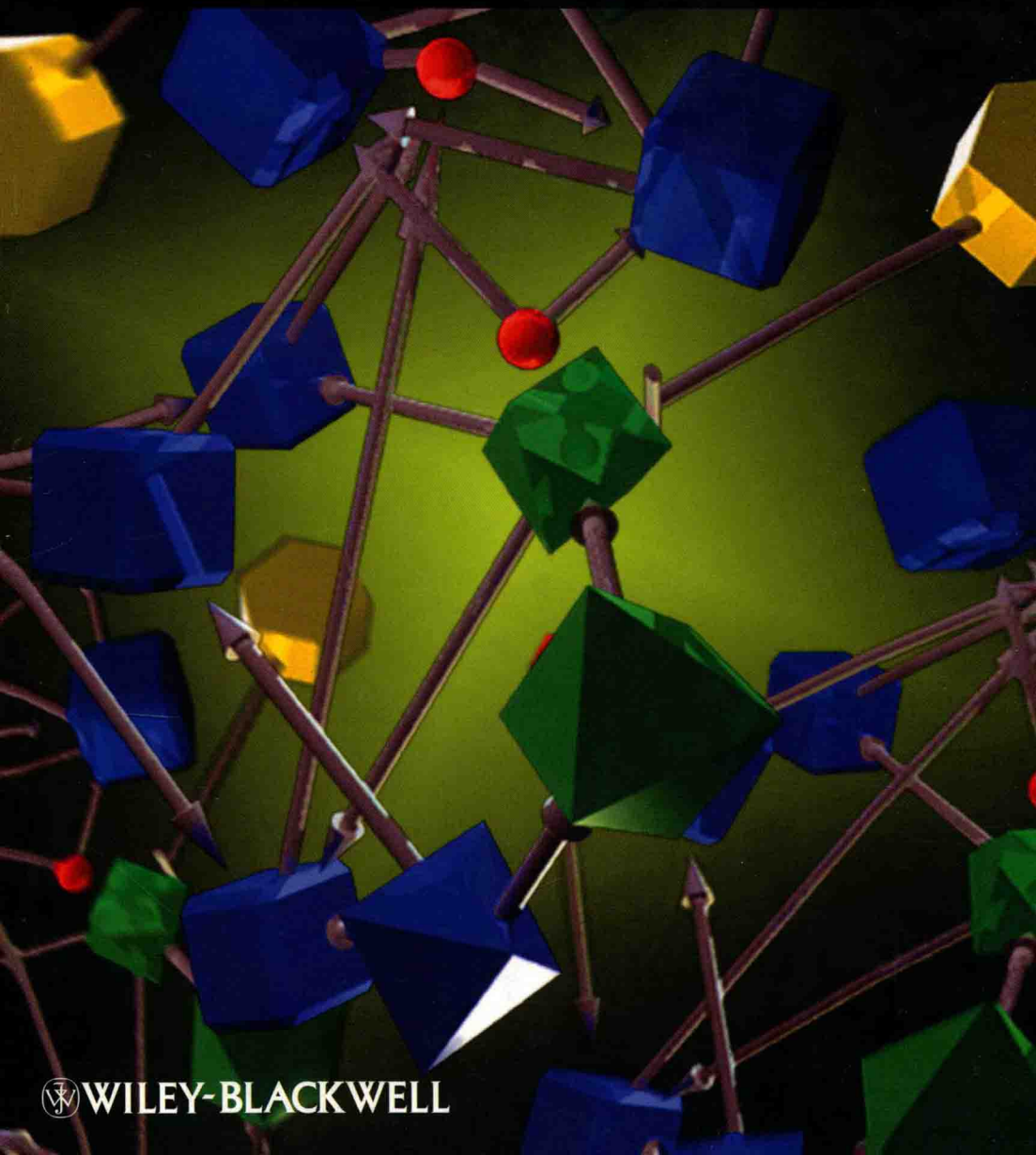
Annual Plant Reviews, Volume 35

Plant Systems Biology

Edited by Gloria M. Coruzzi and Rodrigo A. Gutiérrez



WILEY-BLACKWELL

ANNUAL PLANT REVIEWS VOLUME 35

Plant Systems Biology

Edited by

Gloria M. Coruzzi

Department of Biology and Center for Genomics and Systems Biology
New York University, New York, NY, USA

