Photosynthesis

Plastid Biology, Energy Conversion and Carbon Assimilation

Advances in Photosynthesis and Respiration

VOLUME 34

The scope of our series reflects the concept that photosynthesis and respiration are intertwined with respect to both the protein complexes involved and to the entire bioenergetic machinery of all life. *Advances in Photosynthesis and Respiration* is a book series that provides a comprehensive and state-of-the-art account of research in photosynthesis and respiration. Photosynthesis is the process by which higher plants, algae, and certain species of bacteria transform and store solar energy in the form of energy-rich organic molecules. These compounds are in turn used as the energy source for all growth and reproduction in these and almost all other organisms. As such, virtually all life on the planet ultimately depends on photosynthetic energy conversion. Respiration, which occurs in mitochondrial and bacterial membranes, utilizes energy present in organic molecules to fuel a wide range of metabolic reactions critical for cell growth and development. In addition, many photosynthetic organisms engage in energetically wasteful photorespiration that begins in the chloroplast with an oxygenation reaction catalyzed by the same enzyme responsible for capturing carbon dioxide in photosynthesis. This series of books spans topics from physics to agronomy and medicine, from femtosecond processes to season-long production to evolutionary time scales, from the photophysics of reaction centers, through the electrochemistry of intermediate electron transfer, to the physiology of whole organisms, and from X-ray crystallography of proteins to the morphology of organelles and intact organisms. The goal of the series is to offer beginning researchers, advanced undergraduate students, graduate students, and even research specialists, a comprehensive, up-to-date picture of the remarkable advances across the full scope of research on photosynthesis, respiration and related processes.

For further volumes:
www.springer.com/series/5599

Photosynthesis

Plastid Biology, Energy Conversion and Carbon Assimilation

Edited by

Julian J. Eaton-Rye
University of Otago
Dunedin
New Zealand

Baishnab C. Tripathy
Jawaharlal Nehru University
New Delhi
India

and

Thomas D. Sharkey
Michigan State University
East Lansing
Michigan
USA

Springer

Editors
Julian J. Eaton-Rye
Department of Biochemistry
University of Otago
P.O. Box 56
Dunedin 9054
New Zealand
julian.eaton-rye@otago.ac.nz

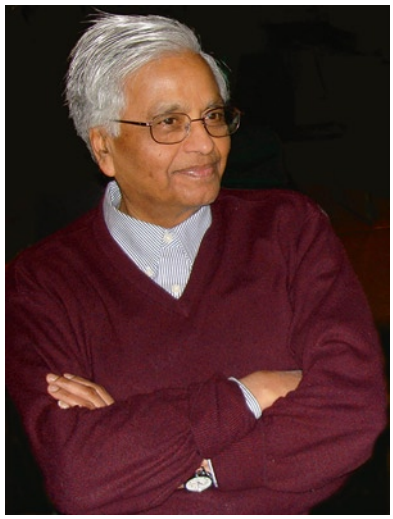
Baishnab C. Tripathy
School of Life Sciences
Jawaharlal Nehru University
New Delhi 110067
India
bctripathy@mail.jnu.ac.in

Thomas D. Sharkey
Department of Biochemistry and Molecular Biology
Michigan State University
410 Biochemistry Building
East Lansing, MI 48824, USA
tsharkey@msu.edu

ISBN 978-94-007-1578-3 (HB) ISBN 978-94-007-1579-0 (e-book)
DOI 10.1007/978-94-007-1579-0
Springer Dordrecht Heidelberg London New York

Library of Congress Control Number: 2011939834

Dedication



Govindjee's passion for photosynthesis has been inspirational for students and researchers for over 50 years. At the start of his 80th year this volume of the Advances in Photosynthesis and Respiration series is dedicated to Govindjee to especially acknowledge not only his unique discoveries in Photosystem II, but also his commitment to educating students and researchers throughout the World (Photo taken in 2009 by Ram Singh).

Govindjee has provided unparalleled educational resources to the field of photosynthesis through his three *Scientific American* articles (1965; 1974; 1990; translated in Russian and in Japanese), and outstanding editorship of authoritative books on Photosynthesis (*Bioenergetics of Photosynthesis*, 1975; *Photosynthesis*, two volumes, 1982 (translated in Russian, 1987); *Light Emission by Plants and Bacteria*, 1986; *Chlorophyll a Fluorescence: A Signature of Photosynthesis*, 2004; reprinted in 2010; *Photosynthesis in Silico: from Molecules to Ecosystems*, 2009; and *Abiotic Stress in Plants*, 2010). Under his leadership, as the chief editor of *Photosynthesis Research*, he made this publication a World-class journal; it took a quantum jump (five-fold) in the number of pages published per year. He then founded the unique 'Historical Corner' of *Photosynthesis Research*, and by his shear persuasion attracted all the leaders in the field to write on their discoveries. This culminated in a unique book 'Discoveries in Photosynthesis'. Govindjee is also the founding Editor of the '*Advances in Photosynthesis and Respiration*' Series; under his leadership more than 30 highly-acclaimed authoritative volumes on all aspects of photosynthesis: from molecules to the whole plant have been published; they are available in all leading libraries and photosynthesis research laboratories of the World. In addition, Govindjee's 1969 book on '*Photosynthesis*' remains a classic as it was used in the past to teach photosynthesis to thousands of students around the World. Lastly, together with Larry Orr, Govindjee has produced the highly cited and heavily used web site '*Photosynthesis and the World Wide Web*' for education. We refer the readers to Chapter 31 (by George C. Papageorgiou), Chapter 32 (by Julian J. Eaton-Rye) and Chapter 33 (by Robert M. Clegg) on Govindjee's research during 1956–1969, 1970–1999, and 2000–2010, respectively; also see the Preface of this book and Govindjee's Biographical Sketch that follows. These achievements have been made possible by Govindjee's personal enthusiasm and dedicated service to photosynthesis research and education. His unparalleled commitment and knowledge have

made him a true advocate, and ambassador, of photosynthetic research and education around the World.

Biographical Sketch

Govindjee, born in 1932, obtained his BSc (Chemistry, Biology) and MSc (Botany) in 1952 and 1954, from the University of Allahabad, India. He was a graduate student of Robert Emerson and of Eugene Rabinowitch, receiving his Ph.D. (Biophysics), in 1960, from the University of Illinois at Urbana-Champaign (UIUC). He has focused mainly on "*Photosystem II*" (PS II, the Water:Plastoquinone Oxidoreductase) throughout his career; research on PS II has included discoveries on excitation energy transfer, light emission, primary photochemistry and electron transfer. His early research included the discovery of a short-wavelength form of chlorophyII (Chl) *a* functioning in the Chl *b*-containing system, now called PS II (in 1960, with Eugene Rabinowitch); and the two-light effect (Emerson Enhancement) in NADP-reduction in chloroplasts (1962–1964, with Rajni Govindjee and George Hoch). In collaboration with his ~25 graduate students and postdoctoral associates, he has worked on the origins of the different spectral fluorescing forms of Chl *a* and the temperature dependence of excitation energy transfer down to 4 K (1963–1970); established basic relationships between Chl *a* fluorescence and photosynthetic reactions (1968–1988); discovered a unique role of bicarbonate on the acceptor side of PS II, particularly in protonation events involving the Q_B binding region (1970–1998); formulated the theory of thermoluminescence in plants (1983, with Don C. De Vault); made the first picosecond measurement on the primary photochemistry of PS II (1989–1997, with Michael Seibert and Michael Wasielewski); and pioneered the use of the lifetime of Chl *a* fluorescence in understanding photoprotection against excess light (with Adam Gilmore). His current focus, however, is on the "*History of Photosynthesis Research*" and in "*Photosynthesis Education*" in addition to his dedicated research on the application of FLIM (Fluorescence Lifetime Imaging Microscopy) to photosynthetic systems to understand photoprotection in plants and algae (with Robert Clegg of UIUC) and on fluorescence spectroscopy of cyanobacterial cells during fluorescence induction (with Ondrej Prasil in The Czech Republic).

