Rattan Lal · Klaus Lorenz
Reinhard F. Hüttl · Bernd Uwe Schneider
Joachim von Braun *Editors*

Recarbonization of the Biosphere

Ecosystems and the Global Carbon Cycle

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Foreword

Recognizing that human activities are a significant geologic force through, for example, land-use change and fossil fuel combustion, Paul Crutzen and Eugene Stoermer (2000) introduced the term "Anthropocene". Through expansion of agricultural and urban ecosystems along with combustion of biomass and fossil fuel, humans have drastically changed the "Face of the Earth". Increase in atmospheric concentration of greenhouse gases (GHGs) and the attendant global climate change are among the principal ramifications of the Anthropocene. Whereas emissions from fossil fuel combustion began with the on-set of industrial revolution ~1800 A.D., those from land-use conversion and deforestation commenced ~10–14 millennia ago with the dawn of settled agriculture. The cumulative emissions from land-use conversion over millennia are estimated by some at about 480 Pg carbon (C), compared with 275 Pg C from fossil fuel combustion and cement production between 1850 and 2000. World soils may have lost 60–100 Pg C through drainage, excessive tillage and the widespread use of extractive farming practices, which does not only affect C emissions but the development potential of people depending on soil resources. The magnitude of loss of the soil C pool and interrelated negative consequences for humans are exacerbated by degradation processes such as accelerated erosion, salinization, acidification, nutrient depletion, and elemental toxicity. Decarbonization of the terrestrial C pool has adversely affected numerous ecosystem services such as the provision of food and fresh water, supporting services such as elemental (C, N, P, S etc.) cycling, biodiversity, among others. The severe decline in agronomic productivity may be the most prominent negative effect of management practices depleting the soil C pool.

Recarbonization of the biosphere is an essential step to reduce the net anthropogenic C emissions through sequestration of carbon dioxide (CO_2) in terrestrial sinks comprising of forests, soils, and wetlands. The drawdown of atmospheric CO_2 through C sequestration in the terrestrial biosphere is estimated at ~50 ppm over a century. In addition to being a cost-effective and a natural process based on enhanced net primary production through adoption of restorative land use and management, the strategy of C sequestration in the terrestrial biosphere has numerous co-benefits such as increasing agronomic productivity and advancing global food security.

Terrestrial biosphere, with a high priority for an immediate action, and those with a high C sink capacity include: drained peat lands, soils degraded by erosion and salinization, agriculturally marginal lands, tropical rainforests and acid savanna soils, and urban ecosystems. In addition to afforestation and reforestation, avoidance of tropical deforestation, conversion of degraded ecosystems to restorative land use, and adoption of recommended soil and crop management practices are important options for recarbonization of the biosphere.

A wide spread adoption of recommended management practices, in particular, by the resource-poor farmers and small land holders of the developing countries requires appropriate, just, and fair process to incentivize them. Land managers could be incentivized, if implemented effectively, through payments for generating ecosystem services such as sequestering C to mitigate climate change, improving quality of natural waters, enhancing biodiversity, and improving environmental quality.

The workshop entitled "Recarbonization of the Biosphere" was held at the IASS Institute for Advanced Sustainability Studies Potsdam, from 20 to 22 March 2011. It was attended by about 30 participants from Germany, USA, Australia, Brazil, Italy, France, Spain, China representing soil science, forestry, climatology, sociology, and political sciences along with policy makers and media representatives. Specific recommendations emerging from the deliberations include the following:

Land-Based Carbon Sinks: Priority ecosystems with large C stocks which must be protected and sustainably managed are: permafrost, wetlands, peatlands, tropical rainforests, tropical savannas, urban lands, degraded or desertified lands, and agricultural lands.

Carbon Sink Capacity Management: The C sink capacity of land-based sinks are continuous, and require long-term management and protection strategy because it grows with a progressive improvement in ecosystem health.

Ecosystem Services and Co-Benefits of Land-Based Carbon Sinks: Protecting and enhancing land-based sinks generate numerous ecosystem services. Important among these are:

- Food security,
- Quality and quantity of renewable fresh water resources,
- Adaptation and mitigation to climate change, and
- Biodiversity

Global Soil Forum: The key roles in advancing food security and providing numerous co-benefits and ecosystems services of vital significance to humanity necessitate identification, nurturing and support of a transdisciplinary process with primary focus on sustainable management and protection of world soils.

