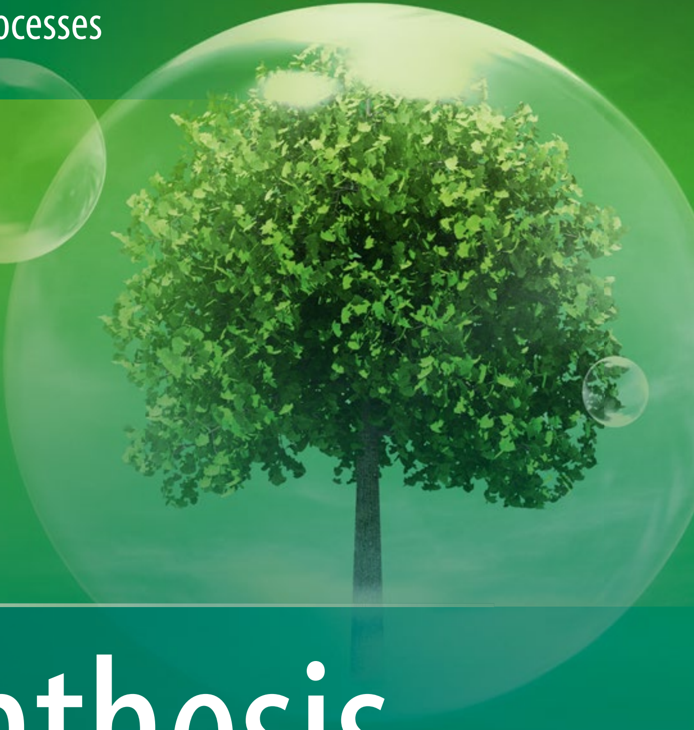
Advances in Photosynthesis and Respiration 45
Including Bioenergy and Related Processes



Anthony W. D. Larkum
Arthur R. Grossman
John A. Raven *Editors*

Photosynthesis in Algae: Biochemical and Physiological Mechanisms

Springer

Photosynthesis in Algae: Biochemical and Physiological Mechanisms

Living stromatolites in intertidal region of Carbla in Hamelin Pool, Shark Bay, Western Australia. These biologically-generated structures are basically small limestone rocks with a superficial mat of many kinds of eubacteria including many cyanobacteria and several kinds of anoxygenic photosynthetic bacteria and sulfur bacteria. They are thought to be similar to fossil structures, which were the first known living structures on the Earth more than 3.5 billion years ago, and which were also the site of the precursors to cyanobacteria and anoxygenic photosynthetic bacteria. Photo by Warwick Hillier, Research School of Biological Sciences, Australian National University, Canberra, Australia

Advances in Photosynthesis and Respiration
Including Bioenergy and Related Processes

VOLUME 45

The book series Advances in Photosynthesis and Respiration – Including Bioenergy and Related Processes provides a comprehensive and state-of-the-art account of research in photosynthesis, respiration, bioenergy production and related processes. Virtually all life on our planet Earth ultimately depends on photosynthetic energy capture and conversion to energy-rich organic molecules. These are used for food, fuel, and fiber. Photosynthesis is the source of almost all Bioenergy on Earth. The fuel and energy uses of photosynthesized products and processes have become an important area of study and competition between food and fuel has led to resurgence in photosynthesis research. This series of books spans topics from physics to agronomy and medicine; from femtosecond processes through season-long production to evolutionary changes over the course of the history of the Earth; from the photophysics of light absorption, excitation energy transfer in the antenna to the reaction centers, where the highly-efficient primary conversion of light energy to charge separation occurs, through intermediate electron transfer reactions, to the physiology of whole organisms and ecosystems; and from X-ray crystallography of proteins to the morphology of organelles and intact organisms. In addition to photosynthesis in natural systems, genetic engineering of photosynthesis and artificial photosynthesis is included in this series. 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 and related energy processes. This series is designed to improve understanding of photosynthesis and bioenergy processes at many levels both to improve basic understanding of these important processes and to enhance our ability to use photosynthesis for the improvement of the human condition.

For more information, please contact the Series Editors Thomas D. Sharkey, Michigan State University, East Lansing, MI, U.S.A. E-mail: tsharkey@msu.edu; phone 1-517-353-0804 or Julian J. Eaton-Rye, Department of Biochemistry, University of Otago, New Zealand, E-mail: julian.eaton-rye@otago.ac.nz; phone 64-(0)3-479-7865. A complete list of references listed per volume can be found following this link: http://www.life.uiuc.edu/govindjee/Reference-Index.htm

More information about this series is available at: http://www.springer.com/series/5599

Photosynthesis in Algae: Biochemical and Physiological Mechanisms

Edited by

Anthony W. D. Larkum
Global Climate Custer, University of Technology Sydney,
Ultimo, NSW, Australia

Arthur R. Grossman
Department of Plant Biology, Carnegie Institution for Science,
Stanford University
Stanford, CA, USA

and

John A. Raven
Division of Plant Sciences, University of Dundee
at the JHI, Dundee, UK

Springer

Editors
Anthony W. D. Larkum
Global Climate Custer
University of Technology Sydney
Ultimo, NSW, Australia

John A. Raven
Division of Plant Sciences
University of Dundee at the JHI
Dundee, UK

Arthur R. Grossman
Department of Plant Biology, Carnegie
Institution for Science
Stanford University
Stanford, CA, USA

ISSN 1572-0233 ISSN 2215-0102 (electronic)
Advances in Photosynthesis and Respiration
ISBN 978-3-030-33396-6 ISBN 978-3-030-33397-3 (eBook)
https://doi.org/10.1007/978-3-030-33397-3

This Springer imprint is published by the registered company Springer Nature Switzerland AG.
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

From the Series Editors

Advances in Photosynthesis and Respiration Including Bioenergy and Related Processes

Volume 45: Photosynthesis in Algae: Biochemical and Physiological Mechanisms

Collectively, algae are a diverse group of eukaryotes including large multicellular organisms such as kelps and many unicellular species. The number of algal species on the planet is not known, but estimates suggest tens of thousands. Their diversity ensures the algae are represented in many, if not all, ecosystems, and as such, they are of major importance as primary producers: they also represent an important group of organisms that benefit mankind. Many nations and cultures already utilize algae for food and fertilizer and a wide range of products such as agar and alginates. It is also recognized that algal cells have the potential to produce more biomass per unit area in a year than any other form of biomass: there is thus great potential for the production of biofuels and other high-value organic compounds.

