



Contents

<i>List of figures, tables and boxes</i>	<i>xi</i>
<i>List of contributors</i>	<i>xix</i>
<i>Preface</i>	<i>xxiii</i>
<i>Foreword by Tim Flannery</i>	<i>xxv</i>
<i>List of abbreviations</i>	<i>xxvii</i>
1 Biochar for Environmental Management: An Introduction	1
<i>Johannes Lehmann and Stephen Joseph</i>	
What is biochar?	1
Biochar terminology	2
The origin of biochar management and research	3
The big picture	5
Adoption of biochar for environmental management	9
2 Physical Properties of Biochar	13
<i>Adriana Downie, Alan Crosky and Paul Munroe</i>	
Introduction	13
Biochars: Old and new	14
Relevance of extended literature	14
Caution on comparing data	15
Origin of biochar structure	15
Influence of molecular structure on biochar morphology	17
Loss of structural complexity during pyrolysis	19
Industrial processes for altering the physical structure of biochar	20
Soil surface areas and biochar	22
Biochar nanoporosity	22
Biochar macroporosity	24
Particle-size distribution	26
Biochar density	27
Mechanical strength	29
Future research	29
3 Characteristics of Biochar: Microchemical Properties	33
<i>James E. Amonette and Stephen Joseph</i>	
Introduction and scope	33
Formation and bulk composition	33
Surface chemistry	43



4	Characteristics of Biochar: Organo-chemical Properties	53
	<i>Evelyn S. Krull, Jeff A. Baldock, Jan O. Skjemstad and Ronald J. Smernik</i>	
	Introduction	53
	Elemental ratios	54
	¹³ C-nuclear magnetic resonance (NMR) spectroscopy	58
	Outlook	63
5	Biochar: Nutrient Properties and Their Enhancement	67
	<i>K. Yin Chan and Zhihong Xu</i>	
	Introduction	67
	Nutrient properties of biochars and crop production responses	68
	Factors controlling nutrient properties of biochar	74
	Improving the nutrient value of biochars: Research opportunities and challenges	79
	Conclusions	81
6	Characteristics of Biochar: Biological Properties	85
	<i>Janice E. Thies and Matthias C. Rillig</i>	
	Introduction	85
	Biochar as a habitat for soil microorganisms	86
	Biochar as a substrate for the soil biota	89
	Methodological issues	91
	Effects of biochar on the activity of the soil biota	92
	Diversity of organisms interacting with biochar	95
	Conclusions	102
7	Developing a Biochar Classification and Test Methods	107
	<i>Stephen Joseph, Cordner Peacocke, Johannes Lehmann and Paul Munroe</i>	
	Why do we need a classification system?	107
	Existing definitions and classification systems for charcoal, activated carbon and coal	108
	Proposed classification system for biochar	112
8	Biochar Production Technology	127
	<i>Robert Brown</i>	
	Introduction	127
	History of charcoal-making	128
	Mechanisms of biochar production from biomass substrates	133
	Opportunities for advanced biochar production	139
9	Biochar Systems	147
	<i>Johannes Lehmann and Stephen Joseph</i>	
	Introduction	147
	Motivation for biochar soil management	148
	Components of biochar systems	149
	Biochar systems	154
	Outlook	164