Govindjee has served the UIUC as an Assistant Professor, Associate Professor and Professor (1961–1999). Since 1999, he has been Professor Emeritus of Biochemistry, Biophysics and Plant Biology at the UIUC. His honors include: Fellow and Life Member of the National Academy of Sciences, India (1978); President of the American Society of Photobiology (1980–1981); Fulbright Senior Lecturer (1996–1997); Honorary President of the 13th International Photosynthesis Congress (Montréal, 2004); the first recipient of the Lifetime Achievement Award of the Rebeiz Foundation for Basic Biology (2006); recipient of the ISPR (International Society of Photosynthesis Research) Communication Award (2007); and the LAS (Liberal Arts and Sciences) Lifetime Achievement Award of the University of Illinois at Urbana-Champaign (2008). He is also listed among the Eminent Indian Botanists, Past and Present (2010).

From the Co-Series Editor

Advances in Photosynthesis and Respiration

Volume 34: Photosynthesis: Plastid Biology, Energy Conversion and Carbon Assimilation

I am delighted to announce the publication, in the *Advances in Photosynthesis and Respiration* (AIPH) Series, of *Photosynthesis: Plastid Biology, Energy Conversion and Carbon Assimilation*. Julian Eaton-Rye and Baishnab Tripathy (coeditors of Vol. 34) conceived a comprehensive look at photosynthesis and I (TDS) joined them in the late stages to put together this volume. Julian and Baishnab had in mind a volume to be dedicated to Govindjee for his extraordinary contributions to both discoveries and education about photosynthesis. (See the Dedication page, his Biographical Sketch, the Preface of this book, and Chapters 31, 32 and 33 in this volume.) Volume 31 of the series marked a turning point, with Govindjee inviting a co-series editor beginning with that volume. Govindjee's invitation to me represents his strong desire to keep the series comprehensive and reflects his view that, while photosynthesis begins with the absorption of a photon, a full understanding of photosynthesis can take investigators on many journeys, some of which can lead to intricacies of carbon metabolism and sugar synthesis while others undertake studies of the role of photosynthesis in ecology and even its very significant role in global change. I can now tell the story of Govindjee's incredible efforts on behalf of this series from the inside. Editors of the previous 30 volumes will recount how Govindjee can be a task-master, making sure that books are produced in a timely manner and making sure the quality is upheld at every step of the process. Above all else, Govindjee cares about photosynthesis. The coeditors of Volume 34 are pleased to reflect on the history of Govindjee's contributions to photosynthesis.

Our Books: Thirty-Three Volumes

Below is listed information on all the past 33 volumes. We are pleased to note that Springer is now producing complete table of contents of these books and electronic copies of individual chapters of these books (http://www.springer.com/series/5599); their web sites include free downloadable front matter as well as indexes. All the available and anticipated web sites of books in this series *Advances in Photosynthesis and Respiration* are listed, within square brackets, at the end of each entry. This volume (34) will be the last with the familiar white cover. A green cover better suited to the increasing web presence will be used for volume 35, which will be published early 2012.

- **Volume 33 (2012): Functional Genomics and Evolution of Photosynthetic Systems**, edited by Robert L. Burnap and Willem F.J. Vermaas, from USA; Fifteen chapters, 428 pp, http://www.springer.com/life+sciences/book/978-94-007-1532-5 [http://www.springerlink.com/content/978-90-481-1532-5/]
- **Volume 32 (2011): C4 Photosynthesis and Related CO_2 Concentrating Mechanisms**, edited by Agepati S. Raghavendra and Rowan Sage, from India and Canada. Nineteen chapters, 425 pp, Hardcover, ISBN 978-90-481-9406-3 [http://www.springerlink.com/content/978-90-481-9406-3/]
- **Volume 31 (2010): The Chloroplast: Basics and Applications**, edited by Constantin Rebeiz (USA), Christoph Benning (USA), Hans J. Bohnert (USA), Henry Daniell (USA), J. Kenneth Hoober (USA), Hartmut K. Lichtenthaler (Germany), Archie R. Portis (USA), and Baishnab C. Tripathy (India). Twenty-five chapters, 451 pp, Hardcover, ISBN: 978-90-481-8530-6 [http://www.springerlink.com/content/978-90-481-8530-6/]
- **Volume 30 (2009): Lipids in Photosynthesis: Essential and Regulatory Functions**, edited by Hajime Wada and Norio Murata, both from Japan. Twenty chapters, 506 pp, Hardcover, ISBN:

978-90-481-2862-4; e-book, ISBN: 978-90-481-2863-1 [http://www.springerlink.com/content/978-90-481-2862-4/]