In volume 45 of the Advances in Photosynthesis and Respiration (AIPH) series, Anthony Larkum, Arthur Grossman, and John Raven have assembled a team of experts on algal biochemistry, biophysics, and molecular biology to consider the diversity of algal photosynthesis, recognizing that these organisms (including the *Cyanobacteria*) can provide new knowledge for creative ways to apply algal photosynthesis to the many issues facing humanity today, from conservation biology to food and energy security. This volume joins volume 14 (*Photosynthesis in Algae*, edited by Anthony Larkum, Susan Douglas, and John Raven) in providing an extensive introduction to the molecular mechanisms utilized by the algae and the enormous potential that is stored in the gene pool of this vast group of organisms.

Authors of Volume 45

The current volume exemplifies the tradition of the AIPH book series in being an international book. It has authors from the following 12 countries: Australia (6), Canada (1), the Czech Republic (3), France (4), Germany (1), Italy (4), Hungary (2), Portugal (1), Sweden (1), Switzerland (1), the UK (4), and the USA (9). There are 37 authors (including the three editors) who, as noted above, are experts in the field of algal photosynthesis. Alphabetically (by last names), they are John **B**eardall, Erica Belgio, Debashish Bhattacharya, Claudia Büchel, Douglas **C**ampbell, Anna Paola Casazza, Paul M.G. Curmi, Geoffry A. **D**avis, Jeffery A. Davis, Nicholas **F**isher, Myriam M.M. **G**oudet, Howard Griffiths, Arthur R. Grossman, Parisa **H**eydarizadeh, Radek **K**aňa, Atsuko Kanazawa, Diana Kirilovsky, David Kramer, Anthony W.D. **L**arkum, Justine **M**archand, Moritz Meyer, Peter **N**eofotis, Ondřej **P**rášil, Dana C. Price, Antonietta **Q**uigg, Harry W. **R**athbone, John A. Raven, Jean-David Rochaix, Stefano

Santabarbara, Benoît Schoefs, João Serôdio, Cornelia Spetea, Milan Szabo, Imre Vass, and Robert Willows. We are grateful for their efforts in making this important volume.

Our Books

We list below information on the 44 volumes that have been published thus far (see http://www.springer.com/series/5599 for the series web site). Electronic access to individual chapters depends on subscription (ask your librarian), but Springer provides free downloadable front matter as well as indexes for all volumes. The available web sites of the books in the Series are listed below:

- **Volume 44 (2018)** ***The Leaf: A Platform for Performing Photosynthesis***, edited by William W. Adams III from the USA and Ichiro Terashima from Japan, with 14 chapters, 575 pp, hardcover ISBN 978-3-319-93592-8, eBook ISBN 978-3-319-93594-2 [http://www.springer.com/gp/book/9783319935928]
- **Volume 43 (2018)** ***Plant Respiration: Metabolic Fluxes and Carbon Balance***, edited by Guillaume Tcherkez from Australia and Jaleh Ghashghaie from France, with 18 chapters, 302 pp, hardcover ISBN 978-3-319-68701-8, eBook ISBN 978-3-319-68703-2 [http://www.springer.com/us/book/9783319687018]
- **Volume 42 (2016)** ***Canopy Photosynthesis: From Basics to Applications***, edited by Kouki Hikosaka from Japan, Ülo Niinemets from Estonia, and Neils P.R. Anten from the Netherlands, with 15 chapters, 423 pp, hardcover ISBN 978-94-017-7290-7, eBook ISBN 978-94-017-7291-4 [http://www.springer.com/book/9789401772907]
- **Volume 41 (2016)** ***Cytochrome Complexes: Evolution, Structures, Energy Transduction, and Signaling***, edited by William A. Cramer and Toivo Kallas from the USA, with 35 chapters, 734 pp, hardcover ISBN 978-94-017-7479-6, eBook ISBN 978-94-017-7481-9 [http://www.springer.com/book/9789401774796]
- **Volume 40 (2014)** ***Non-Photochemical Quenching and Energy Dissipation in Plants, Algae and Cyanobacteria***, edited by Barbara Demmig-Adams, Győző Garab, William W. Adams III, and Govindjee from the USA and Hungary, with 28 chapters, 649 pp, hardcover ISBN 978-94-017-9031-4, eBook ISBN 978-94-017-9032-1 [http://www.springer.com/life+sciences/plant+sciences/book/978-94-017-9031-4]
- **Volume 39 (2014)** ***The Structural Basis of Biological Energy Generation***, edited by Martin F. Hohmann-Marriott from Norway, with 24 chapters, 483 pp, hardcover ISBN 978-94-017-8741-3, eBook ISBN 978-94-017-8742-0 [http://www.springer.com/life+sciences/book/978-94-017-8741-3]
- **Volume 38 (2014)** ***Microbial BioEnergy: Hydrogen Production***, edited by Davide Zannoni and Roberto De Philippis from Italy, with 18 chapters, 366 pp, hardcover ISBN 978-94-017-8553-2, eBook ISBN 978- 94-017-8554-9 [http://www.springer.com/life+sciences/plant+sciences/book/978-94-017-8553-2]
- **Volume 37 (2014)** ***Photosynthesis in Bryophytes and Early Land Plants***, edited by David T. Hanson and Steven K. Rice from the USA, with 18 chapters, approximately 342 pp, hardcover ISBN 978-94-007-6987-8, eBook ISBN 978-94-007-6988-5 [http://www.springer.com/life+sciences/plant+sciences/book/978-94-007-6987-8]
- **Volume 36 (2013)** ***Plastid Development in Leaves During Growth and Senescence***, edited by Basanti Biswal, Karin Krupinska, and Udaya Biswal from India and Germany, with 28 chapters, 837 pp, hardcover ISBN 978-94-007-5723-33, eBook ISBN 978-94-007-5724-0 [http://www.springer.com/life+sciences/plant+sciences/book/978-94-007-5723-3]
- **Volume 35 (2012)** ***Genomics of Chloroplasts and Mitochondria***, edited by Ralph Bock and Volker Knoop from Germany, with 19

chapters, 475 pp, hardcover ISBN 978-94-007-2919-3 eBook ISBN 978-94-007-2920-9 [http://www.springer.com/life+sciences/plant+sciences/book/978-94-007-2919-3]

