ENVIRONMENT & POLICY

Agriculture and Climate Beyond 2015

A New Perspective on Future Land Use Patterns

Edited by
Floor Brouwer and Bruce A. McCarl

E&P

Springer

AGRICULTURE AND CLIMATE BEYOND 2015
A New Perspective on Future Land Use Patterns

ENVIRONMENT & POLICY

VOLUME 46

The titles published in this series are listed at the end of this volume.

Agriculture and Climate Beyond 2015

A New Perspective on Future Land Use Patterns

Edited by

Floor Brouwer

LEI, Wageningen UR,
The Hague, The Netherlands

and

Bruce A. McCarl

Department of Agricultural Economics,
Texas A&M University, College Station,
Texas, U.S.A.

Springer

A C.I.P. Catalogue record for this book is available from the Library of Congress.

ISBN-10 1-4020-4063-6 (HB)
ISBN-13 978-1-4020-4063-4 (HB)
ISBN-10 1-4020-4368-6 (e-book)
ISBN-13 978-1-4020-4368-0 (e-book)

Published by Springer,
P.O. Box 17, 3300 AA Dordrecht, The Netherlands.

www.springer.com

Logos used with permission from IGBP, IHDP and LUCC

Printed on acid-free paper

Printed in the Netherlands.

Contents

Contributors

Harry Aiking is Associate Professor, Chemistry & Food, Institute for Environmental Studies, Vrije Universiteit, De Boelelaan 1087, 1081 HV Amsterdam, The Netherlands (e-mail: harry.aiking@ivm.falw.vu.nl).

Alisson F. Barbieri is Research Associate, Carolina Population Center, University of North Carolina at Chapel Hill. Chapel Hill, 27514, USA (e-mail: barbieri@email.unc.edu).

Marie Boehm is a Research Scientist on the Environment Team of Agriculture and Agri-Food Canada, 51 Campus Drive, Saskatoon, Saskatchewan, Canada S7N 5A8 (e-mail: boehmm@agr.gc.ca).

Alberte Bondeau is a Research Fellow at the Potsdam Institute for Climate Impact Research (PIK), 14412 Potsdam, Germany (alberte.bondeau@pik-potsdam.de).

Gert-Jan van den Born is Senior Researcher, Netherlands Environmental Assessment Agency, National Institute for Public Health and the Environment, P.O. Box 1, 3720, BA Bilthoven, The Netherlands.

Lex Bouwman is Senior Researcher, Netherlands Environmental Assessment Agency, National Institute for Public Health and the Environment, P.O. Box 1, 3720, BA Bilthoven, The Netherlands (e-mail: lex.bouwman@mnp.nl).

Floor Brouwer is Head of the Research Unit Management of Natural Resources, LEI, Wageningen UR, P.O. Box 29703, 2502 LS The Hague, The Netherlands (e-mail: floor.brouwer@wur.nl).

David Carr is Assistant Professor of Geography, University of California, Santa Barbara. Santa Barbara, CA 93106, USA (email: carr@geog.ucsb.edu).

Jinke van Dam is a former researcher at the Energy Supply Cluster of the Department of Science, Technology and Society, Copernicus Institute, Utrecht University, P.O. Box 80115, 3508 TC Utrecht, The Netherlands.

Gerard van Drecht is Senior Researcher, Netherlands Environmental Assessment Agency, National Institute for Public Health and the Environment, P.O. Box 1, 3720, BA Bilthoven, The Netherlands (e-mail: g.van.drecht@mnp.nl).

Bas Eickhout is Researcher, Netherlands Environmental Assessment Agency, National Institute for Public Health and the Environment, P.O. Box 1, 3720, BA Bilthoven, The Netherlands (e-mail: bas.eickhout@mnp.nl).

Frank Ewert is Senior Scientist, Plant Production Systems Group, Department of Plant Sciences, Wageningen University, P.O. Box 430, 6700 AK Wageningen, The Netherlands (e-mail: frank.ewert@wur.nl).