- **Volume 29 (2009): Photosynthesis in Silico: Understanding Complexity from Molecules**, edited by Agu Laisk, Ladislav Nedbal, and Govindjee, from Estonia, The Czech Republic, and USA. Twenty chapters, 525 pp, Hardcover, ISBN: 978-1-4020-9236-7 [http://www.springerlink.com/content/978-1-4020-9236-7/]
- **Volume 28 (2009): The Purple Phototrophic Bacteria**, edited by C. Neil Hunter, Fevzi Daldal, Marion C. Thurnauer and J. Thomas Beatty, from UK, USA and Canada. Forty-eight chapters, 1053 pp, Hardcover, ISBN: 978-1-4020-8814-8 [http://www.springerlink.com/content/978-1-4020-8814-8/]
- **Volume 27 (2008): Sulfur Metabolism in Phototrophic Organisms**, edited by Christiane Dahl, Rüdiger Hell, David Knaff and Thomas Leustek, from Germany and USA. Twenty-four chapters, 551 pp, Hardcover, ISBN: 978-4020-6862-1 [http://www.springerlink.com/content/978-1-4020-6862-1/]
- **Volume 26 (2008): Biophysical Techniques in Photosynthesis**, Volume II, edited by Thijs Aartsma and Jörg Matysik, both from The Netherlands. Twenty-four chapters, 548 pp, Hardcover, ISBN: 978-1-4020-8249-8 [http://www.springerlink.com/content/978-1-4020-8249-8/]
- **Volume 25 (2006): Chlorophylls and Bacteriochlorophylls: Biochemistry, Biophysics, Functions and Applications**, edited by Bernhard Grimm, Robert J. Porra, Wolfhart Rüdiger, and Hugo Scheer, from Germany and Australia. Thirty-seven chapters, 603 pp, Hardcover, ISBN: 978-1-40204515-8 [http://www.springerlink.com/content/978-1-4020-4515-8/]
- **Volume 24 (2006): Photosystem I: The Light-Driven Plastocyanin: Ferredoxin Oxidoreductase**, edited by John H. Golbeck, from USA. Forty chapters, 716 pp, Hardcover, ISBN: 978-1-40204255-3 [http://www.springerlink.com/content/978-1-4020-4255-3/]
- **Volume 23 (2006): The Structure and Function of Plastids**, edited by Robert R. Wise and J. Kenneth Hoober, from USA. Twenty-seven chapters, 575 pp, Softcover, ISBN: 978-1-4020- 6570–6; Hardcover, ISBN: 978-1-4020-4060-3 [http://www.springerlink.com/content/978-1-4020-4060-3/]
- **Volume 22 (2005): Photosystem II: The Light-Driven Water:Plastoquinone Oxidoreductase**, edited by Thomas J. Wydrzynski and Kimiyuki Satoh, from Australia and Japan. Thirty-four chapters, 786 pp, Hardcover, ISBN: 978-1-4020-4249-2 [http://www.springerlink.com/content/978-1-4020-4249-2/]
- **Volume 21 (2005): Photoprotection, Photoinhibition, Gene Regulation, and Environment**, edited by Barbara Demmig-Adams, William W. Adams III and Autar K. Mattoo, from USA. Twenty-one chapters, 380 pp, Hardcover, ISBN: 978-14020-3564-7 [http://www.springerlink.com/content/978-1-4020-3564-7/]
- **Volume 20 (2006): Discoveries in Photosynthesis**, edited by Govindjee, J. Thomas Beatty, Howard Gest and John F. Allen, from USA, Canada and UK. One hundred and eleven chapters, 1304 pp, Hardcover, ISBN: 978-1-4020-3323-0 [http://www.springerlink.com/content/978-1-4020-3323-0/]
- **Volume 19 (2004): Chlorophyll *a* Fluorescence: A Signature of Photosynthesis**, edited by George C. Papageorgiou and Govindjee, from Greece and USA. Thirty-one chapters, 820 pp, Hardcover, ISBN: 978-1-4020-3217-2 [http://www.springerlink.com/content/978-1-4020-3217-2/]
- **Volume 18 (2005): Plant Respiration: From Cell to Ecosystem**, edited by Hans Lambers and Miquel Ribas-Carbo, from Australia and Spain. Thirteen chapters, 250 pp, Hardcover, ISBN: 978-14020-3588-3 [http://www.springerlink.com/content/978-1-4020-3588-3/]
- **Volume 17 (2004): Plant Mitochondria: From Genome to Function**, edited by David Day, A. Harvey Millar and James Whelan, from Australia. Fourteen chapters, 325 pp, Hardcover, ISBN: 978-1-4020-2399-6 [http://www.springerlink.com/content/978-1-7923-2399-6/]
- **Volume 16 (2004): Respiration in Archaea and Bacteria: Diversity of Prokaryotic Respiratory Systems**, edited by Davide Zannoni, from Italy. Thirteen chapters, 310 pp, Hardcover, ISBN: 978-14020-2002-5 [http://www.springerlink.com/content/978-1-4020-2002-5/]
- **Volume 15 (2004): Respiration in Archaea and Bacteria: Diversity of Prokaryotic Electron Transport Carriers**, edited by Davide Zannoni, from Italy. Thirteen chapters, 350 pp, Hardcover, ISBN: 978-1-4020-2001-8 [http://www.springerlink.com/content/978-0-7923-2001-8/]
- **Volume 14 (2004): Photosynthesis in Algae**, edited by Anthony W. Larkum, Susan Douglas and John A. Raven, from Australia, Canada and UK. Nineteen chapters, 500 pp, Hardcover, ISBN:

978-0-7923-6333-0 [http://www.springerlink.com/content/978-0-7923-6333-0/]

- **Volume 13 (2003): Light-Harvesting Antennas in Photosynthesis**, edited by Beverley R. Green and William W. Parson, from Canada and USA. Seventeen chapters, 544 pp, Hardcover, ISBN: 978-07923-6335-4 [http://www.springerlink.com/content/978-0-7923-6335-4/]
- **Volume 12 (2003): Photosynthetic Nitrogen Assimilation and Associated Carbon and Respiratory Metabolism**, edited by Christine H. Foyer and Graham Noctor, from UK and France. Sixteen chapters, 304 pp, Hardcover, ISBN: 978-07923-6336-1 [http://www.springerlink.com/content/978-0-7923-6336-1/]
- **Volume 11 (2001): Regulation of Photosynthesis**, edited by Eva-Mari Aro and Bertil Andersson, from Finland and Sweden. Thirty-two chapters, 640 pp, Hardcover, ISBN: 978-0-7923-6332-3 [http://www.springerlink.com/content/978-0-7923-6332-3/]
- **Volume 10 (2001): Photosynthesis: Photobiochemistry and Photobiophysics**, authored by Bacon Ke, from USA. Thirty-six chapters, 792 pp, Softcover, ISBN: 978-0-7923-6791-8; Hardcover: ISBN: 978-0-7923-6334-7 [http://www.springerlink.com/content/978-0-7923-6334-7/]
- **Volume 9 (2000): Photosynthesis: Physiology and Metabolism**, edited by Richard C. Leegood, Thomas D. Sharkey and Susanne von Caemmerer, from UK, USA and Australia. Twenty-four chapters, 644 pp, Hardcover, ISBN: 978-07923-6143-5 [http://www.springerlink.com/content/978-0-7923-6143-5/]
- **Volume 8 (1999): The Photochemistry of Carotenoids**, edited by Harry A. Frank, Andrew J. Young, George Britton and Richard J. Cogdell, from USA and UK. Twenty chapters, 420 pp, Hardcover, ISBN: 978-0-7923-5942-5 [http://www.springerlink.com/content/978-0-7923-5942-5/]
- **Volume 7 (1998): The Molecular Biology of Chloroplasts and Mitochondria in *Chlamydomonas***, edited by Jean David Rochaix, Michel Goldschmidt-Clermont and Sabeeha Merchant, from Switzerland and USA. Thirty-six chapters, 760 pp, Hardcover, ISBN: 978-0-7923-5174-0 [http://www.springerlink.com/content/978-0-7923-5174-0/]
- **Volume 6 (1998): Lipids in Photosynthesis: Structure, Function and Genetics**, edited by Paul-André Siegenthaler and Norio Murata, from Switzerland and Japan. Fifteen chapters, 332 pp, Hardcover, ISBN: 978-0-7923-5173-3 [http://www.springerlink.com/content/978-0-7923-5173-3/]
- **Volume 5 (1997): Photosynthesis and the Environment**, edited by Neil R. Baker, from UK. Twenty chapters, 508 pp, Hardcover, ISBN: 978-07923-4316-5 [http://www.springerlink.com/content/978-0-7923-4316-5/]
- **Volume 4 (1996): Oxygenic Photosynthesis: The Light Reactions**, edited by Donald R. Ort, and Charles F. Yocum, from USA. Thirty-four chapters, 696 pp, Softcover: ISBN: 978-0-7923- 3684–6; Hardcover, ISBN: 978-0-7923-3683-9 [http://www.springerlink.com/content/978-0-7923-3683-9/]
- **Volume 3 (1996): Biophysical Techniques in Photosynthesis**, edited by Jan Amesz and Arnold J. Hoff, from The Netherlands. Twenty-four chapters, 426 pp, Hardcover, ISBN: 978-0-7923-3642-6 [http://www.springerlink.com/content/978-0-7923-3642-6/]
- **Volume 2 (1995): Anoxygenic Photosynthetic Bacteria**, edited by Robert E. Blankenship, Michael T. Madigan and Carl E. Bauer, from USA. Sixty-two chapters, 1331 pp, Hardcover, ISBN: 978-0-7923-3682-8 [http://www.springerlink.com/content/978-0-7923-3681-5/]
- **Volume 1 (1994): The Molecular Biology of Cyanobacteria**, edited by Donald R. Bryant, from USA. Twenty-eight chapters, 916 pp, Hardcover, ISBN: 978-0-7923-3222-0 [http://www.springerlink.com/content/978-0-7923-3222-0/]

Further information on these books and ordering instructions can be found at http://www.springer.com/series/5599. Contents of volumes 1–29 can also be found at http://www.life.illinois.edu/govindjee/g/References.html.

