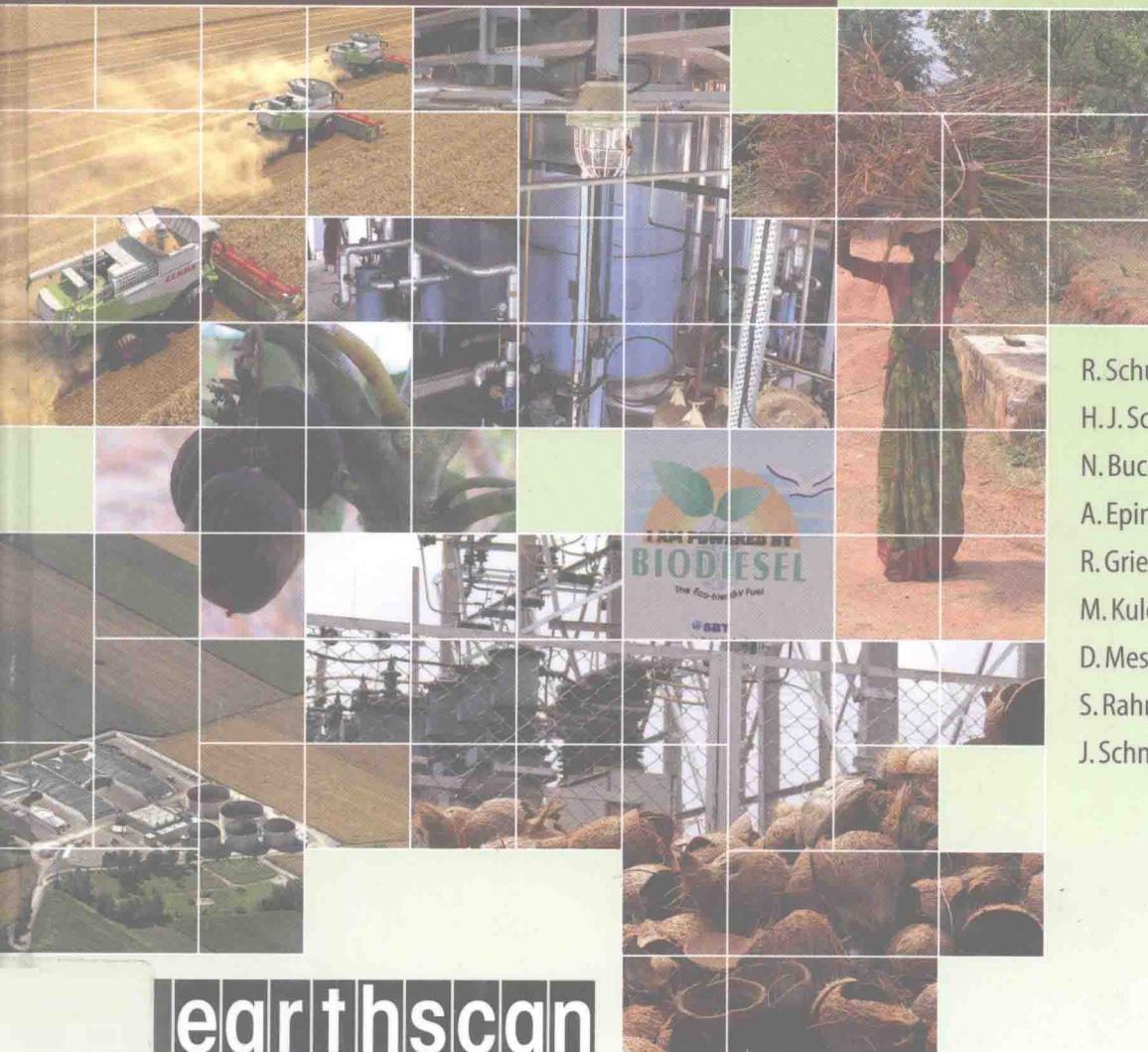




German Advisory Council
on Global Change
(WBGU)

Future Bioenergy and Sustainable Land Use



R. Schubert
H.J. Schellnhuber
N. Buchmann
A. Epiney
R. Grießhammer
M. Kulessa
D. Messner
S. Rahmstorf
J. Schmid

earthscan



WBGU

GERMAN ADVISORY COUNCIL ON GLOBAL CHANGE

Future Bioenergy and Sustainable Land Use



earthscan

London and Sterling, VA

German Advisory Council on Global Change (WBGU)
Secretariat
Reichpietschufer 60-62, 8th Floor
D-10785 Berlin, Germany

<http://www.wbgu.de>

German edition published in 2009, entitled
Welt im Wandel: Zukunftsfähige Bioenergie und nachhaltige Landnutzung
WBGU, Berlin 2009

First published by Earthscan in the UK and USA in 2010

Copyright © German Advisory Council on Global Change, 2010

ISBN 978-1-84407-841-7

Translation by Christopher Hay, Seeheim-Jugenheim, ecotranslator@t-online.de

Pictures for cover design with kind permission of CLAAS Germany (combine harvester Lexion 600) and Schmack Biogas AG, photographer Herbert Stolz (biomethane plant). All other pictures Prof Dr Meinhard Schulz-Baldes, WBGU.