This volume is based on the papers presented at the workshop. The organization of the workshop and publication of the volume were made possible by the staff of IASS in cooperation with The Ohio State University. The volume is edited by an

inter-disciplinary team of scientists comprising of Drs. R. Lal, K. Lorenz, R. F. Hüttl, B. U. Schneider, and J. von Braun. Special thanks are due to all authors for their contributions and willingness to share the knowledge and expertise with others. The efforts of all others who contributed to publishing this volume in a timely manner are greatly appreciated.

Prof. Dr. Klaus Töpfer
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Preface

With increase in world population from seven billion in 2011 to the projected 9.2 billion in 2050, several challenges facing humanity during the Anthropocene include the followings: (i) increasing atmospheric concentration of CO_2 and other greenhouse gases with the attendant risks of global warming, (ii) the need to increase food production by at least 70%, and even more in densely populated developed countries, and the severe decline in per capita productive agricultural soil/land, (iii) high risks of soil degradation and land desertification because of anthropogenic perturbations and those exacerbated by the projected climate change, (iv) pollution and contamination of natural waters, and the severe projected decline in per capita availability of renewable freshwater supply, and (v) a rapid and widespread decline in both above- and below-ground biodiversity.

Some relevant strategies of addressing these challenges include: (i) sequestering carbon (C) in the biosphere (i.e., soils, trees), (ii) making agriculture climate resilient and, as much as possible, C-neutral, (iii) improving quality of soils of agroecosystems, thereby increasing agronomic and net primary production (NPP), (iv) adopting technologies of sustainable intensification and saving land for nature conservancy, and (v) making soils/land integral to any strategy of mitigating the climate change and improving environmental quality.

Thus, the workshop entitled "Recarbonization of the Biosphere" was held at the IASS Institute for Advanced Sustainable Studies in Potsdam, Germany, from 20 to 22 March 2011. About 30 researchers and policy makers, from about ten countries, were invited to present the-state-of-the-knowledge review on thematic issues related to the topic. Two Nobel Prize Laureates, Prof. Dr. Paul Crutzen and Prof. Dr. Carlo Rubbia, also attended the workshop and presented articles on specific topics. The invited participants were specifically chosen to promote and enhance trans-disciplinary and inter-institutional cooperation and discussion. Thus, participants represented soil science, forestry, physics, chemistry, climatology, geology, hydrology, bio-geochemistry, sociology, and political science.

The workshop deliberations made the following conclusions:

1. Sustainable soil and land management is essential to achieve food security, sustainable development, to adapt to and mitigate climate change, and to maintain environmental quality.
2. Global problems of food insecurity, soil degradation, water scarcity and pollution, and energy insecurity are exacerbated by the changing climate, increasing population, and increasing standards of living.
3. For these reasons, IASS was encouraged to pursue the idea of creating a "Global Soil Forum" as an organizational mechanism with focus on sustainable management and protection of world soils.

Based on these conclusions, the workshop made the following recommendations:

1. Invest much more in soil resources, assessment and management in order to advance food security, adapt to and mitigate climate change, and enhance ecosystem services.
2. Identify key technological options to enhance and sustain soil-based ecosystem services, especially those that serve food security and nutrition.
3. Strengthen related institutional and human resource capacity, especially by providing long- and short-term training opportunities and research capacities.
4. Support and coordinate related activities, including program targets, monitoring and evaluation systems, network development and policy implementation at local, regional and global levels, and
5. Create a globally coordinated state-of-the-soils data bank that will facilitate identification and analysis of their properties for specific ecosystem services.

This 25-chapter volume is based on the papers presented at the workshop, and some additional chapters to strengthen the thematic discussion on all biomes. The volume addresses the potential and challenges of recarboninzation of the natural and managed biomes. Important among these are peatlands, forests, savannas/steppes, degraded and desertified lands, croplands, grazing lands and coastal ecosystems.

The organization of the workshop and publication of the volume were made possible by the visionary leadership and support of Prof. Dr. Klaus Töpfer, the Executive Director of IASS. The editors also thank all the authors for their outstanding efforts to document and present the state-of-the-knowledge scientific information on themes of interest to them. Their efforts have contributed to enhancing the overall understanding of the science, practices and policies of this theme of global significance. These articles have enhanced the frontiers of knowledge.