Rodrigo A. Gutiérrez

Department of Biology and Center for Genomics and Systems Biology
New York University, New York, NY, USA
Departamento de Genética Molecular y Microbiología
Pontificia Universidad Católica de Chile, Santiago, Chile

WILEY-BLACKWELL
A John Wiley & Sons, Ltd., Publication

Annual Plant Reviews

This edition first published 2009

Blackwell Publishing was acquired by John Wiley & Sons in February 2007.
Blackwell's publishing programme has been merged with Wiley's global Scientific, Technical and Medical business to form Willey-Blackwell.

Registered office
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

Editorial office
9600 Garsington Road, Oxford, OX4 2DQ, United Kingdom
2121 State Avenue, Ames, Iowa 50014-8300, USA

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com/wiley-blackwell.

Library of Congress Cataloging-in-Publication Data is available

A catalogue record for this book is available from the British Library.

Annual plant reviews (Print) ISSN 1460-1494
Annual plant reviews (Online) ISSN 1756-9710

Set in 10/12 pt Palatino by Aptara® Inc., New Delhi, India
Printed and bound in Singapore by Markono Print Media Pte Ltd

1 2009

ANNUAL PLANT REVIEWS
VOLUME 35

Annual Plant Reviews
A series for researchers and postgraduates in the plant sciences. Each volume in this series focuses on a theme of topical importance and emphasis is placed on rapid publication.

Titles in the series:
1. **Arabidopsis**
   Edited by M. Anderson and J.A. Roberts
2. **Biochemistry of Plant Secondary Metabolism**
   Edited by M. Wink
3. **Functions of Plant Secondary Metabolites and their Exploitation in Biotechnology**
   Edited by M. Wink
4. **Molecular Plant Pathology**
   Edited by M. Dickinson and J. Beynon
5. **Vacuolar Compartments**
   Edited by D.G. Robinson and J.C. Rogers
6. **Plant Reproduction**
   Edited by S.D. O'Neill and J.A. Roberts
7. **Protein–Protein Interactions in Plant Biology**
   Edited by M.T. McManus, W.A. Laing, and A.C. Allan
8. **The Plant Cell Wall**
   Edited by J.K.C. Rose
9. **The Golgi Apparatus and the Plant Secretory Pathway**
   Edited by D.G. Robinson
10. **The Plant Cytoskeleton in Cell Differentiation and Development**
    Edited by P.J. Hussey
11. **Plant–Pathogen Interactions**
    Edited by N.J. Talbot
12. **Polarity in Plants**
    Edited by K. Lindsey

