibberellin-sensitivity of Arabidopsis RGL2 protein. *Plant J.* **44**, 88-99.
Hussain, A., Cao, D. and Peng, J. (2007). Identification of conserved tyrosine residues important for gibberellin sensitivity of Arabidopsis RGL2 protein. *Planta* **226**, 475-483.
Ikeda, A., Ueguchi-Tanaka, M., Sonoda, Y., Kitano, H., Koshioka, M., Futsuhara, Y., Matsuoka, M. and Yamaguchi, J. (2001). slender rice, a constitutive gibberellin response mutant, is caused by a null mutation of the SLR1 gene, an ortholog of the height-regulating gene GAI/RGA/RHT/D8. *Plant Cell* **13**, 999-1010.
Itoh, H., Sasaki, A., Ueguchi-Tanaka, M., Ishiyama, K., Kobayashi, M., Hasegawa, Y., Minami, E., Ashikari, M. and Matsuoka, M. (2005). Dissection of the phosphorylation of rice DELLA protein, SLENDER RICE1. *Plant Cell Physiol.* **46**, 1392-1399.
Jacobsen, S. E. and Olszewski, N. E. (1993). Mutations at the SPINDLY locus of Arabidopsis alter gibberellin signal transduction. *Plant Cell* **5**, 887-896.
Josse, E. M., Gan, Y., Bou-Torrent, J., Stewart, K. L., Gilday, A. D., Jeffree, C. E., Vaistij, F. E., Martínez-García, J. F., Nagy, F., Graham, I. A. et al. (2011). A DELLA in disguise: SPATULA restrains the growth of the developing Arabidopsis seedling. *Plant Cell* **23**, 1337-1351.
King, K. E., Moritz, T. and Harberd, N. P. (2001). Gibberellins are not required for normal stem growth in Arabidopsis thaliana in the absence of GAI and RGA. *Genetics* **159**, 767-776.
Lechner, E., Achard, P., Vansiri, A., Potuschak, T. and Genschik, P. (2006). F-box proteins everywhere. *Curr. Opin. Plant Biol.* **9**, 631-638.
Lee, S., Cheng, H., King, K. E., Wang, W., He, Y., Hussain, A., Lo, J., Harberd, N. P. and Peng, J. (2002). Gibberellin regulates Arabidopsis seed germination via RGL2, a GAI/RGA-like gene whose expression is upregulated following imbibition. *Genes Dev.* **16**, 646-658.
Lovegrove, A., Barratt, D. H., Beale, M. H. and Hooley, R. (1998). Gibberellin-photoaffinity labelling of two polypeptides in plant plasma membranes. *Plant J.* **15**, 311-320.
McGinnis, K. M., Thomas, S. G., Soule, J. D., Strader, L. C., Zale, J. M., Sun, T. P. and Steber, C. M. (2003). The Arabidopsis SLEEPY1 gene encodes a putative F-box subunit of an SCF E3 ubiquitin ligase. *Plant Cell* **15**, 1120-1130.
Middleton, A. M., Úbeda-Tomás, S., Griffiths, J., Holman, T., Hedden, P., Thomas, S. G., Phillips, A. L., Holdsworth, M. J., Bennett, M. J., King, J. R. et al. (2012). Mathematical modeling elucidates the role of transcriptional feedback in gibberellin signaling. *Proc. Natl. Acad. Sci. USA* **109**, 7571-7576.

Murase, K., Hirano, Y., Sun, T. P. and Hakoshima, T. (2008). Gibberellin-induced DELLA recognition by the gibberellin receptor GID1. *Nature* **456**, 459-463.

Nakajima, M., Shimada, A., Takashi, Y., Kim, Y. C., Park, S. H., Ueguchi-Tanaka, M., Suzuki, H., Katoh, E., Iuchi, S., Kobayashi, M. et al. (2006). Identification and characterization of Arabidopsis gibberellin receptors. *Plant J.* **46**, 880-889.

Ogawa, M., Kusano, T., Katsumi, M. and Sano, H. (2000). Rice gibberellin-insensitive gene homolog, OsGAI, encodes a nuclear-localized protein capable of gene activation at transcriptional level. *Gene* **245**, 21-29.

Pearce, S., Saville, R., Vaughan, S. P., Chandler, P. M., Wilhelm, E. P., Sparks, C. A., Al-Kaff, N., Korolev, A., Boulton, M. I., Phillips, A. L. et al. (2011). Molecular characterization of Rht-1 dwarfing genes in hexaploid wheat. *Plant Physiol.* **157**, 1820-1831.

Peng, J., Carol, P., Richards, D. E., King, K. E., Cowling, R. J., Murphy, G. P. and Harberd, N. P. (1997). The Arabidopsis GAI gene defines a signaling pathway that negatively regulates gibberellin responses. *Genes Dev.* **11**, 3194-3205.

Peng, J., Richards, D. E., Hartley, N. M., Murphy, G. P., Devos, K. M., Flintham, J. E., Beales, J., Fish, L. J., Worland, A. J., Pelica, F. et al. (1999). 'Green revolution' genes encode mutant gibberellin response modulators. *Nature* **400**, 256-261.

Sasaki, A., Itoh, H., Gomi, K., Ueguchi-Tanaka, M., Ishiyama, K., Kobayashi, M., Jeong, D. H., An, G., Kitano, H., Ashikari, M. et al. (2003). Accumulation of phosphorylated repressor for gibberellin signaling in an F-box mutant. *Science* **299**, 1896-1898.

Shimada, A., Ueguchi-Tanaka, M., Sakamoto, T., Fujioka, S., Takatsuto, S., Yoshida, S., Sazuka, T., Ashikari, M. and Matsuoka, M. (2006). The rice SPINDLY gene functions as a negative regulator of gibberellin signaling by controlling the suppressive function of the DELLA protein, SLR1, and modulating brassinosteroid synthesis. *Plant J.* **48**, 390-402.