- **Volume 34 (2012)** ***Photosynthesis: Plastid Biology, Energy Conversion and Carbon Assimilation***, edited by Julian J. Eaton-Rye, Baishnab C. Tripathy, and Thomas D. Sharkey from New Zealand, India, and the USA, with 33 chapters, 854 pp, hardcover ISBN 978-94-007-1578-3, eBook ISBN 978-94-007-1579-0 [http://www.springer.com/life+sciences/plant+sciences/book/978-94-007-1578-3]
- **Volume 33 (2012)** ***Functional Genomics and Evolution of Photosynthetic Systems***, edited by Robert L. Burnap and Willem F.J. Vermaas from the USA, with 15 chapters, 428 pp, hardcover ISBN 978-94-007-1532-5, softcover ISBN 978-94-007-3832-4, eBook ISBN 978-94-007-1533-2 [http://www.springer.com/life+sciences/book/978-94-007-1532-5]
- **Volume 32 (2011)** ***C_4 Photosynthesis and Related CO_2 Concentrating Mechanisms***, edited by Agepati S. Raghavendra and Rowan Sage from India and Canada, with 19 chapters, 425 pp, hardcover ISBN 978-90-481-9406-3, softcover ISBN 978-94-007-3381-7, eBook ISBN 978-90-481-9407-0 [http://www.springer.com/life+sciences/plant+sciences/book/978-90-481-9406-3]
- **Volume 31 (2010)** ***The Chloroplast: Basics and Applications***, edited by Constantin Rebeiz, Christoph Benning, Hans J. Bohnert, Henry Daniell, J. Kenneth Hoober, Hartmut K. Lichtenthaler, Archie R. Portis, and Baishnab C. Tripathy from the USA, Germany, and India, with 25 chapters, 451 pp, hardcover ISBN 978-90-481-8530-6, softcover ISBN 978-94-007-3287-2, eBook ISBN 978-90-481-8531-3 [http://www.springer.com/life+sciences/plant+sciences/book/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, with 20 chapters, 506 pp, hardcover ISBN 978-90-481-2862-4, softcover ISBN 978-94-007-3073-1, eBook ISBN 978-90-481-2863-1 [http://www.springer.com/life+sciences/plant+sciences/book/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 the USA, with 20 chapters, 525 pp, hardcover ISBN 978-1-4020-9236-7, softcover ISBN 978-94-007-1533-2, eBook ISBN 978-1-4020-9237-4 [http://www.springer.com/life+sciences/plant+sciences/book/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 the UK, the USA, and Canada, with 48 chapters, 1053 pp, hardcover ISBN 978-1-4020-8814-8, eBook ISBN 978-1-4020-8815-5 [http://www.springer.com/life+sciences/plant+sciences/book/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 the USA, with 24 chapters, 551 pp, hardcover ISBN 978-4020-6862-1, softcover ISBN 978-90-481-7742-4, eBook ISBN 978-1-4020-6863-8 [http://www.springer.com/life+sciences/plant+sciences/book/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, with 24 chapters, 548 pp, hardcover ISBN 978-1-4020-8249-8, softcover ISBN 978-90-481-7820-9, eBook ISBN 978-1-4020-8250-4 [http://www.springer.com/life+sciences/plant+sciences/book/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, with 37 chapters, 603 pp, hardcover ISBN 978-1-40204515-8, softcover ISBN 978-90-481-7140-8, eBook ISBN 978-1-4020-4516-5 [http://www.springer.com/life+sciences/plant+sciences/book/978-1-4020-4515-8]

- **Volume 24 (2006)** ***Photosystem I: The Light-Driven Plastocyanin:Ferredoxin Oxidoreductase***, edited by John H. Golbeck from the USA, with 40 chapters, 716 pp, hardcover ISBN 978-1-40204255-3, softcover ISBN 978-90-481-7088-3, eBook ISBN 978-1-4020-4256-0 [http://www.springer.com/life+sciences/plant+sciences/book/978-1-4020-4255-3]
- **Volume 23 (2006)** ***The Structure and Function of Plastids***, edited by Robert R. Wise and J. Kenneth Hoober from the USA, with 27 chapters, 575 pp, softcover ISBN: 978-1-4020-6570–6; hardcover ISBN 978-1-4020-4060-3, softcover ISBN 978-1-4020-6570-5, eBook ISBN 978-1-4020-4061-0 [http://www.springer.com/life+sciences/plant+sciences/book/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, with 34 chapters, 786 pp, hardcover ISBN 978-1-4020-4249-2, eBook ISBN 978-1-4020-4254-6 [http://www.springer.com/life+sciences/plant+sciences/book/978-1-4020-4249-2]
- **Volume 21 (2006)** ***Photoprotection, Photoinhibition, Gene Regulation, and Environment***, edited by Barbara Demmig-Adams, William W. Adams III, and Autar K. Mattoo from the USA, with 21 chapters, 380 pp, hardcover ISBN 978-14020-3564-7, softcover ISBN 978-1-4020-9281-7, eBook ISBN 978-1-4020-3579-1 [http://www.springer.com/life+sciences/plant+sciences/book/978-1-4020-3564-7]
- **Volume 20 (2006)** ***Discoveries in Photosynthesis***, edited by Govindjee, J. Thomas Beatty, Howard Gest, and John F. Allen from the USA, Canada, and the UK, with 111 chapters, 1304 pp, hardcover ISBN 978-1-4020-3323-0, eBook ISBN 978-1-4020-3324-7 [http://www.springer.com/life+sciences/plant+sciences/book/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 the USA, with 31 chapters, 820 pp, hardcover ISBN 978-1-4020-3217-2, softcover ISBN 978-90-481-3882-1, eBook ISBN 978-1-4020-3218-9 [http://www.springer.com/life+sciences/biochemistry+%26+biophysics/book/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, with 13 chapters, 250 pp, hardcover ISBN978-14020-3588-3, softcover ISBN 978-90-481-6903-0, eBook ISBN 978-1-4020-3589-0 [http://www.springer.com/life+sciences/plant+sciences/book/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, with 14 chapters, 325 pp, hardcover ISBN: 978-1-4020-2399-6, softcover ISBN 978-90-481-6651-0, eBook ISBN 978-1-4020-2400-9 [http://www.springer.com/life+sciences/cell+biology/book/978-1-4020-2399-6]
- **Volume 16 (2004)** ***Respiration in Archaea and Bacteria: Diversity of Prokaryotic Respiratory Systems***, edited by Davide Zannoni from Italy, with 13 chapters, 310 pp, hardcover ISBN 978-14020-2002-5, softcover ISBN 978-90-481-6571-1, eBook ISBN 978-1-4020-3163-2 [http://www.springer.com/life+sciences/plant+sciences/book/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 with 13 chapters,