13. **Plastids**
    Edited by S.G. Moller
14. **Plant Pigments and their Manipulation**
    Edited by K.M. Davies
15. **Membrane Transport in Plants**
    Edited by M.R. Blatt
16. **Intercellular Communication in Plants**
    Edited by A.J. Fleming
17. **Plant Architecture and Its Manipulation**
    Edited by C.G.N. Turnbull
18. **Plasmodeomata**
    Edited by K.J. Oparka
19. **Plant Epigenetics**
    Edited by P. Meyer
20. **Flowering and Its Manipulation**
    Edited by C. Ainsworth
21. **Endogenous Plant Rhythms**
    Edited by A. Hall and H. McWatters
22. **Control of Primary Metabolism in Plants**
    Edited by W.C. Plaxton and M.T. McManus
23. **Biology of the Plant Cuticle**
    Edited by M. Riederer
24. **Plant Hormone Signaling**
    Edited by P. Hadden and S.G. Thomas
25. **Plant Cell Separation and Adhesion**
    Edited by J.R. Roberts and Z. Gonzalez-Carranza
26. **Senescence Processes in Plants**
    Edited by S. Gan
27. **Seed Development, Dormancy and Germination**
    Edited by K.J. Bradford and H. Nonogaki
28. **Plant Proteomics**
    Edited by C. Finnie
29. **Regulation of Transcription in Plants**
    Edited by K. Grasser
30. **Light and Plant Development**
    Edited by G. Whitelam
31. **Plant Mitochondria**
    Edited by David C. Logan
32. **Cell Cycle Control and Plant Development**
    Edited by D. Inzé
33. **Intracellular Signaling in Plants**
    Edited by Z. Yang
34. **Molecular Aspects of Plant Disease Resistance**
    Edited by J. Parker
35. **Plant Systems Biology**
    Edited by Gloria M. Coruzzi and Rodrigo A. Gutiérrez

CONTRIBUTORS

Réka Albert
Department of Physics, Pennsylvania State University, University Park, PA, USA
Huck Institutes of the Life Sciences, Pennsylvania State University, University Park, PA, USA

Sarah M. Assmann
Department of Biology, Pennsylvania State University, University Park, PA, USA

Ivan Baxter
Bindley Bioscience Center, Purdue University, West Lafayette, IN, USA

Philip N. Benfey
Department of Biology and the Institute for Genome Science and Policy, Duke University, Durham, NC, USA

Richard Bonneau
Department of Biology and Center for Genomics and Systems Biology, New York University, New York, NY, USA
Computer Science Department, Courant Institute for Mathematical Sciences, New York University, New York, NY, USA

Siobhan M. Brady
Department of Biology and the Institute for Genome Science and Policy, Duke University, Durham, NC, USA

Alejandro Burga
Departamento de Genética Molecular y Microbiología, Pontificia Universidad Católica de Chile, Santiago, Chile

Gloria M. Coruzzi
Department of Biology and Center for Genomics and Systems Biology, New York University, New York, NY, USA

Ian M. Ehrenreich
Department of Biology and Center for Genomics and Systems Biology, New York University, New York, NY, USA
Department of Genetics, North Carolina State University, Raleigh, NC, USA

Kathleen E. Engelmann
University of Bridgeport, Bridgeport, CT, USA

Anita Fernandez
Department of Biology and Center for Genomics and Systems Biology, New York University, New York, NY, USA
Department of Biology, Fairfield University, Fairfield, CT, USA

Pamela J. Green
Department of Plant and Soil Sciences and Delaware Biotechnology Institute, University of Delaware, Newark, DE, USA

Erich Grotewold
Department of Plant Cellular and Molecular Biology and Plant Biotechnology Center, The Ohio State University, Columbus, OH, USA

Mary Lou Guerinot
Department of Biological Sciences, Dartmouth College, Hanover, NH, USA

Kristin C. Gunsalus
Department of Biology and Center for Genomics and Systems Biology, New York University, New York, NY, USA

Rodrigo A. Gutiérrez
Department of Biology and Center for Genomics and Systems Biology, New York University, New York, NY, USA
Departamento de Genética Molecular y Microbiología, Pontificia Universidad Católica de Chile, Santiago, Chile

Yoshie Hanzawa
Department of Biology and Center for Genomics and Systems Biology, New York University, New York, NY, USA

Thadeous Kacmarczyk
Department of Biology and Center for Genomics and Systems Biology, New York University, New York, NY, USA

Manpreet S. Katari
Department of Biology and Center for Genomics and Systems Biology, New York University, New York, NY, USA

Blake C. Meyers
Department of Plant and Soil Sciences and Delaware Biotechnology Institute, University of Delaware, Newark, DE, USA

Scott C. Peck
Division of Biochemistry, University of Missouri-Columbia, Columbia, MO, USA