Special 25% discounts are available to members of the International Society of Photosynthesis Research, ISPR http://www.photosynthesisresearch.org/: See http://www.springer.com/ispr

This Book: Volume 34

"*Photosynthesis: Plastid Biology, Energy Conversion and Carbon Assimilation*" was conceived as a comprehensive treatment touching on most of the processes important for photosynthesis. Most of the chapters provide a broad coverage that, it is hoped, will be accessible to advanced undergraduates, graduate students, and researchers looking to broaden their knowledge of photosynthesis. For biologists, biochemists, and biophysicists, this volume will provide quick background understanding for the breadth of issues in

photosynthesis that are important in research and instructional settings. This volume will be of interest to advanced undergraduates in plant biology, and plant biochemistry and to graduate students and instructors wanting a single reference volume on the latest understanding of the critical components of photosynthesis.

Solar energy is the source of almost all life on this Earth. An important factor in increasing the production of biomass, bioenergy and biofuels, which is needed to solve the global energy crisis, is the overall efficiency of photosynthesis. To manipulate overall efficiency we must understand the basic reactions of photosynthesis. This volume (*Photosynthesis: Plastic Biology, Energy Conversion and Carbon Assimilation*) in the *Advances in Photosynthesis and Respiration* series provides a comprehensive view of the current understanding of photosynthesis; it is divided into several sections to help the readers see the broad categories of photosynthetic processes. The first twenty-nine chapters in this volume cover the topics central to our current understanding of *Photosynthesis*.

A look back can be very informative and help make sense of the present. A historical perspective comes out in many of the chapters. The term "historical" can have different meaning to different people. A history of photosynthesis research (Chapter 30) caps the chapters on various aspects of photosynthesis in the volume; it traces the development of concepts in photosynthesis.

A strong theme in many of the chapters is a different type of history, the course of evolution that led to the current photosynthetic organisms that exist today. A strong evolutionary thread runs through various chapters; evolutionary insights aid in understanding why photosynthesis today has so many of its special properties. In this volume, readers will find discussions of the origins of photosynthesis as well as the future of photosynthesis, including the prospects for engineering artificial photosynthesis. Readers will learn about bacteria that use just parts of the photosynthetic system found in plants and how duplication and specialization in a small number of progenitor pigments, and proteins, gave rise to the vast array of pigments and proteins that are found in photosynthetic systems today. As Theodosius Dobzhansky wrote in 1973, "*Nothing in biology makes sense except in light of evolution*." Photosynthesis is a rich area for the study of evolution. This volume has a number of chapters that tell fascinating stories tracing the evolution of photosynthetic processes including the photosystems (Chapter 1), plastids (Chapter 2), carbon metabolism (Chapter 26), and sucrose metabolism (Chapter 27). Evolutionary perspectives can be found in many of the other chapters as well.

This book is appropriately dedicated to Govindjee, the founding series editor, on the occasion of a new board of advisors and a new co-editor (officially starting from Volume 31). Govindjee's contributions are enormous, and are included in the last three chapters (Chapters 31, 32 and 33) of this book. In my opinion, Govindjee is, perhaps, the best-known photosynthesis researcher alive today.

Authors

The current book contains 33 chapters written by 76 international authors from 20 different countries (Australia, Canada, China, Finland, France, Germany, Greece, Hungary, India, Israel, Italy, Japan, New Zealand, The Netherlands, Russia, Spain, Sweden, Switzerland, United Kingdom, and the United States of America). The series editors give a special thank you to each and every author for their valuable contribution to the successful production of this unique book:

Iwona **A**damska (Germany; Chapter 14); Elizabeth A. Ainsworth (USA; Chapter 29); Suleyman I. Allakhverdiev (Russia; Chapter 12); Yagut Allahverdiyeva (Finland; Chapter 13); Naohiro Aoki (Australia and Japan; Chapter 28); Eva-Mari Aro (Finland; Chapter 13); Neil R. **B**aker (UK; Chapter 23); Olivier Bastien (France; Chapter 9); Roberto Bassi (Italy; Chapter 5); Carl J. Bernacchi (USA; Chapter 29); Basanti Biswal (India; Chapter 10); Udaya C. Biswal (India; Chapter 10); Robert E. Blankenship (USA; Chapter 1); Maryse A. Block (France; Chapter 9); Robert **C**arpentier (Canada; Chapter 12); Wah Soon Chow (Australia; Chapter 24); Robert MacDonald Clegg (USA; Chapter 33); Gabriel Cornic (France; Chapter 23); Roberta Croce (The Netherlands; Chapter 6); Antoine **D**anon (France; Chapter 15); Ildikó Domonkos (Hungary; Chapter 11); Julian J. **E**aton-Rye (New Zealand; Chapters 20, 32); Johannes Engelken (Germany and Spain; Chapter 14); Denis **F**alconet (France; Chapter 2); Wayne D. Frasch (USA; Chapter 22); Hideya

Fukuzawa (Japan; Chapter 25); Robert T. Furbank (Australia; Chapter 28); Zoltán **G**ombos (Chapter 11; Hungary); Mounia **H**eddad (Switzerland; Chapter 14); Jane F. Hill (USA; Chapter 30); Tatsuro Hirose (Japan; Chapter 28); Martin F. Hohmann-Marriott (New Zealand; Chapter 1); Kenneth J. Hoober (USA; Chapter 16); Tassilo Hornung (USA; Chapter 22); Norman P. A. Hüner (Canada; Chapter 19); Robert **I**shmukhametov (USA; Chapter 22); Alexandra G. Ivanov (Canada; Chapter 19); Lixia **J**in-Day (USA; Chapter 22); Juliette Jouhet (France; Chapter 9); Jacques Joyard (France; Chapter 9); Toivo **K**allas (USA; Chapter 21); Aaron Kaplan (Israel; Chapter 25); Vyacheslav V. Kilmov (Russia; Chapter 12); Vladimir D. Kreslavski (Russia; Chapter 12); Andrew D.B. **L**eakey (USA; Chapter 29); Hartmut K. Lichtenthaler (Chapter 4; Germany); Steve P. Long (USA; Chapter 29); Dmitry A. Los (Russia; Chapter 12); John E. Lunn (Germany; Chapter 27); Elspeth **M**acRae (New Zealand; Chapter 27); Eric Marechal (France; Chapter 9); James Martin (USA; Chapter 22); Mamoru Mimuro (Japan; Chapter 12); Iain L. McConnell (USA; Chapter 20); Prasanna Mohanty (Russia and India; Chapter 12); Pranab K. Mohapatra (India; Chapter 10); Tomas Morosinotto (Italy; Chapter 5); Teruo **O**gawa (China; Chapter 25); Donald R. Ort (USA; Chapter 29); Ulrike Oster (Germany; Chapter 8); Gunnar Öquist (Sweden; Chapter 19); George C. **P**apageorgiou (Greece; Chapters 18, 31); Gopal K. Pattanayak (USA; Chapter 3); Mukesh K. **R**avel (India; Chapter 10); Gernot Renger (Germany; Chapter 17); Wolfhart Rüdiger (Germany; Chapter 8); Prafullachandra Vishnu **S**ane (India; Chapter 19); Thomas D. Sharkey (USA; Chapter 26); David Spetzler (USA; Chapter 22); Balázs Szalontai (Hungary; Chapter 11); Baishnab C. **T**ripathy (India; Chapter 3); Jack J. S. **v**an Rensen (The Netherlands; Chapter 20); Klaas J. van Wijk (USA; Chapter 7); Sean E. **W**eise (USA; Chapter 26); Justin **Y**ork (USA; Chapter 22); Xinguang **Z**hu (China; Chapter 29).