350 pp, hardcover ISBN 978-1-4020-2001-8, softcover ISBN 978-90-481-6570-4, eBook ISBN 978-1-4020-3163-2 [http://www.springer.com/life+sciences/biochemistry+%26+biophysics/book/978-1-4020-2001-8]

- **Volume 14 (2004)** ***Photosynthesis in Algae***, edited by Anthony W.D. Larkum, Susan Douglas, and John A. Raven from Australia, Canada, and the UK, with 19 chapters, 500 pp, hardcover ISBN 978-0-7923-6333-0, softcover ISBN 978-94-010-3772-3, eBook ISBN 978-94-007-1038-2 [http://www.springer.com/life+sciences/plant+sciences/book/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 the USA, with 17 chapters, 544 pp, hardcover ISBN 978-07923-6335-4, softcover ISBN 978-90-481-5468-5, eBook ISBN 978-94-017-2087-8 [http://www.springer.com/life+sciences/plant+sciences/book/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 the UK and France, with 16 chapters, 304 pp, hardcover ISBN 978-07923-6336-1, softcover ISBN 978-90-481-5469-2, eBook ISBN 978-0-306-48138-3 [http://www.springer.com/life+sciences/plant+sciences/book/978-0-7923-6336-1]
- **Volume 11 (2001)** ***Regulation of Photosynthesis***, edited by Eva-Mari Aro and Bertil Andersson from Finland and Sweden, with 32 chapters, 640 pp, hardcover ISBN 978-0-7923-6332-3, softcover ISBN 978-94-017-4146-0, eBook ISBN 978-0-306-48148-2 [http://www.springer.com/life+sciences/plant+sciences/book/978-0-7923-6332-3]
- **Volume 10 (2001)** ***Photosynthesis: Photobiochemistry and Photobiophysics***, edited by Bacon Ke from the USA, with 36 chapters, 792 pp, hardcover ISBN 978-0-7923-6334-7, softcover ISBN 978-0-7923-6791-8, eBook ISBN 978-0-306-48136-9 [http://www.springer.com/life+sciences/plant+sciences/book/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 the UK, the USA, and Australia, with 24 chapters, 644 pp, hardcover ISBN 978-07923-6143-5, softcover ISBN 978-90-481-5386-2, eBook ISBN 978-0-306-48137-6 [http://www.springer.com/life+sciences/plant+sciences/book/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 the USA and the UK, with 20 chapters, 420 pp, hardcover ISBN 978-0-7923-5942-5, softcover ISBN 978-90-481-5310-7, eBook ISBN 978-0-306-48209-0 [http://www.springer.com/life+sciences/plant+sciences/book/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 the USA, with 36 chapters, 760 pp, hardcover ISBN 978-0-7923-5174-0, softcover ISBN 978-94-017-4187-3, eBook ISBN 978-0-306-48204-5 [http://www.springer.com/life+sciences/plant+sciences/book/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, with 15 chapters, 332 pp, hardcover ISBN 978-0-7923-5173-3, softcover ISBN 978-90-481-5068-7, eBook ISBN 978-0-306-48087-4 [http://www.springer.com/life+sciences/plant+sciences/book/978-0-7923-5173-3]
- **Volume 5 (1997)** ***Photosynthesis and the Environment***, edited by Neil R. Baker from the UK, with 20 chapters, 508 pp, hardcover ISBN 978-07923-4316-5, softcover ISBN 978-90-481-4768-7, eBook ISBN 978-0-306-

48135-2 [http://www.springer.com/life+sciences/plant+sciences/book/978-0-7923-4316-5]
- **Volume 4 (1996)** ***Oxygenic Photosynthesis: The Light Reactions***, edited by Donald R. Ort and Charles F. Yocum from the USA, with 34 chapters, 696 pp, hardcover ISBN 978-0-7923-3683-9, softcover ISBN 978-0-7923-3684–6, eBook ISBN 978-0-306-48127-7 [http://www.springer.com/life+sciences/plant+sciences/book/978-0-7923-3683-9]
- **Volume 3 (1996)** ***Biophysical Techniques in Photosynthesis***, edited by Jan Amesz and Arnold J. Hoff from the Netherlands, with 24 chapters, 426 pp, hardcover ISBN 978-0-7923-3642-6, softcover ISBN 978-90-481-4596-6, eBook ISBN 978-0-306-47960-1 [http://www.springer.com/life+sciences/plant+sciences/book/978-0-7923-3642-6]
- **Volume 2 (1995)** ***Anoxygenic Photosynthetic Bacteria***, edited by Robert E. Blankenship, Michael T. Madigan, and Carl E. Bauer from the USA, with 62 chapters, 1331 pp, hardcover ISBN 978-0-7923-3682-8, softcover ISBN 978-0-7923-3682-2, eBook ISBN 978-0-306-47954-0 [http://www.springer.com/life+sciences/plant+sciences/book/978-0-7923-3681-5]
- **Volume 1 (1994)** ***The Molecular Biology of Cyanobacteria***, edited by Donald R. Bryant from the USA, with 28 chapters, 916 pp, hardcover ISBN 978-0-7923-3222-0, softcover ISBN 978-0-7923-3273-2, eBook ISBN 978-94-011-0227-8 [http://www.springer.com/life+sciences/plant+sciences/book/978-0-7923-3222-0]

Further information on these books and ordering instructions is available at http://www. springer.com/series/5599.