10	Changes of Biochar in Soil	169
	<i>Karen Hammes and Michael W.I. Schmidt</i>	
	Introduction	169
	Mechanisms of incorporation and movement of biochar in soil	170
	Physical changes of biochar in soil	172
	Chemical changes of biochar in soil	174
	Biotic changes of biochar in soil	177
	Conclusions	178
11	Stability of Biochar in Soil	183
	<i>Johannes Lehmann, Claudia Czimczik, David Laird and Saran Sohi</i>	
	Introduction	183
	Extent of biochar decay	184
	Biochar properties and decay	188
	Mechanisms of biochar decay	188
	Stabilization of biochar in soil	191
	Environmental conditions affecting biochar stability and decay	196
	A biochar stability framework	198
12	Biochar Application to Soil	207
	<i>Paul Blackwell, Glen Riethmuller and Mike Collins</i>	
	Introduction	207
	Purpose of biochar application	208
	Biochar properties and application methods	214
	Methods of application and incorporation: Specific examples	217
	Comparison of methods and outlook	222
13	Biochar and Emissions of Non-CO₂ Greenhouse Gases from Soil	227
	<i>Lukas Van Zwieten, Bhupinderpal Singh, Stephen Joseph, Stephen Kimber, Annette Cowie and K. Yin Chan</i>	
	Introduction	227
	Evidence for reduced soil greenhouse gas (GHG) emissions using biochar	228
	Biological mechanisms for reduced GHG emissions following biochar application	232
	Abiotic mechanisms influencing GHG emissions using biochar	239
	Conclusions	243
14	Biochar Effects on Soil Nutrient Transformations	251
	<i>Thomas H. DeLuca, M. Derek MacKenzie and Michael J. Gundale</i>	
	Introduction	251
	Nutrient content of biochar	252
	Potential mechanisms for how biochar modifies nutrient transformations	254
	Direct and indirect influences of biochar on soil nutrient transformations	255
	Conclusions	265

15	Biochar Effects on Nutrient Leaching	271
	<i>Julie Major, Christoph Steiner, Adriana Downie and Johannes Lehmann</i>	
	Introduction	271
	Evidence for relevant characteristics of biochar	273
	Magnitude and temporal dynamics of biochar effects on nutrient leaching	279
	Conclusions and research needs	282
16	Biochar and Sorption of Organic Compounds	289
	<i>Ronald J. Smernik</i>	
	Introduction	289
	Sorption properties of 'pure' biochars	290
	Influence of biochar on the sorption properties of soils	292
	Effects on sorption of adding biochar to soil	293
	Direct identification of organic molecules sorbed to biochar	294
	Conclusions and directions for future research	296
17	Test Procedures for Determining the Quantity of Biochar within Soils	301
	<i>David A. C. Manning and Elisa Lopez-Capel</i>	
	Introduction	301
	Biochar quantification methods	303
	Routine quantification of biochar in soils	311
	Conclusions	312
18	Biochar, Greenhouse Gas Accounting and Emissions Trading	317
	<i>John Gaunt and Annette Cowie</i>	
	The climate change context	317
	Greenhouse gas emissions trading	318
	How biochar contributes to climate change mitigation	321
	What mitigation benefits are tradable in a pyrolysis for biochar and bioenergy project?	324
	Greenhouse gas balance of example biochar systems	325
	Issues for emissions trading based on pyrolysis for bioenergy and biochar	333
	Conclusions	336
19	Economics of Biochar Production, Utilization and Greenhouse Gas Offsets	341
	<i>Bruce A. McCarl, Cordner Peacocke, Ray Chrisman, Chih-Chun Kung and Ronald D. Sands</i>	
	Introduction	341
	Pyrolysis and biochar	342
	Examination of a biomass to pyrolysis feedstock prospect	343
	Sensitivity analysis	354
	Omitted factors	355
	Conclusions	356

20	Socio-economic Assessment and Implementation of Small-scale Biochar Projects	359
	<i>Stephen Joseph</i>	
	Introduction	359
	Developing a methodology	360
	Model scenario of a hypothetical village-level biochar project	365
	Conclusions	371
21	Taking Biochar to Market: Some Essential Concepts for Commercial Success	375
	<i>Mark Glover</i>	
	Introduction	375
	Biochar's positioning in the sustainability and climate change agendas	377
	The sustainability context for biomass generally	378
	Inherent characteristics of the biomass resource	379
	Lessons from the first-generation liquid biofuels sector	380
	Biochar commercialization framework	381
	Commercial factors and business modelling	388
22	Policy to Address the Threat of Dangerous Climate Change: A Leading Role for Biochar	393
	<i>Peter Read</i>	
	The tipping point threat	393
	Beyond emissions reductions	394
	Carbon removals	395
	The economics of biosphere C stock management (BCSM) and biochar	396
	A policy framework for carbon removals: The leaky bucket	398
	Food versus fuel and biochar	400
	Conclusions	401
	<i>Index</i>	405