Special thanks are also be given to the staff of IASS and the Carbon Management and Sequestration Center (C-MASC) for their help and support in organizing the Workshop. Valuable contributions were made by Ms. Corinna Bobzien, Ms. Thando Tilmann, Dr. Falk Schmidt, Ms. Astrid Lehmann and other staff of IASS. We thank Ms. Theresa Colson of C-MASC, OSU for production support in preparing the volume for the final submission to the publisher. Thanks are also due to the staff of

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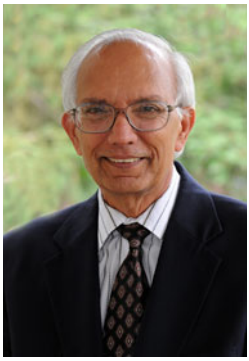

Rattan Lal is a Distinguished University Professor of soil physics in the School of Environment and Natural Resources, and Director of the Carbon Management and Sequestration Center, College of Food, Agricultural, and Environmental Sciences/ Ohio Agriculture Research and Development Center, at The Ohio State University. He has worked at the University of Sydney, Australia (1968–1969), the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria (1970–1987) and at The Ohio State University (1987–). He has been affiliated with the Institute for Advanced Sustainability Studies (IASS), Potsdam as a member of the Scientific Advisory Board (2010) and with the Global Soil Forum (2011–). Professor Lal is a fellow of the Soil Science Society of America, American Society of Agronomy, Third World Academy of Sciences, American Association for the Advancement of Sciences, Soil and Waste Conservation Society, and Indian Academy of Agricultural Sciences. He is a recipient of the International Soil Science Award of the Soil Science Society of America, the Hugh Hammond Bennett Award of the Soil and Water Conservation Society, the 2005 Borlaug Award and 2009 Swaminathan Award. He also received an honorary degree of Doctor of Science from Punjab Agricultural University, India, from the Norwegian University of Life Sciences,

Aas, Norway, and the Alecu Russo Balti State University in Moldova. He is the past president of the World Association of the Soil and Water Conservation, the International Soil Tillage Research Organization and Soil Science Society of America. He was a member of the U.S. National Committee on Soil Science of the National Academy of Sciences (1998–2002, 2007–2010). He has served on the Panel of Sustainable Agriculture and the Environment in the Humid Tropics of the National Academy of Sciences. He has authored and coauthored about 1,500 research papers. He has also written 15 and edited or co-edited 50 books. Prof. Lal has been academic advisor and mentor of ~100 graduate students, 50 postdoctoral researchers and 85 visiting scholars from around the world.

Klaus Lorenz is Research Fellow at the IASS Institute for Advanced Sustainability Studies in Potsdam, Germany. He studied biology at University of Freiburg, Germany, and obtained his Ph.D. in Agricultural Sciences from University of Hohenheim, Germany. His research focuses on agricultural, forest and urban soil use and management to enhance soil organic carbon sequestration for climate change mitigation and adaptation. From 2004 to 2011, he was employed as Research Scientist at the Carbon Management and Sequestration Center, The Ohio State University, USA. He has written the book 'Carbon Sequestration in Forests Ecosystems' (Co-author Rattan Lal). At IASS, he is organizing workshops addressing the sustainable use of soils to meet increasing anthropogenic demands and mitigating global change. Together with colleagues in the IASS Cluster Global Contract for Sustainability, he is implementing the Global Soil Forum and organizing the first Global Soil Week to be held 2012.

Prof. Dr. Dr. h.c. Reinhard Hüttl is the Scientific Executive Director and Chairman of the Board at the Helmholtz Centre Potsdam – GFZ German Research Centre for Geosciences, the National Research Centre for geosciences in Germany. Reinhard Hüttl is also President of the German National Academy of Science and Engineering (acatech) as well as Vice-president of the Helmholtz Association and Coordinator of the Research Field "Earth and Environment".