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

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 forthcoming books (not necessarily arranged in the order of future appearance):

- *Photosynthesis and Climate Change* (working title) (Editors: Katie M. Becklin, Joy K. Ward, and Danielle A. Way)
- *Cyanobacteria* (Editor: Donald Bryant)
- *Photosynthesis in Algae: Biofuels and Value-Added Products* (Editors: Anthony Larkum and John Raven)
- *Our Photosynthetic Planet* (Editors: Mike Behrenfeld, Joe Berry, Lianhong Gu, Nancy Jiang, Anastasia Romanou, and Anthony Walker)
- *Modeling Photosynthesis and Growth* (Editors: Xin-Guang Zhu and Thomas D. Sharkey)

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

Algae, *Cyanobacteria*: Biofuel and Bioenergy
Artificial Photosynthesis
ATP Synthase: Structure and Function
Bacterial Respiration II
Evolution 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

If you have any interest in editing/coediting any of the above listed books or being an author, please send an e-mail to Tom Sharkey (tsharkey@msu.edu) and/or to Julian Eaton-Rye (julian.eaton-rye@otago.ac.nz). Suggestions for additional topics are also welcome. Instructions for writing chapters in books in our series are available by sending e-mail requests to one or both of us.

We take this opportunity to thank and congratulate Anthony Larkum, Arthur Grossman, and John Raven for their outstanding editorial work; they have collectively done an excellent job not only in editing but also in organizing this book for all of us, and for their highly professional dealing with the reviewing process. We thank all 37 authors of this book (see the list given earlier and on the following pages); without their authoritative chapters, there would be no such volume. We give special thanks to Mr. Joseph Daniel of SPi Global, India, for directing the typesetting of this book. Once again, his expertise has been crucial in guiding the final steps that have brought this book to completion. We also thank Jacco Flipsen and Ineke Ravesloot (of Springer) for their friendly working relation with us that led to the production of this book and thank Zuzana Bernhart and her team at Springer for their ongoing organization and assistance with the AIPH series.

January 6, 2020

Thomas D. Sharkey
Biochemistry and
Molecular Biology
Michigan State University
East Lansing, MI, USA

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

Series Editors

A 2017 informal photograph of Govindjee (right) and his wife, Rajni (left), in Champaign-Urbana, Illinois (photograph by Dilip Chhajed)

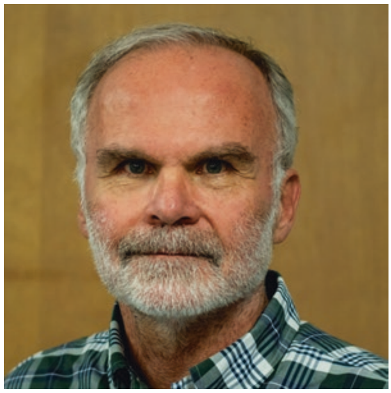
Govindjee, who uses one name only, was born on October 24, 1932, in Allahabad, India. Since 1999, he has been Professor Emeritus of Biochemistry, Biophysics, and Plant Biology at the University of Illinois at Urbana-Champaign (UIUC), Urbana, IL, USA. He obtained his B.Sc. in Chemistry, Botany, and Zoology and his M.Sc. in Botany and Plant Physiology in 1952 and 1954, respectively, from the University of Allahabad. He learned his Plant Physiology from Shri Ranjan, who was a student of Frederick Frost Blackman (of Cambridge, UK). He then studied *Photosynthesis* at the UIUC, under two giants in the field, Robert Emerson (a student of Otto Warburg) and Eugene Rabinowitch (who had worked with James Franck), obtaining his Ph.D. in Biophysics in 1960.

Govindjee is best known for his research on excitation energy transfer, light emission (prompt and delayed fluorescence and thermoluminescence), primary photochemistry, and electron transfer in *Photosystem II* (PS II, water-plastoquinone oxidoreductase). His research, with many others, includes the discovery of a short-wavelength form of chlorophyll (Chl) *a* functioning in PS II, of the two-light effect in Chl *a* fluorescence, and, with his wife Rajni Govindjee, of the two-light effect (Emerson enhancement) in $NADP^+$ reduction in chloroplasts. His major achievements, together with several others, include an understanding of the basic relationship between Chl *a* fluorescence and photosynthetic reactions; a unique role of bicarbonate/carbonate on the electron acceptor side of PS II, particularly in the protonation events involving the Q_B binding region; the theory of thermoluminescence in plants; the first picosecond measurements on the primary photochemistry of PS II; and the use of fluorescence lifetime imaging microscopy (FLIM) of Chl *a* fluorescence in understanding photoprotection by plants against excess light. His current focus is on the *history of* *photosynthesis research* and on *photosynthesis education*. He has served on the faculty of the UIUC for ~40 years.

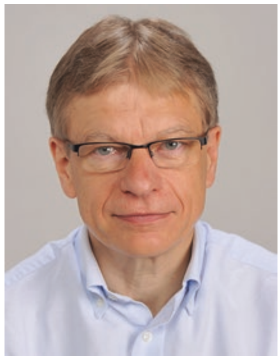
Govindjee's honors include Fellow of the American Association for the Advancement of Science (AAAS); Distinguished Lecturer of the School of Life Sciences, UIUC; Fellow and Lifetime Member of the National Academy of Sciences (India); President of the American Society for Photobiology (1980–1981); Fulbright Scholar (1956), Fulbright Senior Lecturer (1997), and Fulbright Specialist (2012); Honorary President of the 2004 International Photosynthesis Congress (Montréal, Canada); First Recipient of the Lifetime Achievement Award of the Rebeiz Foundation for Basic Biology (2006); and Recipient of the Communication Award of the International Society of Photosynthesis Research (2007) and of the Liberal Arts and Sciences Lifetime Achievement Award of the UIUC (2008). Furthermore, he has been honored many times: (1) in 2007, through two special volumes of *Photosynthesis Research*, celebrating his 75th birthday and his 50-year dedicated research in photosynthesis (Julian J. Eaton-Rye, Guest Editor); (2) in 2008, through a special international symposium on "photosynthesis in a global perspective" held in November 2008 at the University of Indore, India, this was followed by a book *Photosynthesis: Basics and Applications* (edited by S. Itoh, P. Mohanty, and K.N. Guruprasad); (3) in 2012, through *Photosynthesis: Plastid Biology, Energy Conversion and Carbon Assimilation*, edited by Julian J. Eaton-Rye, Baishnab C. Tripathy, and Thomas D. Sharkey; (4) in 2013, through special issues of *Photosynthesis Research* (volumes 117 and 118), edited by Suleyman Allakhverdiev, Gerald Edwards, and Jian-Ren Shen celebrating his 80th (or rather 81st) birthday; (5) in 2014, through celebration of his 81st birthday in Třeboň, Czech Republic (O. Prasil [2014] *Photosynth Res* 122: 113–119); and (6) in 2016, through the award of the prestigious Prof. B.M. Johri Memorial Award of the Society of Plant Research, India. In 2018, *Photosynthetica* published a special issue to celebrate his 85th birthday (Julian J. Eaton-Rye, Editor).