For a full list of publications please contact:

Earthscan
Dunstan House
14a St Cross St
London, EC1N 8XA, UK
Tel: +44 (0)20 7841 1930
Fax: +44 (0)20 7242 1474
Email: earthinfo@earthscan.co.uk
Web: www.earthscan.co.uk

22883 Quicksilver Drive, Sterling, VA 20166-2012, USA

Earthscan publishes in association with the International Institute for Environment and Development

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

Library of Congress Cataloging-in-Publication Data has been applied for.

At Earthscan we strive to minimize our environmental impacts and carbon footprint through reducing waste, recycling and offsetting our CO₂ emissions, including those created through publication of this book. For more details of our environmental policy, see www.earthscan.co.uk.

This book was printed in Malta by Gutenberg Press
using soya-based inks. The paper is FSC certified.



The paper used for this book is FSC-certified and totally chlorine-free. FSC (the Forest Stewardship Council) is an international network to promote responsible management of the world's forests.

Council Staff and Acknowledgments

This Special Report builds upon the expert and committed work performed by the WBGU Secretariat staff and by the WBGU members and their assistants.

Scientific Staff at the Secretariat

Prof Dr Meinhard Schulz-Baldes
(Secretary-General)

Dr Carsten Loose
(Deputy Secretary-General)

Dr Karin Boschert

Dr Oliver Deke

Dipl Umweltwiss Tim Hasler

Dr Nina V. Michaelis

Dr Benno Pilardeaux
(Media and Public Relations)

Dr Astrid Schulz

Administration, Editorial work and Secretariat

Vesna Karic-Fazlic (Accountant)

Martina Schneider-Kremer, MA (Editorial work)

Margot Weiß (Secretariat)

Scientific Staff to the Council Members

Dipl Phys Jochen Bard (Institute for Solar Energy Technology, ISET Kassel, until 30.06.2007)

Steffen Bauer, MA (German Development Institute, DIE Bonn)

Dipl Volksw Julia E Blasch (Institute for Environmental Decisions, ETH Zurich, Switzerland)

Dr Georg Feulner (Potsdam Institute for Climate Impact Research, PIK)

Dr Sabina Keller (ETH Zurich, Switzerland)

Dipl Geogr Andreas Manhart (Institute for Applied Ecology, Freiburg, until 30.04.2008)

Dr Martin Scheyli (University Fribourg, Switzerland)

MSc Dipl Ing Michael Sterner (Institut für Solare Energieversorgungstechnik, ISET Kassel, from 01.07.2007)

Dr Ingeborg Schinninger (ETH Zurich, Switzerland, until 31.05.2007)

Dr Jennifer Teufel (Institute for Applied Ecology, Freiburg, from 01.05.2008)

WBGU owes a debt of gratitude to the important contributions and support provided by other members of the research community. This report builds on the following expert studies:

- Dipl.-Umweltwiss. Tim Beringer, Prof. Wolfgang Lucht (Potsdam Institute for Climate Impact Research, PIK): 'Simulation nachhaltiger Bioenergiepotentiale'.
- Dr Göran Berndes (Department of Energy and Environment, Physical Resource Theory, Chalmers University of Technology, Gothenburg, Sweden): 'Water demand for global bioenergy production: trends, risks and opportunities'.
- Dr André Faaij (Utrecht University, Copernicus Institute): 'Bioenergy and global food security'.
- Dr Uwe R. Fritzsche, Kirsten Wiegmann (Öko-Institut, Darmstadt Office): 'Treibhausgasbilanzen und kumulierter Primärenergieverbrauch von Bioenergie-Konversionspfaden unter Berücksichtigung möglicher Landnutzungsänderungen'.
- Dr Les Levidow, PhD (The Open University, Development Policy and Practice (DPP) Group, Milton Keynes, UK), Helena Paul (EcoNexus, Oxford, UK): 'Land-use, Bioenergy and Agro-biotechnology'.
- Dipl.-Ing. Franziska Müller-Langer, Anastasios Perimenis, Sebastian Brauer, Daniela Thrän, Prof. Dr-Ing. Martin Kaltschmitt (German Biomass Research Centre – DBFZ, Leipzig): 'Technische und ökonomische Bewertung von Bioenergie-Konversionspfaden'.
- Mark W. Rosegrant, Anthony J. Cavalieri (International Food Policy Research Institute – IFPRI, Washington, DC): 'Bioenergy and Agro-biotechnology'.
- Mark W. Rosegrant, Mandy Ewing, Siwa Msangi, and Tingju Zhu (International Food Policy Research Institute – IFPRI, Washington, DC): 'Bioenergy and Global Food Situation until 2020/2050'.
- Dr Ingeborg Schinninger (ETH Zürich, Institut für Pflanzenwissenschaften): 'Globale Landnutzung'.
- Dr oec. troph. Karl von Koerber, Dipl. oec. troph. Jürgen Kretschmer, Dipl. oec. troph. Stefanie Prinz (Beratungsbüro für Ernährungsökologie, Munich): 'Globale Ernährungsgewohnheiten und -trends'.