André P.C. Faaij is Co-ordinator of the Energy Supply Cluster of the Department of Science, Technology and Society, Copernicus Institute, Utrecht University, P.O. Box 80115, 3508 TC Utrecht, The Netherlands (e-mail: a.faaij@chem.uu.nl).

Patricia L. Farnese is the Senior Law Fellow at the Centre for Studies in Agriculture, Law and the Environment (www.csale.usask.ca) and Assistant Professor in the College of Law at the University of Saskatchewan, Saskatoon SK Canada S7N 5A8 (e-mail: patricia.farnese@usask.ca).

Murray Fulton is Professor of Agricultural Economics at the University of Saskatchewan, Agriculture Building, 51 Campus Drive, Saskatoon, Saskatchewan, Canada S7N 5A8. He is also the Director of the Centre for Studies in Agriculture, Law and the Environment at the University of Saskatchewan (e-mail: Murray. Fulton@usask.ca).

Helmut Geist is Executive Director of the Land-Use/Cover Change (LUCC) Project, University of Louvain, 3, Place Louis Pasteur, 1348 Louvain-la-Neuve, Belgium (e-mail: geist@geog.ucl.ac.be).

Dhazn Gillig is an Economist and Manager with American Express Corporation, Phoenix Arizona, USA (email dhazn.w.gillig@aexp.com).

Matthijs Hisschemöller is Senior Researcher, Institute for Environmental Studies, Vrije Universiteit, De Boelelaan 1087, 1081 HV Amsterdam, The Netherlands (e-mail: matthijs.hisschemoller@ivm.falw.vu.nl).

Klaas van der Hoek, Senior Researcher Agricultural Sciences, Laboratory for Environmental Monitoring, National Institute for Public Health and the Environment, P.O. Box 1, 3720, BA Bilthoven, The Netherlands (e-mail: klaas.van.der.hoek@rivm.nl).

Ekko van Ierland is Professor of Environmental Economics, Wageningen University, P.O. Box 8130, 6700 EW Wageningen The Netherlands (e-mail: ekko.vanierland@wur.nl).

Heide Iranavi B.A., is a Fullbright Scholar in Jordan, 2005 University of North Carolina, Chapel Hill, USA (e-mail: iravani@email.unc.edu).

Henry Janzen is a Research Scientist on the Environment Team of Agriculture and Agri-Food Canada, PO Box 3000, Lethbridge, Alberta, Canada T1J 4B1 (e-mail: Janzen@agr.gc.ca).

Eric Lambin is Chair of the Land-Use/Cover Change (LUCC) Project and Professor at the Geography Department, University of Louvain, 3, Place Louis Pasteur, 1348 Louvain-la-Neuve, Belgium (e-mail: lambin@geog.ucl.ac.be).

Heng-Chi Lee is an Assistant Professor of Applied Economics, National Taiwan Ocean University, Keelung, Taiwan (email hlee@ntou.edu.tw).

Rik Leemans is Professor of Environmental Systems Analysis at Wageningen University, Department of Environmental Sciences, Wageningen UR, P.O. Box 47, 6700 AA Wageningen, The Netherlands (e-mail: rik.leemans@wur.nl).

Wilfrid Legg is Head of Policies and Environment Division in the Agriculture Directorate of the Organisation for Economic Cooperation and Development (OECD), 2 Rue André Pascal, F-75775 Paris, France. (e-mail: wilfrid. legg@ oecd.org).

Jan Peter Lesschen is PhD student, Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, Nieuwe Achtergracht 166, 1018WV Amsterdam, The Netherlands (e-mail: lesschen@science.uva.nl).

Iris M. Lewandowski is Senior Researcher at the Energy Supply Cluster of the Department of Science, Technology and Society, Copernicus Institute, Utrecht University, P.O. Box 80115, 3508 TC Utrecht, The Netherlands (e-mail: i.lewandowski@chem.uu.nl).