Govindjee's unique teaching of the Z-scheme of photosynthesis, where students act as different intermediates, has been published in two papers: (1) P.K. Mohapatra and N.R. Singh [2015] *Photosynthesis Research* (123:105–114) and (2) S. Jaiswal, M. Bansal, S. Roy, A. Bharati, and B. Padhi [2017] *Photosynthesis Research* (131: 351—359). Govindjee is a Coauthor of a classic and highly popular book *Photosynthesis* (with E.I. Rabinowitch, 1969) and of the historical book *Maximum Quantum Yield of Photosynthesis: Otto Warburg and the Midwest Gang* (with K. Nickelsen, 2011). He is Editor (or Coeditor) of many books including *Bioenergetics of Photosynthesis* (1975); *Photosynthesis* (two volumes (1982)); *Light Emission by Plants and Bacteria* (1986); *Chlorophyll a Fluorescence: A Signature of Photosynthesis* (2004); *Discoveries in Photosynthesis* (2005); and *Non-Photochemical Quenching and Energy Dissipation in Plants, Algae and Cyanobacteria* (2015).

Since 2007, each year a **Govindjee and Rajni Govindjee Award** is given to graduate students by the Department of Plant Biology (odd years) and by the Department of Biochemistry (even years), at the UIUC, to recognize excellence in biological sciences. For further information on Govindjee, see his website at http://www.life.illinois.edu/govindjee.



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, USA. After 2 years as a Research Technician, he entered a Ph.D. program in the Department of Energy Plant Research Laboratory at Michigan State University under the mentorship of Klaus Raschke and finished in 1979. His postdoctoral research was carried out with Graham Farquhar at the Australian National University, Canberra, where he coauthored a landmark review on photosynthesis and stomatal conductance. For 5 years, he worked in the Desert Research Institute, Reno, Nevada. After Reno, he spent 20 years as Professor of Botany at the University of Wisconsin in Madison. In 2008, he became Professor and Chair of the Department of Biochemistry and Molecular Biology at Michigan State University. In 2017, he stepped down as Department Chair and moved to the MSU-DOE Plant Research Laboratory completing a 38-year sojourn back to his beginnings. His research interests center on the exchange of gases between plants and the atmosphere and carbon metabolism of photosynthesis. 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, an exhaustive study of short-term feedback effects in carbon metabolism, and a significant contribution to elucidation of the pathway by which leaf starch breaks down at night. In the isoprene research field, his laboratory has cloned many of the genes that underlie isoprene synthesis, and he has published many important papers on the biochemical regulation of isoprene synthesis. His work has been cited over 26,000 times according to Google Scholar in 2017. He has been named an Outstanding Faculty Member by Michigan State University and, in 2015, was named a University Distinguished Professor. He is a Fellow of the American Society of Plant Biologists and of the American Association for the Advancement of Science. He has coedited three books, the first on trace gas emissions from plants in 1991 (with Elizabeth Holland and Hal Mooney), volume 9 of this series (with Richard Leegood and Susanne von Caemmerer) on the physiology of carbon metabolism of photosynthesis in 2000, and volume 34 (with Julian J. Eaton-Rye and Baishnab C. Tripathy), *Photosynthesis*: *Plastid Biology*, *Energy Conversion and Carbon Assimilation*. He has been Coeditor of this series since volume 31.



Julian J. Eaton-Rye is a Professor in the Department of Biochemistry at the University of Otago, New Zealand. He received his undergraduate degree in Botany from the University of Manchester in the UK in 1981 and his Ph.D. from the University of Illinois in 1987, where he worked with Govindjee on the role of bicarbonate in the regulation of electron transfer through Photosystem II. Before joining the Biochemistry Department at Otago University in 1994, he was a Postdoctoral Researcher focusing on various aspects of Photosystem II protein biochemistry with Professor Norio Murata at the National Institute for Basic Biology in Okazaki, Japan, with Professor Wim Vermaas at Arizona State University and with Dr. Geoffrey Hind at Brookhaven National Laboratory. His current research interests include structure-function relationships of Photosystem II proteins in both biogenesis and electron transport as well as the role of additional protein factors in the assembly of Photosystem II. He has been a Consulting Editor for the Advances in Photosynthesis and Respiration series since 2005 and edited volume 34 (with Baishnab C. Tripathy and Thomas D. Sharkey), *Photosynthesis*: *Plastid Biology*, *Energy Conversion and Carbon Assimilation*. He is also an Associate Editor for the *New Zealand Journal of Botany* and for the Plant Cell Biology section *Frontiers in Plant Science*. He edited Frontiers Research Topic *Assembly of the Photosystem II Membrane-Protein Complex of Oxygenic Photosynthesis* (with Roman Sobotka) in 2016, which is available as an eBook [ISBN 978-2-88945-233-0]. He has served as the President of the New Zealand Society of Plant Biologists (2006–2008) and of the New Zealand Institute of Chemistry (2012) and has been a Member of the International Scientific Committee of the Triennial International Symposium on Phototrophic Prokaryotes (2009–2018). Currently, he is the Secretary of the International Society of Photosynthesis Research.