For help in creating the graphics we are indebted to Danny Rothe, Design Werbung Druck, Berlin.

During its intensive conference held in May 2008 in Schmöckwitz, Berlin, WBGU drew valuable input from the papers on 'THG-Emission Bio-Prozesse mit LUC' by Dr Uwe R. Fritzsche (Öko-Institut, Darmstadt Office) and on 'Technischen und ökonomischen Bewertung von Bioenergiekonversionsp-

faden' by Dipl.-Ing. Franziska Müller-Langer (German Biomass Research Centre – DBFZ, Leipzig). We should also like to thank Tim Beringer (Potsdam Institute for Climate Impact Research, PIK) for presenting the results of his 'Modellierung zu nachhaltigem globalen Bioenergiopotenzial'.

WBGU also wishes to thank all those who promoted the progress of this report through discussion, comments, advice and research or by reviewing parts of the report:

Prof. Dr Markus Antonietti (Max-Planck-Institut für Kolloid- und Grenzflächenforschung, Potsdam); Ing. Michael Beil (Institut für Solare Energieversorgungstechnik – ISET Hanau); Verena Brinkmann (Sector Project HERA – Household Energy Programme, GTZ Eschborn); Qays Hamad, Advisor to the Executive Director for Germany (The World Bank, Washington, DC); Peter Herkenrath and Dr Lera Miles (UNEP-WCMC, Cambridge); DirProf. Dr Christian Hey and Dr Susan Krohn (German Advisory Council on the Environment – SRU, Berlin); Holger Hoff (Potsdam Institute for Climate Impact Research and Stockholm Environment Institute); Philipp Mensch (ETH Zürich); Gregor Meerganz von Medeazza, PhD (Sustainable Energy and Climate Change Initiative – SECCI, Washington, DC); Ritah Mubbala (Institut für Solare Energieversorgungstechnik – ISET, Kassel); Dipl.-Volksw. Markus Ohndorf (ETH Zürich); Dr Alexander Popp (Potsdam Institute for Climate Impact Research, PIK); Dr Timothy Searchinger (Princeton University, Princeton, NJ); Dr Karl-Heinz Stecher (KfW Bankengruppe, Berlin); Dr-Ing. Alexander Vogel (German Biomass Research Centre – DBFZ, Leipzig) and Dr Tilman Altenburg, Dr Michael Brüntrup, Dr Matthias Krause, Christian von Drachenfels, Dipl.-Ing. agr. Heike Höffler, Julia Holzbach and Kathrin Seelige (German Development Institute – DIE, Bonn).

WBGU is much indebted to the persons who received the WBGU delegation visiting India from 5 to 17 February 2008, and to the organizers of the visit. The German Embassy in New Delhi provided extensive support in making the necessary arrangements. WBGU proffers warmest thanks to Ambassador Müzelburg and all the embassy staff for their invaluable assistance. WBGU is particularly indebted to Dr von Münchow-Pohl and Ms Subhedar, who planned the different parts of the itinerary and arranged meetings and discussions. Thanks are also due to Ms Holzhauser, Mr Wirth and Ms Tiemann, who accompanied WBGU to meetings in Delhi. We should also like to thank the GTZ team: Ms Kashyap, Mr Glück, Dr Bischoff, Dr Porst and Mr Babu.

Many local experts from politics, administration and science offered guided tours, prepared presenta-

tions and were available for in-depth discussions and conversations. WBGU proffers them all its warmest thanks.