Reinhard Hüttl was born on January 1, 1957. He studied Forest and Soil Sciences at the Albert-Ludwigs-University (ALU), Freiburg, Germany and at the Oregon State University (USA) from 1978 to 1983 and was awarded a Ph.D. at the ALU Freiburg in April 1986. From 1986 to 1992 he was Head of the International Research Department at the mining company Kali & Salz AG/BASF-group, Kassel, Germany. He worked as an Assistant Professor for Geobotany at the University of Hawaii, Honolulu, USA in 1990/1991 and was appointed to the Chair of Soil Protection and Recultivation at the Brandenburg University of Technology (BTU) in Cottbus, Germany in 1992 where he is Director of the collaborative research centre "Artificial Watershed Catchment" which is funded by the German Science Foundation.

He was member of the Council of Experts for Environmental Questions of the German Government, and both member and chairman of the Scientific Commission of the Scientific Council of the German Government as well as member of the Ethics Commission on the Safe and Secure Provision of Energy of the German Government. He is also member of a number of national and international Academies and was conferred with the Cross of Merit, First Class of the Federal Republic of Germany in July 2008.

Dr. Bernd Uwe Schneider is Head of Staff of the Scientific Executive Board at the Helmholtz Centre Potsdam – GFZ German Research Centre for Geosciences, the National Research Centre for geosciences in Germany.

Uwe Schneider completed his degree in Forest Engineering at the Faculty of Forest Sciences in Göttingen in 1984 and was awarded a Ph.D. in Soil Sciences and Plant Nutrition at the University of Bayreuth, Faculty of Geosciences in 1989.

He spent 5 years in Guatemala and Honduras as a Forest Expert for the German Technical Mission (GTZ). From 1995 to 2006 he was employed at the Brandenburg University of Technology (BTU) in Cottbus where he headed different working groups on soil biology, soil-root-interactions and spatial structure of root systems, forest ecology, renewable energy production and alternative land-use systems.

Uwe Schneider has coordinated several EU and German joint research projects in addition to a number of basic research projects funded by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) and the BMBF. He is member of the German Soil Science Society (DBG) and has lectured at both German and international study courses. He was member of the Faculty Council, the Scientific Commission and the Senate at the BTU in Cottbus. Uwe Schneider is co-founder of the Institute for Advanced Sustainability Studies (IASS) in Potsdam, and the Lead Science Coordinator on behalf of the Helmholtz Association for the Helmholtz Alberta Research Initiative (HAI).

Joachim von Braun is Director of the Center for Development Research (ZEF), and Professor for Economic and Technological Change at University of Bonn, Germany. His research addresses international development economics topics, economics of natural resources, poverty; science and technology; food policy, and trade. von Braun was Director General of the International Food Policy Research Institute (IFPRI) based in Washington, DC, U.S.A. 2002–2009. 2000–2003 he was President of the International Association of Agricultural Economists (IAAE).He serves on various international, UN, and European advisory councils, and is member of the International Policy Council (IPC). von Braun is member of the German National Academy of Science and Engineering, the Academy of Science of North-Rhine Westphalia, Fellow of the American Association for the Advancement of Sciences; received a honorary Doctoral degree from University of Hohenheim, and the Bertebos Prize of the Swedish Academy of Agricultural Sciences 2009 and the Justus von Liebig Prize of the Fiat Panis foundation 2011 for his research on world food security.

Contents

1 Terrestrial Biosphere as a Source and Sink of Atmospheric Carbon Dioxide 1
Rattan Lal, K. Lorenz, R.F. Hüttl, B.U. Schneider, and Joachim von Braun

2 Climate Change Mitigation by Managing the Terrestrial Biosphere 17
Rattan Lal

3 Atmospheric Chemistry and Climate in the Anthropocene 41
K. Lorenz, P.J. Crutzen, Rattan Lal, and K. Töpfer

4 Historic Changes in Terrestrial Carbon Storage 59
R.A. Houghton

5 Soil Erosion and Soil Organic Carbon Storage on the Chinese Loess Plateau 83
Ch. Dahlke and H.-R. Bork

6 Methane Emissions from China's Natural Wetlands: Measurements, Temporal Variations and Influencing Factors 99
Xiaoke Wang, Fei Lu, and Le Yang

7 Accounting More Precisely for Peat and Other Soil Carbon Resources 127
Hermann F. Jungkunst, Jan Paul Krüger, Felix Heitkamp, Stefan Erasmi, Stephan Glatzel, Sabine Fiedler, and Rattan Lal