Future Advances in Photosynthesis and Respiration and Other Related Books

The readers of the current series are encouraged to watch for the publication of the following books (not necessarily arranged in the order of future appearance):

- The Bioenergetic Processes of Cyanobacteria: From Evolutionary Singularity to Ecological Diversity (Editors: Günter A. Peschek, Christian Obinger, and Gernot Renger) http://www.springer.com/life+sciences/book/978-94-007-0352-0
- Chloroplast Biogenesis: During Leaf Development and Senescence (Editors: Basanti Biswal, Karin Krupinska and Udaya Chand Biswal)
- The Structural Basis of Biological Energy Generation (Editor: Martin Hohmann-Marriott)
- Genomics of Chloroplasts and Mitochondria (Editors: Ralph Bock and Volker Knoop)
- Photosynthesis in Bryophytes and Early Land Plants (Editors: David T. Hanson and Steven K. Rice)

In addition to the above contracted books, the following topics are under consideration:

- Algae, Cyanobacteria, Biofuel and Bioenergy
- Artificial Photosynthesis
- ATP Synthase and Proton Translocation
- Bacterial Respiration II
- Biohydrogen Production
- Carotenoids II
- Cyanobacteria II
- The Cytochromes
- Ecophysiology
- Evolution of Photosynthesis
- Excitation Energy Transfer in Photosynthesis
- The FACE Experiments
- Global Aspects of Photosynthesis
- Green Bacteria and Heliobacteria
- Interactions between Photosynthesis and other Metabolic Processes
- Limits of Photosynthesis: Where do we go from here
- Photosynthesis, Biomass and Bioenergy
- Photosynthesis under Abiotic and Biotic Stress
- Plant Canopies and Photosynthesis
- Plant Respiration II

If you have any interest in editing/co-editing any of the above listed books, or being an author, please send an E-mail to Govindjee at gov@illinois.edu, and/or to me (tsharkey@msu.edu). Suggestions for additional topics are also welcome

In view of the interdisciplinary character of research in photosynthesis and respiration, it is our earnest hope that this series of books will be used in educating students and researchers not only in Plant Sciences, Molecular and Cell Biology, Integrative Biology, Biotechnology, Agricultural Sciences, Microbiology, Biochemistry, Chemical Biology, Biological Physics, and Biophysics, but

also in Agricultural Engineering, Bioengineering, Chemistry, and Physics.

We take this opportunity to thank and congratulate Julian Eaton-Rye and Baishnap Tripathy for their outstanding editorial work; they have done a fantastic job not only in editing, but also in organizing this book for Springer, and for their highly professional dealing with the typesetting process. We have thanked all the 76 authors of this book (see the list above): without their authoritative chapters, there would be no such volume. We give special thanks to A. Lakshmi Praba, Project Manager, SPi Content Solutions – SPi Global, India for directing the typesetting of this book; her expertise has been crucial in bringing this book to completion. We owe Jacco Flipsen, Ineke Ravesloot and André Tournois (of Springer) thanks for their friendly working relation with us that led to the production of this book. Thanks are also due to Govindjee, the Series Founding Editor. Some of the text above was originally written by him and adapted by me. Govindjee has been involved and keenly interested at every stage to bring this book to fruition.

Thomas D. Sharkey
Series Co-Editor, Advances in Photosynthesis and Respiration
Department of Biochemistry and Molecular Biology
Michigan State University
East Lansing, MI 48824, USA
tsharkey@msu.edu

Contents

Part IV: Energy Conversion

Part VI: Climate Change and Photosynthesis

Part VII: Historical Perspective

Part VIII: The Career of Govindjee

Preface

During 1945–1956, Govindjee's Ph.D. mentor, Eugene Rabinowitch, wrote a comprehensive three-volume treatise on photosynthesis; however, today the amount of knowledge makes such a project out of the reach of a single author. Perhaps Govindjee recognized this when he produced his own excellent multi-author two-volume *Photosynthesis* in 1982. However, the Advances in Photosynthesis and Respiration series, under Govindjee's editorial leadership, has provided an ongoing authoritative presentation of photosynthesis and related research over the past 17 years. This book, volume 34 in the series, differs from many of its predecessors in that its scope includes topics in many branches of photosynthesis. This is no accident as the book is dedicated to Govindjee and reflects his far reaching interests and many of the chapters provide excellent introductions to different branches of the subject that are suitable for senior students or for researchers wishing to introduce themselves to aspects other than their own research specialty. The selection of topics also reflects the research interests of Govindjee. These include chapters on photosynthetic water splitting by photosystem II, fluorescence emission by the photosynthetic apparatus, thermoluminescence and the regulation of photosystem II electron transport by bicarbonate.

The material in this book is divided into *eight parts*. The *first part* is a single chapter that introduces the photosynthetic world in all its diversity. The chapter provides a unique perspective on the many ways nature has harvested light to drive photosynthesis and the variety of photosynthetic reaction centers served by these antenna both in prokaryotic and eukaryotic photosynthetic organisms. The *second part* covers nine topics in plastid biochemistry and physiology. Following from the material covered in the first introductory chapter, section two opens with a chapter on the origin, evolution and division of plastids: this is followed by four chapters that introduce chlorophyll and carotenoid biosynthesis, the assembly of pigments into light-harvesting pigment-protein complexes and the diversity of the chlorophyll-binding proteins of plants and cyanobacteria. Section two continues with chapters on the application of proteomics to photosynthesis research, the intricacies of cell signaling between the plastid and the nucleus and the role of the plastid envelope membrane in glycerolipid biosynthesis. Section two concludes with a chapter on leaf senescence and the interconversion of chloroplasts into gerontoplasts.

In *Part III* the subject matter turns to the response of the photosynthetic apparatus to different environmental stress factors. Individual chapters cover the susceptibility and adaptations to low-temperature stress, high temperatures, too much light and environmentally-induced oxidative stress. In *Part IV* the emphasis is on energy conversion and it is in these nine chapters that the topics most closely aligned with the research career of Govindjee are covered. The first of these chapters focuses on light absorption by chlorophyll and the unique biological functions of the accessory chlorophylls *b* and *c*. The next chapter focuses on the apparatus and mechanism of Photosystem II and presents a current understanding of water splitting in oxygenic photosynthesis. Govindjee's many seminal contributions to our understanding of Photosystem II began with establishing basic relationships between chlorophyll *a* fluorescence and photosynthetic reactions: these relationships are explored in the subsequent chapter that addresses fluorescence emission by the photosynthetic apparatus. Together with Don DeVault, Govindjee also formulated the theory of thermoluminescence and this is the next topic in this section of the book. Govindjee also discovered the role of bicarbonate in Photosystem II where it acts as a ligand to the non-heme iron of the photosystem; this subject has a long history going back to early experiments by Otto Warburg and this story is told in a chapter exploring the regulation of Photosystem II electron transport by bicarbonate. The remaining chapters of this section review the pivotal role of the cytochrome b_6f complex in photosynthetic electron transport, the mechanism of energy transduction by the F_1F_0 ATP synthase, electron transport in leaves and finally the currently available technologies for developing artificial photosynthetic systems for the planet's future energy needs.