Contents

Part II Molecular Genetics of Algae

Part III Biochemistry and Physiology of Algae

Part IV Light-Harvesting Systems in Algae

Preface: A Brief Introduction to the Algae

This book covers the process and development of photosynthesis in algae. Photosynthesis is the process by which light energy, predominantly from the sun, is converted into the energy of organic compounds. These photosynthetic products underpin almost all life on Earth; previously, with geological processes, they produced petroleum and coal, and in the future, they can contribute to a wide range of ecological and societal needs. As the world is using up its reserves of petroleum and coal at increasing rates, it is becoming important to understand the replenishment processes, with both biological and geological systems involved. At the same time, the alarming increases in greenhouse gases and the harmful effects on global climate make the use of these fossil fuels less and less desirable. The alternative is to develop new technologies for solar energy conversion, and these will undoubtedly involve algal biofuel production on a massive scale. Much work has been done in this area over the last two decades. On the purely mechanical-physical level, it is possible to set up solar farms and convert sunlight into electrical energy. And from there, it is possible to generate hydrogen by splitting water or to drive chemical half cells involving algae or components of algae to generate hydrogen or useful organic products. Alternatively, it is possible to "farm" algae in a variety of ways to generate fuels or value-added products. However, before any of these futuristic developments can be envisaged, it is necessary to know much more about the photosynthetic processes that occur on the Earth today and the role that algae play in the ecosystems of the Earth. Algae are eukaryotic organisms that exist in a multiplicity of forms and carry out oxygenic photosynthesis. In this book, our definition also includes *Cyanobacteria* (bacteria which nevertheless possess a process of photosynthesis able to split water). About half a billion years ago (BYA), one branch of green algae (see below) finally colonized the land and gave rise to "land plants" (embryophytes), and all these plants inherit to a greater or lesser extent the photosynthetic mechanisms of their algal forebears. So algae can be used directly in the freshwater and marine systems of the world to generate fuels or value-added organic products, or they can be studied to understand how to enhance the photosynthetic systems that developed from a fraction of the gene pool available in algae.

The Evolution of Photosynthesis

Photosynthesis evolved on the Earth at a very early stage, maybe as early as 3.8 billion years ago (BYA). The earliest mechanisms would have used available sources of hydrogen including hydrogen gas itself, which was much more abundant on the early Earth. The organisms were anaerobic bacteria, but as available sources of reductant were depleted, a new form of photosynthesis was evolving by at least 3 BYA, and maybe much earlier in a primitive form, which could split water and use the hydrogen of water as its source. By 2.45 BYA, cyanobacteria had fully evolved and were liberating oxygen into the Earth's atmosphere. The oxygenation of the atmosphere in the Great Oxidation Event (GOE) was a revolutionary step, which made possible the endosymbiosis of aerobic proteobacteria and photosynthetic cyanobacteria in protists, which, with genetic integration, evolved into mitochondria and plastids.

The Evolution of Algae

Some dozen phyla of eukaryotic protist organisms, from a total of 60 odd phyla, were algae, i.e., they possessed plastids (photosynthetic organelles developed from cyanobacteria by endosymbiosis) and were oxygenically photosynthetic. After about 2 billion years of evolution and massive diversification, the scene was set for the colonization of the land. One phylum, the green algae, gave rise to a multicellular subgroup, the streptophytes. The streptophytes colonized the land, becoming embryophytes and giving rise to mosses, ferns, and cone-bearing and flowering plants. At the same time, a multicellular group of protists evolved which gave rise to the animals, which also colonized the land, leading to all the animal groups with which we are familiar and eventually leading just 2 million years ago, or so, to man.

The Evolution of Eukaryotic Algae

The oldest algae date to at least 1.5 BYA and are red algae. However, some of the algae appear to be much more recent. For example, the diatoms that have a characteristic outer "shell," the frustule, are only found in sediments which are from 135 MYA. Other algal groups do not have a characteristic skeleton and cannot be dated in this way. Their origins can only be estimated by phylogenetic means, that is, by comparing their DNA with known fossil ages. Such studies reveal a rich and diverse lineage to the algae, where a "primary endosymbiosis" that involved the transfer of all the modern algal pigments was followed by a secondary, and in some cases tertiary, endosymbiosis with interesting pigment combinations. On one of these lines, that leading to the Apicomplexans, of which the malarial parasite is an example, all photosynthetic pigments and most of the photosynthetic mechanisms were lost.

The Rainbow of Algal Photosynthetic Mechanisms

With this rich and diverse history, many different patterns of photosynthesis evolved to suit a rainbow of light climates and ecological niches. Today, it is instructive to understand the fundamental differences involved. However, it is just as important that our understanding reveals how to utilize these varying arrays of pigments and photosynthetic approaches in devising technological approaches to harvesting solar energy by algae.

This book is divided into 17 chapters. These deal with all the major aspects of algal photosynthesis. However, the use of algae to produce biofuels and value-added products has been left to a second volume.

Anthony W. D. Larkum
Ultimo, NSW, Australia

Arthur R. Grossman
Stanford, CA, USA

John A. Raven
Dundee, UK

About the Editors

Anthony (Tony) Larkum is Emeritus Professor at the University of Sydney, Australia, where he was a Staff Member in Plant Sciences for 25 years. He has had a distinguished career in plant physiology, marine biology and phylogenetics. In addition, he has published a book on Charles Darwin and his cousin, William Darwin Fox, entitled *A Natural Calling: Life, Letters and Diaries of Charles Darwin and William Darwin Fox* (Springer Verlag). One of the first scientists to apply underwater techniques, he has contributed over a wide range of fields to advancing the study of underwater organisms, including cyanobacteria, marine algae, seagrasses and corals. In addition to this, he has contributed extensively to the field of light-harvesting and photoinhibition in photosynthetic organisms, having published many papers, a number of reviews and several books on the subject. Overall, he has published 254 papers in scientific journals; and these have an h-index of 65 (35 since 2014). His most cited papers are on coral bleaching in corals (632) and the discovery of fluorescent pigments in corals (590). And his third most cited work is for coediting a book on seagrasses (*Seagrasses: Biology, Ecology and Conservation*, Springer) in 2006. The current book is the culmination of a lifetime of work in the many fields of photosynthesis in cyanobacteria, eukaryotic algae and seagrasses. His contribution to these fields has been acknowledged by awards and election to scientific committees and boards of scientific journals over the years. He is currently on the Editorial Committee of the *Journal of the Royal Society Interface*.

Arthur Robert Grossman has been a Staff Scientist at the Carnegie Institution for Science, Department of Plant Biology, since 1982 and holds a courtesy appointment as Professor in the Department of Biology at Stanford University. He has performed research across fields ranging from plant biology, microbiology, marine biology, ecology, genomics, engineering and photosynthesis and initiated large-scale algal genomics by leading the *Chlamydomonas* genome project. In 2002, he received the Darbaker Prize (Botanical Society of America) for work on microalgae and in 2009 received the Gilbert Morgan Smith Medal (National Academy of Sciences) for the quality of his publications on marine and freshwater algae. In 2017, he was Chair of the Gordon Research Conference on Photosynthesis and gave the Arnon endowed lecture on photosynthesis in Berkeley in March 2017. He has given numerous plenary lectures and received a number of fellowships throughout his career, including the Visiting Scientist Fellowship, Department of Life and Environmental Sciences (DiSVA), Università Politecnica delle Marche (UNIVPM) (Italy, 2014), the Lady Davis Fellowship (Israel, 2011) and most recently the Chaire Edmond de Rothschild (to work at the IBPC in Paris in 2017–2018). He has been Co-Editor-in-Chief of *Journal of Phycology* and has served on the editorial boards of many well-respected biological journals including the *Annual Review of Genetics*, *Plant Physiology*, *Eukaryotic Cell*, *Journal of Biological Chemistry*, *Molecular Plant* and *Current Genetics*. He has also served on scientific advisory boards for both nonprofit and for profit companies including Phoenix Bioinformatics, Exelixis, Martek Biosciences, Solazyme/TerraVia, Checkerspot and Phycoil.