8 Permafrost – Physical Aspects, Carbon Cycling, Databases and Uncertainties 159
Julia Boike, Moritz Langer, Hugues Lantuit, Sina Muster, Kurt Roth, Torsten Sachs, Paul Overduin, Sebastian Westermann, and A. David McGuire

9 Carbon Sequestration in Temperate Forests 187
Rattan Lal and K. Lorenz

10 Decarbonization of the Atmosphere: Role of the Boreal Forest Under Changing Climate 203
Jagtar Bhatti, Rachhpal Jassal, and T. Andy Black

11 Recarbonization of the Humid Tropics 229
Michelle Venter, Oscar Venter, Susan Laurance, and Michael Bird

12 Carbon Cycling in the Amazon 253
Carlos Clemente Cerri, Martial Bernoux, Brigitte Josefine Feigl, and Carlos Eduardo Pellegrino Cerri

13 Grassland Soil Organic Carbon Stocks: Status, Opportunities, Vulnerability 275
Richard Theodore Conant

14 Cropland Soil Carbon Dynamics 303
Klaus Lorenz and Rattan Lal

15 The Carbon Cycle in Drylands 347
Penélope Serrano-Ortiz, Enrique P. Sánchez-Cañete, and Cecilio Oyonarte

16 Carbonization of Urban Areas 369
Galina Churkina

17 Potential Carbon Emission Trajectories of Shanghai, China from 2007 to 2050 383
Ru Guo, Xiaojing Cao, Jing Zhang, Fengting Li, and Hongtao Wang

18 Processes of Soil Carbon Dynamics and Ecosystem Carbon Cycling in a Changing World 395
Felix Heitkamp, Anna Jacobs, Hermann F. Jungkunst, Stefanie Heinze, Matthias Wendland, and Yakov Kuzyakov

19 Soil Carbon and Nitrogen Interactions and Biosphere-Atmosphere Exchange of Nitrous Oxide and Methane 429
Klaus Butterbach-Bahl and Michael Dannenmann

20 Carbon Storage and Sequestration in Subsoil Horizons: Knowledge, Gaps and Potentials 445
Cornelia Rumpel, Abad Chabbi, and Bernd Marschner

21 Transforming Carbon Dioxide from a Liability into an Asset 465
Carlo Rubbia

22 Bioenergy and Biospheric Carbon 481
Tim Beringer and Wolfgang Lucht

23 The Economics of Land and Soil Degradation-Toward an Assessment of the Costs of Inaction 493
Joachim von Braun and Nicolas Gerber

24 Assessment of Carbon Sequestration Potential in Coastal Wetlands 517
James T. Morris, James Edwards, Stephen Crooks, and Enrique Reyes

25 Research and Development Priorities Towards Recarbonization of the Biosphere 533
Rattan Lal, Klaus Lorenz, Reinhard F. Hüttl, Bernd Uwe Schneider, and Joachim von Braun

Index 545

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Chapter 1
Terrestrial Biosphere as a Source and Sink of Atmospheric Carbon Dioxide

Rattan Lal, K. Lorenz, R.F. Hüttl, B.U. Schneider, and Joachim von Braun

Abstract The terrestrial biosphere has lost a considerable amount of its antecedent carbon (C) pool because of anthropogenic activities since the dawn of settled agriculture about 12–14 millennia ago. Deforestation and land use conversion has presumably caused cumulative emission of 476 Pg C (1 Pg = 10^{15} g). Of this, 78 ± 12 Pg C may have been depleted from world's soils. Globally, about 2,300 Pg C are stored to 3-m depth in the soil organic carbon (SOC) pool, 1,700 Pg C in permafrost, 600 Pg C in peatlands, and up to 1,700 Pg C in the soil inorganic carbon (SIC) pool. While a large fraction of C emissions may have been absorbed by the ocean and land-based sinks, the knowledge about the historic loss provides a reference point about the technical C sink capacity of the terrestrial biosphere. The later may be as much as a draw-down of 50 ppm of atmospheric carbon dioxide (CO_2) over century or more, which in view of the already accumulated levels of atmospheric CO_2 of 390 ppm is significant. Priority soils and ecosystems for recarbonization of the

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