Hermann Lotze-Campen is a Research Fellow at the Potsdam Institute for Climate Impact Research (PIK), 14412 Potsdam, Germany (e-mail: lotze- campen @pik-potsdam.de).

Wolfgang Lucht is a Senior Researcher at the Potsdam Institute for Climate Impact Research (PIK), 14412 Potsdam, Germany (e-mail: wolfgang.lucht@pik-potsdam.de).

Robert J. MacGregor is Chief, Agriculture and Environmental Policy Analysis in the Strategic Policy Branch of Agriculture and Agri-Food Canada, Building 74, 960 Carling Ave. Ottawa, Ontario, Canada K1A 0C6 (e-mail: macgrbo@agr.gc.ca).

Bruce A. McCarl is Regents Professor, Department of Agricultural Economics, Texas A&M University, MS 2124, College Station, Texas, 77845-2124, USA (e-mail: mccarl@tamu.edu).

Marc Metzger is PhD student in the Plant Production Systems Group, Department of Plant Sciences, Wageningen University, P.O. Box 430, 6700 AK Wageningen, The Netherlands (e-mail: Marc.Metzger@wur.nl).

Christoph Müller is a Ph.D. Student at the Potsdam Institute for Climate Impact Research (PIK), 14412 Potsdam, Germany, and the Max Planck Institute for Meteorology, 20146 Hamburg, Germany (e-mail: christoph.mueller@pik-potsdam.de).

Brian C. Murray is Director, Center for Regulatory Economics and Policy Research, RTI International, Hobbs 131, 3040 Cornwallis Road, Research Triangle Park, NC 27709, USA (e-mail: bcm@rti.org).

Sanderine Nonhebel is Lecturer at the Center for Energy and Environmental Studies, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands (e-mail: S.Nonhebel@rug.nl).

Cheryl Palm is Senior Research Scientist at The Earth Institute at Columbia University in New York, New York, United States of America (e-mail: cpalm@iri.columbia.edu).

William Pan is an Assistant Scientist in the Department of International Health, Bloomberg School of Public Health, Johns Hopkins University, Baltimore, MD 21205, USA (e-mail: wpan@jhsph.edu).

Isabelle Reginster is Reseach Associate in the Département de Géographie, Université Catholique de Louvain, Place Pasteur 3, 1348 Louvain-la-Neuve, Belgium (e-mail: reginster@geog.ucl.ac.be).

Jan Ros is Senior Researcher, Netherlands Environmental Assessment Agency, National Institute for Public Health and the Environment, P.O. Box 1, 3720, BA Bilthoven, The Netherlands (e-mail: jan.ros@mnp.nl).

Mark Rounsevell is Professor in the Département de Géographie, Université Catholique de Louvain, Place Pasteur 3, 1348 Louvain-la-Neuve, Belgium (e-mail: rounsevell@geog.ucl.ac.be).

Neeraj Sharma is Assistant General Manager with the National Bank for Agriculture and Rural Development, India. Presently he is a faculty member in National Bank Staff College, Lucknow, India (e-mail: neeraj.shr@gmail.com).

Edward M.W. Smeets is Researcher at the Energy Supply Cluster of the Department of Science, Technology and Society, Copernicus Institute, Utrecht

University, P.O. Box 80115, 3508 TC Utrecht, The Netherlands (e-mail: e.m.w.smeets@chem.uu.nl).

Pascalle Smith is a Ph.D. Student at the Laboratoire des Sciences du Climat et l'Environnement (LSCE), F-91191 Gif-sur-Yvette, France (e-mail: pascalle.smith@cea.fr).

Thomas Tomich is Principal Economist at the World Agroforestry Centre (ICRAF) and Global Coordinator of the Alternatives to Slash-and-Burn (ASB) Programme, P.O. Box 30677, Nairobi, Kenya (e-mail: t.tomich@cgiar.org).

Peter H. Verburg is Assisting Professor, Department of Environmental Sciences, Wageningen University, PO Box 37, 6700AA Wageningen, The Netherlands (e-mail: peter.verburg@wur.nl).