The *fifth part* of this book turns to the topics of carbon assimilation as well as sucrose synthesis and transport. The uptake of CO_2 by cyanobacteria and microalgae is covered and the diversity of carbon fixing mechanisms together with the operation and control of the Calvin-Benson-Bassham cycle are discussed in a chapter devoted to autotrophic carbon fixation. This section concludes with a chapter providing a unique evolutionary perspective on photosynthetic sucrose biosynthesis and a chapter detailing sucrose transport in higher plants. The *sixth and the seventh parts* each contain a single chapter. The first looks at photosynthesis in the context of climate change and considers photosynthesis in a CO_2 rich atmosphere. The second provides a detailed history of the early pioneers of photosynthesis research. The book concludes with the last section (*Part VIII*) detailing Govindjee's extensive research, teaching and service contributions to the photosynthesis community.

We thank all the contributors to this volume. We have endeavored to edit these chapters to the best of our abilities and we apologize where we have missed something. We hope our readers enjoy learning more about photosynthesis from reading the contributions included here. We thank Govindjee for his inspiration to so many in the field of photosynthesis to do good science, to remember those whose contributions our own work has built on and to take up his example of excellence in teaching to our undergraduate and postgraduate students.

Julian J. Eaton-Rye
Department of Biochemistry
University of Otago
P.O. Box 56
Dunedin
New Zealand

Tel: +64 3 479 7865
Fax: +64 3 479 7866
e-mail: **julian.eaton-rye@otago.ac.nz**

Baishnab C. Tripathy
School of Life Sciences
Jawaharlal Nehru University
New Delhi 110067
India

Tel: +91-11-26704524
Fax: +91-11-26742558
e-mail: **bctripathy@mail.jnu.ac.in**

Thomas D. Sharkey
Michigan State University
Department of Biochemistry and Molecular Biology
410 Biochemistry Building
East Lansing, MI 48824
USA

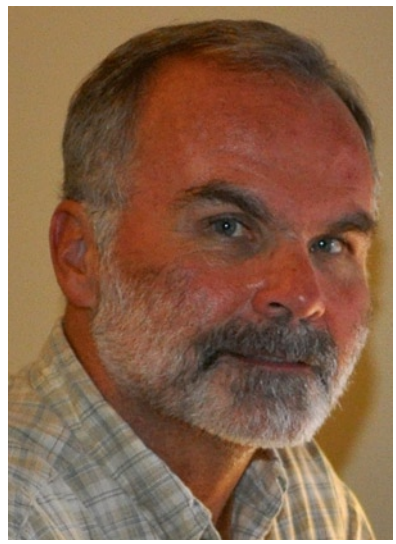
Tel: +1 517 353-3257
e-mail: **tsharkey@msu.edu**

The Editors

Julian J. Eaton-Rye is currently in the Department of Biochemistry at the University of Otago in New Zealand. He completed a BSc Honors degree in Botany from the University of Manchester, UK in 1981 and obtained his Ph.D. (Plant Physiology) in 1987 at the University of Illinois at Urbana-Champaign under the supervision of Govindjee. His Ph.D. thesis research addressed the role of the bicarbonate cofactor in Photosystem II and showed that the reduction of the secondary plastoquinone electron acceptor and the turnover of the two-electron gate were impaired in bicarbonate-depleted membranes consistent with bicarbonate acting as a ligand to the non-heme iron of Photosystem II and participating in the protonation reactions associated with plastoquinone reduction on the acceptor side of the photosystem. He then obtained a Japan Society for the Promotion of Science postdoctoral fellowship (through the Royal Society, UK) and worked with Professor Norio Murata at the National Institute for Basic Biology in Okazaki, Japan (1987–1989). In Professor Murata's laboratory he studied the binding of the manganese-stabilizing protein (MSP or more usually nowadays, PsbO) to isolated Photosystem II complexes and demonstrated the requirement of an N-terminal domain of MSP for the binding of this protein to Photosystem II. In 1989 he moved to the Center for Early Event in Photosynthesis at Arizona State University to take up a postdoctoral position in the laboratory of Professor Wim Vermaas. In Professor Vermaas' laboratory he began working with the cyanobacterial model organism *Synechocystis* sp. PCC 6803, and produced the first site-directed mutations in the chlorophyll *a*-binding core antenna protein CP47 targeting putative chlorophyll ligands and the large hydrophilic loop of this protein that interacts with MSP. In 1993, he moved to Brookhaven National Laboratory as a Senior Research Fellow in the laboratory of Geoffrey Hind and demonstrated, using isoelectric focusing and kinase activity assays, that the then candidate Light-Harvesting Complex II protein kinase was in fact a *substrate* of a then as yet unidentified thylakoid-membrane-associated kinase. Since his appointment to a lectureship in the Department of Biochemistry at the University of Otago in 1994 his research group has studied the role of either the lumenal "extrinsic proteins" of Photosystem II or low-molecular-weight membrane-spanning "auxiliary" Photosystem II subunits found at the monomer-monomer interface of the Photosystem II supercomplex. His laboratory

is also actively studying the role of three additional Photosystem II lipoproteins (Psb27, CyanoP and CyanoQ) that are present in isolated Photosystem II complexes from *Synechocystis* sp. PCC 6803 but are absent from the current atomic resolution structures from the thermophilic cyanobacteria *Thermosynechococcus elongatus* and *T. vulcanus*. This work has produced the first X-ray-derived crystal structure of CyanoQ and NMR solution structures of Psb27 and CyanoP. With respect to other professional activities Julian currently serves on the Executive Committee of the International Society of Photosynthesis and the International Scientific Committee of the Triennial International Symposium on Phototrophic Prokaryotes. He is also a consulting editor for the Advances in Photosynthesis and Respiration book series and an Associate Editor of the New Zealand Journal of Botany. He served as the President of the New Zealand Society for Plant Biologists (2006–2008) and will serve as the President of the New Zealand Institute of Chemistry in 2012.

