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Plant growth and development — the new wave

Editorial overview

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Christian Hardtke The research in Christian Hardtke's Lab revolves around the control of plant growth, with a focus on the role of hormone pathways in root system and vascular development. He is particularly interested in nonessential modifiers of quantitative aspects of growth. To isolate such genes, his lab exploits the natural genetic variation found among Arabidopsis populations. By characterization of the gene products in the broader genetic, biochemical, and cell biological context, and in other plant systems, his lab aims to provide novel insight into molecular developmental mechanisms and their conservation across species.

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Keiko Torii is interested in understanding fundamental logics of development of multicellular organisms: How cellular interactions specify cell fate and pattern formation? Her group investigates cell–cell-signaling pathways mediated by receptor kinases to address how positional signals are generated and how such signals ultimately coordinate plant cell proliferation and differentiation. She uses Arabidopsis organ growth and stomatal patterning as specific models. Recent discoveries of signaling components and key transcription factors directing stomatal differentiation opened her eyes to explore the origin of stomata — the developmental innovation that allowed plants to successfully conquer the terrestrial environment.

The current debate on climate change has fueled public interest in sustainability, which is at many levels intricately linked to plant science. Awareness of the critical importance of the planetary flora in climate regulation and the possible benefits of exploiting this role is increasing, thanks to public relations efforts of plant science community members as well as excellent popular science literature (e.g. [1]). Conceivably, plant growth and development will stay at the center stage of plant biology in this context, providing basic knowledge relevant for biomedical science, agriculture, environmental science, and energy biomass production. The impact of plants on the environment is mirrored by their capacity to adapt to environmental conditions in a highly plastic manner. In particular, within genetically defined limits, plants can adapt their growth, which is often required to execute developmental decisions that are triggered by external stimuli. Thus, spatio-temporal coordination of growth and development is a distinct feature of plants. Integrative approaches to better understand classic questions at such a higher level of complexity become increasingly common and have already led to exciting discoveries, marking a so to say new wave of plant growth and development.

For example, as more and more key signaling components and downstream targets of plant hormone pathways are identified, a question emerged: how do multiple hormone pathways interact to control growth at the molecular level? The hypocotyl, whose growth is controlled by multiple hormones, is an ideal system to investigate this topic. Jennifer Nemhauser provides an overview of interdependence and independence of various hormone signals that influence hypocotyl elongation. Representing such complex interactions comprehensively is difficult, so be sure to not miss her gearbox model, a refreshing way to display the interplay between hormone and photomorphogenesis pathways. Highlighting a specific example, Claus Schwechheimer summarizes our current knowledge and open questions with regard to GA signaling.

Another important question regarding hormone-signaling pathways is which mechanisms control their spatio-temporal activity? In case of auxin, regulated transport by auxin efflux carriers surely has a pivotal role. Recently, it was demonstrated that auxin transport is sufficient to generate an auxin gradient in the root meristem, with its maximum at the tip [2]. The findings are consistent with the idea that auxin-mediated plant growth is robust and multi-layered. With auxin transport being so accurately controlled, is there a role left for auxin metabolism? Apparently, the answer is yes. Yunde Zhao describes regulation at the level of auxin biosynthesis, highlighting the emerging role of YUCCA monoxygenases in seedling and flower development. Zhao also covers the roles of local cytokinin biosynthesis, while a review from Sabrina Sabatini's lab summarizes our knowledge about the emerging role of cytokinins in regulating cellular differentiation.

Controlled differentiation is of course a central feature of development, and the comparatively invariant patterning of the embryo is an ideal system for its investigation. Nicely illustrated, Wolfgang Lukowitz and coworkers summarize our current understanding of embryo patterning. Distinct asymmetric cell divisions are a characteristic of embryogenesis and are also found in adult development. Collette ten Hove and Renze Heidstra summarize our latest understanding of the mechanisms of asymmetric cell division by focusing on specific examples of stem cell maintenance, root patterning, and stomatal development.

A long-standing debate concerning all sporophytic growth processes concerns to what degree different tissue layers contribute to organ growth? Sigal Salvadi-Goldstein and Joanne Chory summarize recent breakthroughs in understanding the role of the epidermis in restricting and driving organ growth. These findings are also pertinent for the control of flower size, which however also appears to be under strict selection, depending on pollination systems. Although molecular tools now allow us to address cellular mechanisms associated with floral organ size, mysteries still remain: for example, what is the evolutionary driving force for 'extraordinarily large' blossoms, such as Rafflesia? Charles Davis and colleagues provide unique prospects on this fascinating topic. Although regulatory networks in flower development have seen long-standing interest, fruit development is less well characterized. Graham Seymour and colleagues update our recent understanding of fruit development, with an emphasis on genetic and epi-genetic aspects. How are epi-genetic marks established and maintained? Be sure to check the review by Vivian Exner and Lars Hennig, who present epi-genetic mechanisms from a developmental perspective. The Seymour review also highlights the increasingly important knowledge transfer from Arabidopsis into other systems, a theme that reoccurs in the contribution from the Hochholdinger lab, which summarizes our knowledge on similarities and disparities in root system development of dicotyledons and monocotyledons.

In the past decade, peptides important in plant development have been discovered. Among them, CLE peptides, initially discovered as shoot meristem homeostasis regulators, are now known to control diverse processes [3]. Melissa Goellner-Mitchum provides updates on conserved and nonconserved roles of CLE peptides, with the tantalizing implication that worm pathogens may have hijacked plant peptide genes to turn them against the root system. Related to this issue, Thierry Desnos reviews our understanding of the complex interactions of the root system with the rhizosphere and the resulting developmental feedbacks that shape root system growth.

Scientific discoveries intimately rely on technology advancements and vice versa. The new wave of plant research also takes advantage of live imaging tools, which dynamically capture biological processes at resolutions none of us would have imagined a decade ago. Two contributions from the Reddy and Shaw labs highlight the dynamics of plant growth and development and how it can be captured experimentally. Both reviews feature fascinating images, focusing on understanding the dynamics of cell–cell interactions at the organ level (Reddy), as well as highlighting the subcellular cytoskeleton dynamics that shape plant cells (Shaw).

The importance of addressing growth and development dynamics is, for instance, apparent from recent studies. In diurnal conditions, hypocotyls elongate in a 'stop and go' growth mode, accompanied by diurnal variation in auxin sensitivity and signaling [4]. Strikingly, the circadian clock directly interferes with this process by gating auxin effects on hypocotyl growth [5]. These recent examples highlight how examination of growth at higher spatio-temporal resolution can advance our understanding of plants in the physiological and environmental context. If you like, you may call this Systems Biology. You may also call it physiology, but whichever you prefer, it becomes apparent that the next wave in plant growth and development research will probably produce refreshed integrative views of various molecular processes.

The next wave of research in our field will also be partly driven by another wave of a different kind — a new wave of principal investigators. As this journal celebrates its tenth birthday, molecular genetic analysis of plant development has come of age as well, and so have those involved in it. Those who witnessed the years of the 'Cambrian radiation' of Arabidopsis genetics and genomics as graduate students and post-docs now harvest the fruits of these efforts to set up their research programs, advancing the level of detail, increasing the scale of approaches, and transferring knowledge from model systems into economically, ecologically, and evolutionarily important species (while the rest of us continue to do so!). In this issue, we aimed, wherever possible, to give this new wave of principal investigators the opportunity to voice their *Current Opinions*. We hope you will enjoy reading them!

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