Fabio Piano
Department of Biology and Center for Genomics and Systems Biology, New York University, New York, NY, USA

Chris Poultney
Courant Institute for Mathematical Sciences, Computer Science Department, New York University, New York, NY, USA

Michael D. Purugganan
Department of Biology and Center for Genomics and Systems Biology, New York University, New York, NY, USA

Christina L. Richards
Department of Biology and Center for Genomics and Systems Biology, New York University, New York, NY, USA

David E. Salt
Center for Plant Environmental Stress Physiology, Purdue University, West Lafayette, IN, USA
Bindley Bioscience Center, Purdue University, West Lafayette, IN, USA

Dennis Shasha
Courant Institute for Mathematical Sciences, Computer Science Department, New York University, New York, NY, USA

Nathan Springer
Department of Plant Biology, University of Minnesota, St. Paul, MN, USA

Peter Waltman
Computer Science Department, Courant Institute for Mathematical Sciences, New York University, New York, NY, USA

Wolfram Weckwerth
Department of Molecular Plant Physiology and Systems Biology, University of Vienna, Vienna, Austria
GoFORSY, Potsdam, Germany
Max Planck Institute of Molecular Plant Physiology, Potsdam, Germany

PREFACE

'Just as we cannot think of spatial objects at all apart from space, or temporal objects apart from time, so we cannot think of any object apart from the possibility of its connections with other things'

Ludwig Wittgenstein – Tractatus Logico-Philosophicus (2.012)

This volume captures the avant-garde of biological systemic research and aims to be an introductory material for undergraduate and graduate students, as well as researchers who wish to immerse themselves in the relevant questions and problems that system biology is facing today. But, what is systems biology? Herein, we provide the opinion of experts in fields impacting systems biology ranging from statistics to ecology, with emphasis given to case studies where the concepts of systems biology are applied to particular problems such as the study of development, environmental response, metabolism in plants and diverse model organisms.

In the first part of this volume, an overview of the systems biology field is presented with a focus on plant systems biology. A fundamental conceptual framework such as Network Theory is covered as well as the progress achieved for diverse model organisms: prokaryotes, due to their 'simplicity', and *C. elegans*, one of the most tractable animal models. The second part of this volume deals with the diverse sources of information necessary for a systemic understanding of plants. Insights are given into the software tools developed for systems biology and how they can be applied for plants and a comprehensive analysis of the data that can be integrated, that is, genome, transcriptome, proteome, metabolome and ionome. Finally, an interesting case study regarding root development is presented as well as important ecological and evolutionary considerations regarding living systems.

Despite huge advances in technology in the genomic era, we are far from having a complete description of the molecular components of biological systems and the ways they interact. In the particular case of Arabidopsis, advances in plant systems biology studies lag behind other model organism in terms of the data sets available (e.g. interactomes). However, this lack of complete information has not precluded creative researchers from taking advantage of systems biology approaches to conduct research to develop testable hypotheses, which in turn fuel a new cycle of systems level research.

After reading this volume, we hope you have more questions about systems biology than when you started reading it. We will consider our book

a success if, after reading it, you discover novel ideas and ways to apply systems biology approaches in your own area of research. When used as an educational platform, we hope this volume will inspire the next generation of young scientists to enter the field of systems biology in the post-genomic era.

ACKNOWLEDGEMENTS

We would like to thank all the authors who contributed their time and expertise to this volume on systems biology. We believe that the individual chapters, like the field of systems biology, have great synergies and interconnections. We appreciate the enormous amount of insight and information encapsulated by each of the authors. We would like to especially acknowledge Alexis Cruikshank for her superb organizational and technical editing skills on this volume, as well as for her unending patience on completing this project. We also acknowledge the superb artwork of Suzan Runko who created the cover art for this volume, which conveys the science of systems biology in an exceptionally artistic fashion.

CONTENTS

Part I

Systems Biology: An Overview