Acronyms and Abbreviations

ACP	African, Caribbean and Pacific Group of States
ADB	Asian Development Bank
AfDB	African Development Bank
BEFS	Bioenergy and Food Security Project (FAO)
BMELV	Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz [Federal Ministry of Food, Agriculture and Consumer Protection, Germany]
BMU	Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Germany]
BMZ	Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung [Federal Ministry for Economic Cooperation and Development, Germany]
BtL	Biomass-to-Liquid
CAP	Common Agricultural Policy (EU)
CBD	Convention on Biological Diversity
CCS	Carbon Capture and Storage
CDM	Clean Development Mechanism (Kyoto Protocol)
CGIAR	Consultative Group on International Agricultural Research
CHP	Combined Heat and Power
CITES	Convention on International Trade in Endangered Species of Wild Fauna and Flora (UN)
COP	Conference of the Parties
CO ₂	Carbon Dioxide
CRIC	Committee for the Review of the Implementation of the Convention (UNCCD)
CPD	Centers of Plant Diversity (IUCN)
CSD	Commission on Sustainable Development (UN)
CST	Committee on Science and Technology (UNCCD)
DALY	Disability Adjusted Life Years
dLUC	Direct Land-Use Change
DM	Dry Matter
EEG	Renewable Energy Sources Act (Germany)
EGS	Environmental Goods and Services (WTO)
EMPA	Swiss Federal Laboratories for Materials Testing and Research
ETI	Ethical Trading Initiative
ETS	Greenhouse Gas Emission Trading Scheme (EU)
EU	European Union
EUGENE	European Green Electricity Network
EUIE	EU-Initiative Energy for Poverty Reduction and Sustainable Development
FATF	Financial Action Task Force on Money Laundering
FAO	Food and Agriculture Organization of the United Nations
FLO	Fairtrade Labelling Organizations International
FSC	Forest Stewardship Council
GATT	General Agreement on Tariffs and Trade
GBEP	Global Bioenergy Partnership (FAO)
GDP	Gross Domestic Product

GEF	Global Environment Facility (UNDP, UNEP, World Bank)
GHG	Greenhouse Gas
GIS	Geographical Information System
GLASOD	The Global Assessment of Human Induced Soil Degradation (ISRIC)
GSP	Generalized System of Preferences (EU)
GSPC	Global Strategy for Plant Conservation (CBD)
GTZ	Deutsche Gesellschaft für Technische Zusammenarbeit [German Society on Development Cooperation]
GuD	Gas-steam Power Plant
GMO	Genetically Modified Organisms
HANPP	Human Appropriation of Net Primary Production
HCVA	High Conservation Value Areas
IBEP	International Bioenergy Platform (FAO)
IAASTD	International Assessment of Agricultural Knowledge, Science and Technology for Development
IADB	Inter-American Development Bank
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics (CGIAR)
ICSB	International Conference on Sustainable Bioenergy (recommended)
ICSU	International Council for Science
IDA	International Development Association (World Bank)
IEA	International Energy Agency (OECD)
IFAD	International Fund for Agricultural Development
IFC	International Finance Corporation (World Bank)
IFOAM	International Federation of Organic Agriculture Movements
IFPRI	International Food Policy Research Institute (FAO)
IGBP	International Geosphere Biosphere Program (ICSU)
IHDP	International Human Dimensions Programme on Global Environmental Change (ISSC, ICSU)
ILO	International Labour Organization (UN)
iLUC	Indirect Land-Use Change
IPCC	Intergovernmental Panel on Climate Change (WMO, UNEP)
IRENA	International Renewable Energy Agency
ISCC	International Sustainability and Carbon Certification (BMELV)
ISRIC	International Soil Reference and Information Centre
ISSC	International Social Science Council (UNESCO)
ITTO	International Tropical Timber Organization
IUCN	World Conservation Union
IMF	International Monetary Fund
KfW	German Development Bank
LDC	Least Developed Countries
LIFDC	Low Income Food Deficit Countries (FAO, WFP)
LULUCF	Land Use, Land-Use Change and Forestry
MA	Millennium Ecosystem Assessment (UN)
MDG	Millennium Development Goals (UN)
MERCOSUR	Mercado Común del Sur (Argentina, Brazil, Paraguay, Uruguay)
MESA	Multilaterales Energiesubventionsabkommen (recommended)
MODIS	Moderate Resolution Imaging Spectroradiometer
NaWaRo	Nachwachsende Rohstoffe
NEDC	New European Driving Cycle
NGO	Non-governmental Organization
OECD	Organisation for Economic Co-operation and Development
PEFC	Programme for the Endorsement of Forest Certification Schemes
PIK	Potsdam Institute for Climate Impact Research
PSA	Programm Pagos por Servicios Ambientales (Costa Rica)
REC	Renewable Energy Certificates
REDD	Reducing Emissions from Deforestation and Degradation (UNFCCC)