Baishnab C. Tripathy was born in Kutilo, Cuttack, located on the east eastern coast of India. After 11 years of primary, middle and high school education in a rural setting, he joined Ravenshaw College, Cuttack in 1967, and subsequently Buxi Jagabandhu Bidyadhar (BJB) College, Bhubaneswar in 1969, where he received a BSc (Major: Botany) in 1971. Then he obtained an MSc (Botany) in 1973 form Utkal University, Orissa, India. In 1981, he was awarded a Ph.D. degree, form Jawaharlal Nehru University (JNU), New Delhi, India, for his work on the 'Primary production and role of metal ions on the primary processes of photosynthesis' under the supervision of Professor Prasanna Mohanty, who had obtained his Ph.D. under Govindjee in 1972. During 1981–1983, he was a post-doctoral research associate, with Professors Elizabeth Gross and John S. Rieske, at the Ohio State University, Columbus, Ohio, USA, where he worked on '*The role of cations on chlorophyll a fluorescence and on electron transport from plastocyanin to cytochrome c through complex III of mitochondria*'. From December 1983 till March 1987, he worked with Professor Constantin A Rebeiz, at the University of Illinois at Urbana-Champaign, Illinois, USA on '*Chloroplast biogenesis and biochemistry of chlorophylls*'. In 1987, he joined as an Assistant Professor of Photobiology in the School of Life Sciences, JNU, where he was promoted to an Associate Professor and finally as a Professor in 2002. At JNU, Baishnab teaches and does research in plant physiology and photobiology. His research work has significantly contributed to our knowledge of plant tetrapyrroles and chloroplast biogenesis. His work on plant senescence in relation to chlorophyll metabolism has demonstrated the presence of different sets of enzymes i.e., kinetin-sensitive and kinetin-insensitive that are responsible for the degradation of chlorophyll and protochlorophyllide, respectively. His demonstration of the role of the meristematic layer in the intra- and inter-cellular signaling system in relation to chloroplast development of wheat and rice plants grown under red or red plus blue light, are novel and interesting. At the National Aeronautics and Space Administration (NASA), USA, he has published research papers on photosynthetic responses of plants growing in space. In addition to research articles, he has contributed several chapters to books and has edited books on photosynthesis. He has mentored a large number of Ph.D., MPhil and MSc students. Baishnab is on the editorial board of "*Horticulture, Environment and Biotechnology*". He is a member of the Board of Directors of the Rebeiz Foundation for Basic Research, is a fellow of the National Academy of Sciences, India, of the Indian National Science Academy and of the National Academy of Agricultural Sciences, India.



Thomas D. (Tom) Sharkey obtained his Bachelor's degree in Biology in 1974 from Lyman Briggs College, a residential science college at Michigan State University, East Lansing, Michigan. After 2 years as a research technician, Tom entered a Ph.D. program in the federally funded Plant Research Laboratory at Michigan State University under the mentorship of Professor Klaus Raschke and graduated in 1980 after 3 years and 3 months. Post-doctoral research was carried out with Professor Graham Farquhar at the Australian National University, in Canberra, where he co-authored a landmark review on photosynthesis and stomatal conductance that continues to receive much attention even today. For 5 years, he worked at the Desert Research institute, followed by 20 years as a professor of botany at the University of Wisconsin in Madison. In 2008, Tom became Professor and Chair of the Department of Biochemistry and Molecular Biology at Michigan State University. Tom's research interests center on the exchange of gases between plants and the atmosphere. The biochemistry and biophysics underlying carbon dioxide uptake and isoprene emission from plants form the two major research topics in his laboratory. Among his contributions are measurement of the carbon dioxide concentration inside leaves, and exhaustive study of short-term feedback effects on carbon metabolism, as well as a significant contribution to the elucidation of the pathway by which leaf starch breaks down at night. In the isoprene research field, Tom is recognized as the leading advocate for thermotolerance of photosynthesis as the explanation for why plants emit isoprene. In addition, his laboratory has cloned many of the genes that underlie isoprene synthesis, and he has published many papers on the biochemical regulation of isoprene synthesis. Tom has co-edited two books: T.D. Sharkey, E.A. Holland and H.A. Mooney (eds.) *Trace Gas Emissions from Plants*, Academic, San Diego, CA, 1991; and R.C. Leegood, T.D. Sharkey, and S, von Caemmerer (eds.) Physiology and Metabolism, Advances in Photosynthesis (and Respiration), Volume 9 of this Series, Kluwer (now Springer), Dordrecht, 2000. Tom is a "highly cited researcher" according to the Thomson Reuters Institute for Scientific Information.

Contributors

Iwona Adamska
Department of Physiology and Plant Biochemistry, University of Konstanz, Universitäts Str. 10, D-78457, Konstanz, Germany

Elizabeth A. Ainsworth
USDA/ARS, Department of Plant Biology and Institute for Genomic Biology, University of Illinois, Urbana, IL 61801, USA

Yagut Allahverdiyeva
Laboratory of Plant Physiology and Molecular Biology, Biology Department, University of Turku, Turku FIN-20014, Finland

Suleyman I. Allakhverdiev
Institute of Basic Biological Problems, Russian Academy of Sciences, Pushchino, Moscow Region 142290, Russia;
Institute of Plant Physiology, Russian Academy of Sciences, Moscow 127276, Russia

Naohiro Aoki
CSIRO Plant Industry, GPO Box 1600, Canberra, ACT 2601, Australia
Graduate School of Agricultural and Life Sciences, The University of Tokyo, Tokyo 113–8657, Japan

Eva-Mari Aro
Laboratory of Plant Physiology and Molecular Biology, Biology Department, University of Turku, Turku FIN-20014, Finland

Neil R. Baker
Department of Biological Sciences, University of Essex, Colchester, Essex CO4 3SQ, UK

Roberto Bassi
Dipartimento Scientifico e Tecnologico, Università di Verona, Strada Le Grazie 15, Verona I-37134, Italy

Olivier Bastien
Laboratorie de Physiologie Cellulaire Végétale, CEA-Grenoble, F-38054 Grenoble, France

Carl J. Bernacchi
USDA/ARS, Department of Plant Biology, University of Illinois, Urbana, IL 61801, USA

Basanti Biswal
School of Life Sciences, Sambalpur University, Jyoti Vihar768019, Orissa, India

Udaya C. Biswal
School of Life Sciences, Sambalpur University, Jyoti Vihar 768019, Orissa, India

Robert E. Blankenship
Departments of Biology and Chemistry, Washington University, Campus Box 1137, St. Louis, MO 63130, USA

Maryse A. Block
Laboratorie de Physiologie Cellulaire Végétale, CEA-Grenoble, F-38054, Grenoble, France

Robert Carpentier
Groupe de Recherche en Biologie Végétable, Université du Québec à Trois-Rivières, C.P. 500, Trois-Rivières, Québec G9A 5H7, Canada

Wah Soon Chow
Photobioenergetics Group, School of Biology, College of Medicine, Biology and Environment, The Australian National University, GPO Box 475, Canberra, ACT 2601, Australia

Robert MacDonald Clegg
Department of Physics, 301 Loomis Laboratory, University of Illinois at Urbana-Champaign, 1110 West Green Street, Urbana, IL 61801–3080, USA

Gabriel Cornic
Laboratoire d'Ecologie Systématique et Evolution, Faculté des Sciences d'Orsay, Bât. 362, Université Paris Sud-XI, F-91405 Orsay, France

Roberta Croce
Department of Biophysical Chemistry, Groningen Biotechnology and Biological Sciences Institute, University of Groningen, Nijenborgh 4, 9747 Groningen AG, The Netherlands

Antoine Danon
Laboratoire Physiologie Cellulaire et Moléculaire des Plantes, Université Pierre et Marie Curie, UR5 UPMC, EAC7180 CNRS, Case courrier 156, BâtC, pièce 317, 4 Place Jussieu, 75252, Paris Cedex 05, France

Ildikó Domonkos
Institute of Plant Biology, Biological Research Center, Hungarian Academy of Sciences, Szeged H-6701, Hungary

Julian J. Eaton-Rye
Department of Biochemistry, University of Otago, P.O. Box 56, Dunedin 9054, New Zealand

Johannes Engelken
Department of Physiology and Plant Biochemistry, University of Konstanz, Universitäts Str. 10, D-78457 Konstanz, Germany
Institute of Evolutionary Biology (CSIC-UPF), Pompeu Fabra University, Barcelona, Spain