Shimada, A., Ueguchi-Tanaka, M., Nakatsu, T., Nakajima, M., Naoe, Y., Ohmiya, H., Kato, H. and Matsuoka, M. (2008). Structural basis for gibberellin recognition by its receptor GID1. *Nature* **456**, 520-523.

Silverstone, A. L., Ciampaglio, C. N. and Sun, T. (1998). The Arabidopsis RGA gene encodes a transcriptional regulator repressing the gibberellin signal transduction pathway. *Plant Cell* **10**, 155-169.

Silverstone, A. L., Jung, H. S., Dill, A., Kawaide, H., Kamiya, Y. and Sun, T. P. (2001). Repressing a repressor: gibberellin-induced rapid reduction of the RGA protein in Arabidopsis. *Plant Cell* **13**, 1555-1566.

Silverstone, A. L., Tseng, T. S., Swain, S. M., Dill, A., Jeong, S. Y., Olszewski, N. E. and Sun, T. P. (2007). Functional analysis of SPINDLY in gibberellin signaling in Arabidopsis. *Plant Physiol.* **143**, 987-1000.

Tyler, L., Thomas, S. G., Hu, J., Dill, A., Alonso, J. M., Ecker, J. R. and Sun, T. P. (2004). Della proteins and gibberellin-regulated seed germination and floral development in Arabidopsis. *Plant Physiol.* **135**, 1008-1019.

Ubeda-Tomás, S., Swarup, R., Coates, J., Swarup, K., Laplaze, L., Beemster, G. T., Hedden, P., Bhalerao, R. and Bennett, M. J. (2008). Root growth in Arabidopsis requires gibberellin/DELLA signalling in the endodermis. *Nat. Cell Biol.* **10**, 625-628.

Ueguchi-Tanaka, M., Ashikari, M., Nakajima, M., Itoh, H., Katoh, E., Kobayashi, M., Chow, T. Y., Hsing, Y. I., Kitano, H., Yamaguchi, I. et al. (2005). GIBBERELLIN INSENSITIVE DWARF1 encodes a soluble receptor for gibberellin. *Nature* **437**, 693-698.

Ueguchi-Tanaka, M., Nakajima, M., Katoh, E., Ohmiya, H., Asano, K., Saji, S., Hongyu, X., Ashikari, M., Kitano, H., Yamaguchi, I. et al. (2007). Molecular interactions of a soluble gibberellin receptor, GID1, with a rice DELLA protein, SLR1, and gibberellin. *Plant Cell* **19**, 2140-2155.

Ueguchi-Tanaka, M., Hirano, K., Hasegawa, Y., Kitano, H. and Matsuoka, M. (2008). Release of the repressive activity of rice DELLA protein SLR1 by gibberellin does not require SLR1 degradation in the gid2 mutant. *Plant Cell* **20**, 2437-2446.

Wen, C. K. and Chang, C. (2002). Arabidopsis RGL1 encodes a negative regulator of gibberellin responses. *Plant Cell* **14**, 87-100.

Wild, M., Davière, J. M., Cheminant, S., Regnault, T., Baumberger, N., Heintz, D., Baltz, R., Genschik, P. and Achard, P. (2012). The Arabidopsis DELLA RGA-LIKE3 is a direct target of MYC2 and modulates jasmonate signaling responses. *Plant Cell* **24**, 3307-3319.

Willige, B. C., Ghosh, S., Nill, C., Zourelidou, M., Dohmann, E. M., Maier, A. and Schwechheimer, C. (2007). The DELLA domain of GA INSENSITIVE mediates the interaction with the GA INSENSITIVE DWARF1A gibberellin receptor of Arabidopsis. *Plant Cell* **19**, 1209-1220.

Yabuta, T. and Sumiki, Y. (1938). On the crystal of gibberellin, a substance to promote plant growth. *J. Agric. Chem. Soc. Japan* **14**, 1526.

Yamaguchi, S. (2008). Gibberellin metabolism and its regulation. *Annu. Rev. Plant Biol.* **59**, 225-251.

Yang, D. L., Yao, J., Mei, C. S., Tong, X. H., Zeng, L. J., Li, Q., Xiao, L. T., Sun, T. P., Li, J., Deng, X. W. et al. (2012). Plant hormone jasmonate prioritizes defense over growth by interfering with gibberellin signaling cascade. *Proc. Natl. Acad. Sci. USA* **109**, E1192-E1200.

Yu, S., Galvao, V. C., Zhang, Y. C., Horrer, D., Zhang, T. Q., Hao, Y. H., Feng, Y. Q., Wang, S., Markus, S. and Wang, J. W. (2012). Gibberellin regulates the Arabidopsis floral transition through miR156-targeted SQUAMOSA PROMOTER BINDING-LIKE transcription factors. *Plant Cell*, **24**, 3320-3332.

Zentella, R., Zhang, Z. L., Park, M., Thomas, S. G., Endo, A., Murase, K., Fleet, C. M., Jikumaru, Y., Nambara, E., Kamiya, Y. et al. (2007). Global analysis of della direct targets in early gibberellin signaling in Arabidopsis. *Plant Cell* **19**, 3037-3057.

Zhang, Z. L., Ogawa, M., Fleet, C. M., Zentella, R., Hu, J., Heo, J. O., Lim, J., Kamiya, Y., Yamaguchi, S. and Sun, T. P. (2011). Scarecrow-like 3 promotes gibberellin signaling by antagonizing master growth repressor DELLA in Arabidopsis. *Proc. Natl. Acad. Sci. USA* **108**, 2160-2165.