REEEP	Renewable Energy and Energy Efficiency Partnership (UK)
REN21	Renewable Energy Policy Network for the 21st Century
RIL	Reduced-impact Logging
RSB	Roundtable on Sustainable Biofuels
RSPO	Roundtable on Sustainable Palmoil
RTRS	Roundtable on Responsible Soy Association (Switzerland)
SAFE	Silvorable Forestry for Europe Project
SAI	Social Accountability International
SAN	Sustainable Agriculture Network (Rainforest Alliance)
SRF	Short-rotation Forestry; or: Short-rotation Coppice
SRU	Sachverständigenrat für Umweltfragen
UBA	[Council of Environmental Experts, Germany] Umweltbundesamt [Federal Environment Agency]
UNCCD	United Nations Convention to Combat Desertification in Countries Experiencing Serious Drought and/or Desertification, Particularly in Africa
UNCTAD	United Nations Conference on Trade and Development
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
UNIDO	United Nations Industrial Development Organisation
WBGU	Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen [German Advisory Council on Global Change]
WCD	World Commission on Dams (World Bank, IUCN)
WCMC	World Conservation Monitoring Centre (UNEP)
WDPA	World Database on Protected Areas (UNEP, IUCN)
WFP	World Food Programme (UN)
WHO	World Health Organization (UN)
WSSD	World Summit on Sustainable Development
WTO	World Trade Organization
WWF	World Wide Fund for Nature

Contents

Council Staff and Acknowledgments	V
Boxes	XVII
Tables	XIX
Figures	XXI
Acronyms and Abbreviations	XXIV
1 Introduction	19
2 Motives for deploying bioenergy	21
2.1 Current discourses on bioenergy	21
2.2 Sustainable global energy systems and land-use systems	23
2.2.1 Bioenergy, energy system transformation and climate change mitigation	23
2.2.2 Bioenergy, energy system transformation and energy poverty	24
2.2.3 Specific properties of biomass	24
3 Sustainability constraints upon bioenergy	27
3.1 Ecological sustainability	27
3.1.1 Guard rail for climate protection	27
3.1.2 Guard rail for biosphere conservation	28
3.1.3 Guard rail for soil protection	28
3.1.4 Additional ecological sustainability requirements	29
3.2 Socioeconomic sustainability	29
3.2.1 Guard rail for securing access to sufficient food	29
3.2.2 Guard rail for securing access to modern energy services	30
3.2.3 Guard rail for avoiding health risks through energy use	31
3.2.4 Additional socioeconomic sustainability requirements	31
3.3 Conclusion	32
4 Bioenergy, land use and energy systems: Situation and trends	33
4.1 Bioenergy in the global energy system	33
4.1.1 Current bioenergy use	33
4.1.1.1 Bioenergy in the global energy system	33
4.1.1.2 Use of bioheat and bio-electricity in the energy system	35
4.1.1.3 Use of biofuels	37

4.1.2	Current bioenergy promotion policy	40
4.2	Global land cover and land use	46
4.2.1	Global land cover	47
4.2.2	Global land use	50
4.2.3	The influence of land-use changes on ecosystem services	52
4.2.3.1	Conversion of forest	52
4.2.3.2	Conversion of wetlands	54
4.2.3.3	Conversion of grassland	54
4.2.3.4	Conversion of arable land	55
4.2.4	Summing up	56
5	Competing uses	57
5.1	Introduction	57
5.2	Competition with food and feed production	57
5.2.1	Introduction	57
5.2.2	Growing food supply and rising demand	58
5.2.3	Challenges arising from changed dietary habits	59
5.2.3.1	A summary of individual foods: Global trends	59
5.2.3.2	Land requirements of dietary habits and foods	60
5.2.3.3	Additional land requirements as a result of changing dietary habits	62
5.2.4	Limits to potential food production	62
5.2.4.1	Potentially available land and soil degradation	63
5.2.4.2	Climate change impacts on production potential	63
5.2.5	Impacts of the bioenergy boom on food security	63
5.2.5.1	The four dimensions of food security	64
5.2.5.2	The influence of the bioenergy boom on prices and incomes	65
5.2.6	Summary: Ways to defuse competition for land use	70
5.3	Using biomass as an industrial feedstock	70
5.3.1	Feedstock use of plant raw materials (excluding wood) in Germany	70
5.3.2	Feedstock use of forestry products	72
5.3.3	Cascade use	73
5.3.4	The outlook for material production without oil, gas and coal	73
5.4	Competition with biological diversity	74
5.4.1	Competition between energy crop cultivation and existing protected areas	74
5.4.2	Competition between energy crops and natural ecosystems outside protected areas	76
5.4.3	Competition between energy crops and the conservation of biological diversity in agricultural areas	78
5.4.4	The cross-cutting issue of climate change	80
5.4.5	Conclusions	81
5.5	Land-use options for climate change mitigation	81
5.5.1	Forests and climate change mitigation	82
5.5.1.1	Avoiding deforestation and forest degradation	82
5.5.1.2	Afforestation	83
5.5.1.3	Forest management, sustainable forestry	85
5.5.2	Agriculture and climate change mitigation	85
5.5.3	Climate change mitigation through the use of long-lived biomass products	86
5.5.4	Conclusions	87
5.6	Competing use of soil and water	89
5.6.1	Soil degradation and desertification	89