John Raven, FRS, is an Emeritus Professor at the University of Dundee, UK; an Honorary Fellow of the James Hutton Institute, UK; a Visiting Professor at the University of Technology Sydney; and an Adjunct Professor at the University of Western Australia. He has wide research interests, including astrobiology, bioenergetics, biogeochemistry, ecophysiology, evolutionary biology and palaeobiology. The majority of his publications have involved studies on algae. He has published 482 scientific papers (Web of Science, 30 July 2019) and is a Clarivate Analytics Highly Cited Researcher in the Cross Field research area. Among his contributions to our knowledge of algal photosynthesis are studies of inorganic carbon acquisition mechanisms in the laboratory and in nature, photosynthetic electron flow pathways other than from water to carbon dioxide, interactions of photosynthetic and respiratory reactions in organismal bioenergetics, and the extremes of photon flux density at which algal photosynthesis and photolithotrophic growth can occur.

Contributors

Roberto Bassi
Department of Biotechnology, University of Verona, Verona, Italy

John Beardall
School of Biological Sciences, Monash University, Clayton, VIC, Australia

Erica Belgio
Centre Algatech, Institute of Microbiology, Academy of Sciences of the Czech Republic, Třeboň, Czech Republic

Debashish Bhattacharya
Department of Biochemistry and Microbiology, Rutgers University, New Brunswick, NJ, USA

Claudia Büchel
Institute of Molecular Sciences, Goethe University, Frankfurt am Main, Germany

Douglas A. Campbell
Department of Biology, Mount Allison University, Sackville, NB, Canada

Anna Paola Casazza
Istituto di Biologia e Biotecnologia Agraria, Consiglio Nazionale delle Ricerche, Milan, Italy

Paul M. G. Curmi
School of Physics, The University of New South Wales, Sydney, NSW, Australia

Geoffry A. Davis
DOE Plant Research Laboratory, Department of Chemistry and Department of Biochemistry and Molecular biology, Michigan State University, East Lansing, MI, USA

Jeffrey A. Davis
Centre for Quantum and Optical Science, Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn, VIC, Australia

Nicholas Fisher
DOE Plant Research Laboratory, Department of Chemistry and Department of Biochemistry and Molecular biology, Michigan State University, East Lansing, MI, USA

Myriam M. M. Goudet
Department of Plant Sciences, University of Cambridge, Cambridge, UK

Howard Griffiths
Department of Plant Sciences, University of Cambridge, Cambridge, UK

Arthur R. Grossman
Department of Plant Biology, Carnegie Institution for Science, Stanford University, Stanford, CA, USA

Parisa Heydarizadeh
Metabolism, Bioengineering of Microalgal Molecules and Applications (MIMMA), Mer Molécules Santé, IUML – FR 3473 CNRS, Le Mans University, Le Mans, France

Radek Kaňa
Centre Algatech, Institute of Microbiology, Academy of Sciences of the Czech Republic, Třeboň, Czech Republic

Atsuko Kanazawa
DOE Plant Research Laboratory, Department of Chemistry and Department of Biochemistry and Molecular biology, Michigan State University, East Lansing, MI, USA

U.S. Department of Energy Plant Research Laboratory, Michigan State University, East Lansing, MI, USA

Diana Kirilovsky
Institute for Integrative Biology of the Cell (I2BC), CNRS, CEA, Université Paris-Sud, Université Paris-Saclay, Gif sur Yvette, France

David M. Kramer
DOE Plant Research Laboratory, Department of Chemistry and Department of Biochemistry and Molecular biology, Michigan State University, East Lansing, MI, USA

Anthony W. D. Larkum
Global Climate Custer, University of Technology Sydney, Ultimo, NSW, Australia

Justine Marchand
Metabolism, Bioengineering of Microalgal Molecules and Applications (MIMMA), Mer Molécules Santé, IUML – FR 3473 CNRS, Le Mans University, Le Mans, France

Moritz T. Meyer
Department of Plant Sciences, University of Cambridge, Cambridge, UK

Department of Molecular Biology, Princeton University, Princeton, NJ, USA

Peter Neofotis
DOE Plant Research Laboratory, Department of Chemistry and Department of Biochemistry and Molecular biology, Michigan State University, East Lansing, MI, USA

Ondřej Prášil
Centre Algatech, Institute of Microbiology, Academy of Sciences of the Czech Republic, Třeboň, Czech Republic

Faculty of Science, University of South Bohemia, České Budějovice, Czech Republic

Dana C. Price
Department of Plant Biology, Rutgers University, New Brunswick, NJ, USA

Antonietta Quigg
Texas A&M University at Galveston, Galveston, TX, USA

Harry W. Rathbone
School of Physics, The University of New South Wales, Sydney, NSW, Australia

John A. Raven
Division of Plant Sciences, University of Dundee at the James Hutton Institute, Dundee, UK

Climate Change Cluster, University of Technology Sydney, Ultimo, NSW, Australia

Jean-David Rochaix
Departments of Molecular Biology and Plant Biology, University of Geneva University, Geneva, Switzerland

Stefano Santabarbara
Centre for Fundamental Research in Photosynthesis, Vergiate, Varese, Italy

Photosynthesis Research Unit, Centro Studi sulla Biologia Cellulare e Molecolare delle Piante, Milano, Italy

Christo Schiphorst
Department of Biotechnology, University of Verona, Verona, Italy

Benoît Schoefs
Metabolism, Bioengineering of Microalgal Molecules and Applications (MIMMA), Mer Molécules Santé, IUML – FR 3473 CNRS, Le Mans University, Le Mans, France