Denis Falconet
Laboratoire de Physiologie Cellulaire Végétale, UMR 5168 CNRS-CEA-INRA-Université Joseph Fourier Grenoble, iRTSV-LPCV, CEA-Grenoble, Grenoble Cedex 9 38054, France

Wayne D. Frasch
School of Life Sciences, Arizona State University, Tempe, AZ 85287–4501, USA

Hideya Fukuzawa
Division of Integrated Life Science, Graduate School of Biostudies, Kyoto University, Kyoto 606–8502, Japan

Robert T. Furbank
CSIRO Plant Industry, GPO Box 1600, Canberra, ACT 2601, Australia

Zoltán Gombos
Institute of Plant Biology, Biological Research Center, Hungarian Academy of Science, Szeged H-6701, Hungary

Mounia Heddad
Department of Molecular and Plant Biology, University of Geneva, 30 Quai Ernest Ansermet 1211 Geneva, Switzerland

Jane F. Hill
8211 Hawthorne Road, Bethesda, MD 20817, USA

Tatsuro Hirose
National Agricultural Research Center, Joetsu, Niigara 943–0193, Japan

Martin F. Hohmann-Marriott
Department of Biochemistry, University of Otago, P.O. Box 56, Dunedin 9054, New Zealand

J. Kenneth Hoober
School of Life Sciences, Arizona State University, Tempe, AZ 85287–4501, USA

Tassilo Hornung
School of Life Sciences, Arizona State University, Tempe, AZ 85287–4501, USA

Norman P. A. Hüner
Department of Biology and The Biotron, Experimental Climate Change Research Centre, University of Western Ontario, 1151 Richmond Str. N., London N6A 5B7, Canada

Robert Ishmukhametov
School of Life Sciences, Arizona State University, Tempe, AZ 85287–4501, USA

Alexander G. Ivanov
Department of Biology and The Biotron, Experimental Climate Change Research Centre, University of Western Ontario, 1151 Richmond Str. N., London, N6A 5B7, Canada

Lixia Jin-Day
School of Life Sciences, Arizona State University, Tempe, AZ 85287–4501, USA

Juliette Jouhet
Laboratorie de Physiologie Cellulaire Végétale, CEA-Grenoble, F-38054 Grenoble, France

Jacques Joyard
Laboratorie de Physiologie Cellulaire Végétale, CEA-Grenoble, F-38054 Grenoble, France

Toivo Kallas
Department of Biology and Microbiology, University of Wisconsin-Oshkosh, 800 Algoma Boulevard, Oshkosh, WI 54901, USA

Aaron Kaplan
Department of Plant and Environmental Sciences, The Hebrew University of Jerusalem, Jerusalem, Israel

Vyackeslav V. Kilmov
Institute of Basic Biological Problems, Russian Academy of Sciences, Pushchino, Moscow Region 142290, Russia

Vladimir D. Kreslavski
Institute of Basic Biological Problems, Russian Academy of Sciences, Pushchino, Moscow Region 142290, Russia

Andrew D.B. Leakey
Department of Plant Biology and Institute for Genomic Biology, University of Illinois, Urbana, IL 61801, USA

Hartmut K. Lichtenthaler
Botanisches Institut (Molecular Biology and Biochemistry of Plants), University of Karlsruhe, Kaiserstr. 12, D-76133 Karlsruhe, Germany

Stephen P. Long
Department of Plant Biology and Department of Crop Science, Institute for Genomic Biology, University of Illinois, Urbana, IL 61801, USA

Dmitry A. Los
Institute of Plant Physiology, Russian Academy of Sciences, Moscow 127276, Russia

John E. Lunn
Max Planck Institut für Molekulare Pflanzenphysiologie, Am Mühlenberg 1, 14424, Potsdam, Germany

Elspeth MacRae
Lunn Scion, Te Papa Tipu Innovation Park, 49 Sala Street, Private Bag 3020 Rotorua, New Zealand

Eric Maréchal
Laboratorie de Physiologie Cellulaire Végétale, CEA-Grenoble, F-38054 Grenoble, France

James Martin
School of Life Sciences, Arizona State University, Tempe, AZ 85287–4501, USA

Iain L. McConnell
Department of Chemistry, Yale University, 208107, New Haven, CT 06520–8107, USA

Mamoru Mimuro
Graduate School of Human and Environmental Studies, Kyoto University, Kyoto 606–8501, Japan

Prasanna Mohanty
Regional Plant Resource Center, Nayapalli, Bhubaneswar, 751015, India;
Jawaharlal Nehru University, New Delhi 11006, India

Pranab K. Mohapatra
School of Life Sciences, Sambalpur University, Jyoti Vihar 768019, Orissa, India

Tomas Morosinotto
Dipartimento di Biologia, Università di Padova, Via Ugo Bassi 58, Padova 35131, Italy

Teruo Ogawa
Institute of Plant Physiology and Ecology, Shanghai 200032, China

Gunnar Öquist
Umeå Plant Science Center, Department of Plant Physiology, University of Umeå, Umeå, SE-90187, Sweden

Donald R. Ort
USDA/ARS, Department of Plant Biology, Department of Crop Science and Institute for Genomic Biology, University of Illinois, Urbana, IL 61801, USA

Ulrike Oster
Department Biologie I, Botanik der Ludwig-Maximilians-Universität, Menzinger Str. 67, D-80638 Munich, Germany

George C. Papageorgiou
Institute of Biology, National Center for Scientific Research Demokritos, Athens 153 10, Greece

Gopal K. Pattanayak
Department of Molecular Genetics and Cell Biology, University of Chicago, 1103 East 57th Street, EBC 409, Chicago, IL 60637, USA

Mukesh K. Ravel
Department of Chemistry, G.M. College (Autonomous), Sambalpur, 768004 Orissa, India

Gernot Renger
Technische Universität Berlin, Institut für Chemie, Max-Volmer-laboratorium für Biophysikalische Chemie, Straβe des 17. Juni 135, D-10623 Berlin, Germany

Wolfhart Rüdiger
Department Biologie, I, Botanik der Ludwig-Maximilians-Universität, Menzinger Str. 67, D-80638 Munich, Germany

Prafullachandra Vishnu Sane
Jain Irrigation Systems Limited, Jain Hills, Jalgaon 425001, India

Thomas D. Sharkey
Department of Biochemistry and Molecular Biology, Michigan State University, 410 Biochemistry Building, East Lansing, MI 48824–1319, USA

David Spetzler
School of Life Sciences,
Arizona State University, Tempe,
AZ 85287-4501, USA

Balázs Szalontai
Institute of Biophysics, Biological Research Center, Hungarian Academy of Science, Szeged H-6701, Hungary

Baishnab C. Tripathy
School of Life Sciences, Jawaharlal Nehru University, New Delhi 110067, India

Jack J.S. van Rensen
Laboratory of Plant Physiology, Wageningen University, 658, 6700 AR, Wageningen, The Netherlands

Klaas J. van Wijk
Department of Plant Biology, Cornell University, Emerson Hall, Room 332, Ithaca, NY 14853, USA

Sean E. Weise
Department of Biochemistry and Molecular Biology, Michigan State University,
410 Biochemistry Building, East Lansing, MI 48824–1319, USA

Justin York
School of Life Sciences, Arizona State University, Tempe, AZ 85287–4501, USA

Xinguang Zhu
Institute for Genomic Biology, University of Illinois, Urbana, IL 61801, USA
Plant Systems Biology Group, Institute of Computational Biology, Chinese Academy of Sciences/Max Planck Society of Germany, Shanghai, China

Author Index