5.6.2	Overuse of freshwater resources	90
5.6.3	Conclusion: Integrate energy crop cultivation into sustainable soil and water management	92
6	Modelling global energy crop potential	95
6.1	Previous appraisals of bioenergy potential	95
6.1.1	Bioenergy potentials in the recent literature.....	95
6.1.2	Summary and evaluation	98
6.2	Global land-use models: The state of scientific knowledge	98
6.2.1	Effects and impacts of human land use	98
6.2.2	Typology of global models of land use and land-use change	100
6.3	Description of the model	100
6.3.1	Methods used in the model	100
6.3.1.1	Modelling plant productivity	100
6.3.1.2	Agriculture in LPJmL	101
6.3.1.3	Modelling the cultivation of energy crops	101
6.3.1.4	Comparison with measured data	101
6.3.1.5	Calculation of global bioenergy potential	101
6.3.2	Data sets used in the model	102
6.3.2.1	Climate change and climate data	102
6.3.2.2	Land-use data	102
6.4	Model assumptions and scenarios	102
6.4.1	Climate models and emissions scenarios	102
6.4.2	Irrigation scenarios	102
6.4.3	Scenarios for the calculation of biomass potentials	103
6.4.3.1	Scenarios for securing food production	103
6.4.3.2	Scenarios for nature conservation	105
6.4.3.3	Scenarios for greenhouse gas emissions from land-use changes	106
6.5	Results of the modelling of the global potential of energy crops	108
6.5.1	Influence of the climate models and emissions scenarios	108
6.5.2	Influence of the compensation period	108
6.5.3	Bioenergy potentials for four scenarios	110
6.5.4	Geographical distribution of possible land for energy crop cultivation	116
6.5.5	Biomass yields for trees and grasses	116
6.6	Key uncertainties in the modelling	116
6.6.1	Quality of the climate data	116
6.6.2	Response of plants and ecosystems to climate change.....	116
6.6.3	Availability of water and nutrients	117
6.6.4	Development of energy crop yields	122
6.6.5	Land-use data	122
6.6.6	Future irrigation possibilities	123
6.7	Regional survey	123
6.7.1	Latin America and the Caribbean	126
6.7.2	China and neighbouring countries	126
6.7.3	Pacific Asia	127
6.7.4	South Asia and India	127
6.7.5	Sub-Saharan Africa	127
6.7.6	Community of Independent States (CIS)	128

6.8 Interpretation and conclusions	128
7 Biomass cultivation and conversion to energy.....	133
7.1 Cultivation systems for biomass production as energy resource.....	133
7.1.1 Energy crop cultivation in monoculture.....	133
7.1.1.1 Perennial crops in the tropics	134
7.1.1.2 Rotational crops in temperate latitudes	138
7.1.1.3 Perennial crops in temperate latitudes	140
7.1.2 Short-rotation plantations (SRPs)	140
7.1.3 Agroforestry	141
7.1.4 Permanent grassland and pastures	143
7.1.5 Forests as biomass producers.....	145
7.1.5.1 Biomass use in tropical forests	145
7.1.5.2 Biomass use in temperate forests	147
7.1.5.3 Biomass use in boreal forests	147
7.1.6 Summary evaluation of currently predominant cultivation systems.....	151
7.2 Technical and economic analysis and appraisal of bioenergy pathways.....	151
7.2.1 Overview of energy conversion options.....	151
7.2.2 Energy conversion technologies	151
7.2.2.1 Combustion and thermochemical processes	151
7.2.2.2 Physical-chemical processes	155
7.2.2.3 Biochemical conversion	155
7.2.3 Efficiencies of various modern conversion processes.....	157
7.2.3.1 Overview of the bioenergy pathways investigated.....	157
7.2.3.2 Efficiencies	158
7.2.4 Efficiencies of various traditional conversion processes	165
7.2.5 Economic analysis and assessment of conversion processes	166
7.2.5.1 Production costs of modern conversion processes	166
7.2.5.2 Discussion of future developments of bioenergy pathway costs	166
7.3 Greenhouse gas balances	170
7.3.1 Life-cycle assessment methodology	170
7.3.2 Greenhouse gas balances of selected bioenergy pathways	171
8 Optimizing bioenergy integration and deployment in energy systems	189
8.1 Bioenergy as a part of sustainable energy supply in industrialized countries	189
8.1.1 Transforming energy systems for improved energy efficiency and climate change mitigation	189
8.1.1.1 Transformation components	189
8.1.1.2 Transforming energy systems by combining the components.....	194
8.1.2 The role of bioenergy in the sustainable energy supply of industrialized countries ..	195
8.1.2.1 Bioenergy for transport: Bio-electricity versus biofuels	196
8.1.2.2 Bioenergy for central and decentral heat supply	196
8.1.2.3 Bioenergy for electricity generation: Control energy and cogeneration ..	197
8.1.2.4 Overall assessment of bioenergy in industrialized countries	199
8.1.2.5 Stages en route to sustainable bioenergy use in industrialized countries ..	199
8.2 Bioenergy as a part of sustainable energy supply in developing countries	201
8.2.1 A revolution in traditional biomass use	201
8.2.2 Supplying energy in rural areas with the aid of modern biomass use	202
8.2.3 The role of bioenergy in the sustainable and integrated energy supply of developing countries	204
8.2.3.1 Bioenergy for transport	204

8.2.3.2	Bioenergy for heat and light	204
8.2.3.3	Bioenergy for central and decentral electricity generation	207
8.2.3.4	Overall assessment of bioenergy in developing countries	207
8.2.3.5	Technological stages en route to sustainable bioenergy use in developing countries	207
9	Sustainable biomass production and bioenergy deployment: A synthesis	209
9.1	Sustainable production of biomass as an energy resource: The key considerations	209
9.1.1	Biogenic wastes and residues	209
9.1.2	Land-use changes	209
9.1.3	Cultivation systems	210
9.2	Conversion, application and integration of bioenergy	210
9.2.1	Climate change mitigation	211
9.2.1.1	Reducing greenhouse gases through bioenergy use: Measurement and standard-setting	211
9.2.1.2	Taking account of indirect land-use change	211
9.2.1.3	Replacing fossil energy carriers	212
9.2.1.4	Climate change mitigation effect of different technical applications/ pathways	212
9.2.2	Energy poverty	216
9.2.3	Bioenergy as a bridging technology	217
10	Global bioenergy policy	219
10.1	Introduction	219
10.2	International climate policy	220
10.2.1	The UNFCCC as an actor in global bioenergy policy	220
10.2.2	Evaluation, attribution and accounting of emissions	221
10.2.2.1	The current rules and associated problems	221
10.2.2.2	Criteria and opportunities for the further development of the rules	224
10.2.3	Bioenergy and the Clean Development Mechanism	227
10.2.3.1	Existing rules on bioenergy and its evaluation	228
10.2.3.2	Options for further development of the rules	230
10.2.4	Approaches to an integrated post-2012 solution	231
10.2.5	Conclusions	232
10.3	Standards for the production of bioenergy carriers	233
10.3.1	WBGU's criteria for a bioenergy standard	233
10.3.1.1	A minimum standard for bioenergy carriers	234
10.3.1.2	Promotion criteria for biomass production	236
10.3.2	Schemes for the implementation of standards for bioenergy carriers	237
10.3.2.1	Standards established by private, state and supranational organizations ..	238
10.3.2.2	Bilateral agreements	243
10.3.2.3	Multilateral approaches	244
10.3.3	Implications of the adoption of standards for trade in bioenergy carriers	245
10.3.3.1	Standards as a barrier to trade	246
10.3.3.2	Implications for trade relations with developing countries and emerging economies	246
10.3.3.3	Preferential treatment of bioenergy carriers through qualification as environmental goods and services	246
10.3.4	WTO compliance of standards for bioenergy carriers	247
10.3.4.1	Relevance of WTO law in standard-setting	247
10.3.4.2	Justifying discriminatory measures	248

10.3.4.3	Legal assessment of the sustainability standards recommended by WBGU	250
10.3.5	Interim conclusion	250
10.4	Options for securing the world food supply in the context of a sustainable bioenergy policy	252
10.4.1	New challenges arising from bioenergy use	252
10.4.2	Short-term coping measures	253
10.4.2.1	Safety nets and other fiscal measures	253
10.4.2.2	Administrative price ceilings.....	253
10.4.2.3	Short-term aid for smallholders	253
10.4.2.4	Export restrictions on agricultural products	254
10.4.2.5	Removal of distortions of trade in world agricultural markets	254
10.4.2.6	Financial assistance, emergency aid and reform of the Food Aid Convention	255
10.4.3	Medium-term and long-term measures	256
10.4.3.1	Bioenergy strategies to avoid land-use competition	256
10.4.3.2	Promotion of the small-scale agricultural sector in developing countries .	256
10.4.3.3	More extensive and more differentiated liberalization of world agricultural markets	257
10.4.3.4	Promoting awareness of the consequences of different dietary habits ..	258
10.4.3.5	Establishment of early warning and risk management systems	259
10.4.4	Conclusions	260
10.5	International biodiversity policy and sustainable bioenergy	261
10.5.1	Protected areas and protected area systems	262
10.5.1.1	CBD work programme on protected areas	262
10.5.1.2	Further provisions of the CBD.....	263
10.5.1.3	Options for further elaboration	263
10.5.2	Financing protected area systems through compensation payments	264
10.5.2.1	Financing the global network of protected areas through international payments	266
10.5.2.2	Options for further elaboration – criteria for an international compensation regime.....	267
10.5.3	Contributions of the CBD to bioenergy standards development	268
10.5.3.1	Provisions of the CBD as the basis for bioenergy standards.....	268
10.5.3.2	Routes towards implementation of biodiversity-relevant guidelines or standards on bioenergy	269
10.5.4	Conclusions	270
10.6	Water and soil conservation in the context of sustainable bioenergy policy	271
10.6.1	Soil conservation and desertification control: Potential and limitations of the Desertification Convention.....	271
10.6.2	Conservation and sustainable use of freshwater.....	272
10.7	State promotion of bioenergy: Agricultural and industrial policies	273
10.7.1	Promoting bioenergy pathways through climate policy	273
10.7.2	Promotion and intervention approaches under sustainable bioenergy policy.....	274
10.7.3	Agricultural policy: Promoting biomass cultivation for energy production.....	275
10.7.3.1	Favouring particular cultivation methods and ecosystem services	275
10.7.3.2	International initiatives	275
10.7.4	Promoting the conversion of biogenic wastes and residues into energy	276
10.7.5	Technology policy and the promotion of selected conversion pathways	278
10.7.5.1	Conversion of biomethane to energy.....	278
10.7.5.2	Efficient system technology in electricity and heat production	280
10.7.5.3	Direct combustion of solid biomass to generate heat for private households	281

10.7.6	Promoting bioenergy in final use	281
10.7.7	International initiatives and institutions for the promotion of sustainable bioenergy	283
10.7.7.1	International Renewable Energy Agency	283
10.7.7.2	International Conference on Sustainable Bioenergy	284
10.7.7.3	Multilateral Energy Subsidies Agreement	284
10.7.8	Conclusions	285
10.8	Bioenergy and development cooperation	285
10.8.1	Current bioenergy activities in international development cooperation	286
10.8.1.1	The World Bank Group and regional development banks	286
10.8.1.2	Programmes and specialized agencies of the United Nations	288
10.8.1.3	Development cooperation activities of the European Union and Germany	289
10.8.1.4	The state of international development cooperation in the field of bioenergy	291
10.8.2	Bioenergy strategies for developing countries	292
10.8.2.1	Combating energy poverty through off-grid rural energy provision	293
10.8.2.2	Modernization of the energy sector and export production	295
10.8.2.3	Core elements of national bioenergy strategies for developing countries	296
10.8.3	Action under uncertainty: Consequences for active promotion policies	300
11	Research recommendations	303
11.1	Bioenergy use and the greenhouse gas balance	303
11.1.1	Improving greenhouse gas balancing of energy crop cultivation	303
11.1.2	Integrated assessment of climate change mitigation options in land and biomass use	304
11.1.3	Sequestration of CO ₂ in depots and black carbon in soils	305
11.2	Sustainable bioenergy potential	305
11.2.1	Sustainable agriculture and energy crop cultivation	305
11.2.2	International research programmes on sustainable and economic bioenergy potentials	306
11.2.3	Social sustainability	307
11.3	Bioenergy and energy systems	308
11.3.1	Technologies of bioenergy use	308
11.3.2	Potential for using residues and waste for energy	309
11.3.3	Modernizing traditional bioenergy use to overcome energy poverty	309
11.3.4	Integrated technology development and assessment for bioenergy	310
11.4	Bioenergy and global land-use management	310
11.4.1	Data on global land use and degradation	310
11.4.2	Integrated scientific and economic land-use modelling	311
11.4.3	Agents and drivers	311
11.4.4	Linkages between energy crop cultivation and food security	311
11.4.5	Effects of changes in dietary patterns and lifestyles on climate and land use	311
11.5	Shaping international bioenergy policy	312
11.5.1	Managing global land use	312
11.5.2	Standard-setting and the WTO regime	312
11.5.3	Bioenergy policy and security policy	313
11.5.4	Developing commitments under the UNFCCC and CBD	313
11.5.5	Methods of supporting decision-making under uncertainty	313

12 Recommendations for action	315
12.1 Making bioenergy a consistent part of international climate policy	316
12.2 Introducing standards and certification for bioenergy and sustainable land use	318
12.3 Regulating competition between uses sustainably	320
12.3.1 Developing an integrated bioenergy and food security strategy	320
12.3.2 Taking greater account of the coupling of land use, food markets and energy markets	321
12.3.3 Taking greater account of increasing pressure on land use caused by changing dietary habits	322
12.3.4 Implementing biodiversity policy for sustainable energy crop cultivation	323
12.3.5 Improving long-term water and soil protection through energy crop cultivation . .	324
12.4 Targeting bioenergy promotion policies	325
12.4.1 Reforming agricultural subsidies	325
12.4.2 Advancing energy recovery from biogenic wastes and residues	326
12.4.3 Reorienting technology policy	326
12.5 Harnessing sustainable bioenergy potential in developing and newly industrializing countries	328
12.6 Building structures for sustainable global bioenergy policy	330
13 References	333
14 Glossary	361