Jan Vos is Associate Professor, Crop and Weed Ecology Group, Department of Plant Sciences, Wageningen University, P.O. Box 430, 6700 AK Wageningen, The Netherlands (e-mail: jan.vos@wur.nl).

Alfons Weersink is a Professor in the Department of Agricultural Economics and Business, University of Guelph, Guelph, Ontario, Canada N1G 2W1 (e-mail: aweersin@uoguelph.ca).

Frank Willemsen is Researcher Chemistry & Food, Institute for Environmental Studies, Vrije Universiteit, De Boelelaan 1087, 1081 HV Amsterdam, The Netherlands (e-mail: frank.willemsen@ivm.falw.vu.nl).

Xinyou Yin is Assistant Professor, Crop and Weed Ecology Group, Department of Plant Sciences, Wageningen University, P.O. Box 430, 6700 AK Wageningen, The Netherlands (e-mail: xinyou.yin@wur.nl)

Xueqin Zhu is Researcher, Department of Spatial Economics, Vrije Universiteit, De Boelelaan 1105, 1081 HV Amsterdam, The Netherlands (e-mail: xzhu@feweb.vu.nl) & CPB Netherlands Bureau for Economic Policy Analysis, P.O. Box 80510, 2508 GM The Hague, The Netherlands (e-mail: x.zhu@cpb.nl). She was a PhD candidate of the Environmental Economics and Natural Resources Group, Wageningen University, when she made the contribution in this book.

List of abbreviations

AEZ	Agro-ecological zones
AGE	Applied general equilibrium (model)
ALGAS	Asia Least-cost Greenhouse Gas Abatement Strategy
ASB	Alternatives to Slash-and-Burn
ATEAM	Advanced Terrestrial Ecosystem Analysis and Modelling
ATLAS	Aggregate Timber Land Analysis System
BLS	Basic Linked System
CAP	Common Agricultural Policy
CCMLP	Carbon Cycle Model Linkage Project
CDM	Clean Development Mechanism
CFT	Crop functional type
CGE	Computable general equilibrium (model)
CGIAR	Consultative Group on International Agricultural Research
CLUE	Conversion of Land Use and its Effects
CLUE-S	Conversion of Land Use and its Effects at Small regional extent
COOL	Climate OptiOns for the Long term
CRU	Climate Research Unit
ECHAM	European Centre for Medium-Range Weather Forecasts model
EU	European Union
FAO	Food and Agriculture Organisation of the United Nations
FARM	Future Agricultural Resources Model
FASOM	Forest and Agricultural Sector Optimization Model
FASOMGHG	Greenhouse gas version of FASOM
GDP	Gross domestic product
GECROS	Genotype-by-Environment CROp Simulator
Gg	10^9 grammes
Gha	10^9 ha
GHG	Greenhouse gas
GTAP	Global Trade Analysis Project
GWP	Global Warming Potential
ha	hectare
ICLIPS	Integrated Assessment of Climate Protection Strategies
ICRAF	World Agroforestry Centre
IFPRI	International Food Policy Research Institute
IGBP	International Geosphere-Biosphere Programme

IHDP	International Human Dimensions Programme on Global Environmental Change
IIASA	International Institute for Applied Systems Analysis
IMAGE	Integrated Model to Assess the Global Environment
IMPACT	International Model for Policy Analysis of Commodities and Trade
IPCC	Intergovernmental Panel on Climate Change
Kg	10^3 grammes
KP	Kyoto Protocol
LCA	Life Cycle Analysis
LPJ	Lund-Potsdam-Jena Dynamic Global Vegetation Model
LUCC	Land Use and Land Cover Change
MAgPIE	Management Model of Agricultural Production and its Impact on the Environment
MEA	Millenium Ecosystem Assessment
Mha	million ha
MINAS	Mineral accounting system
Mton	Megaton
NPF	Novel Protein Food
NPL	National Physical Laboratory
NRR	Net reproduction rate
OECD	Organisation for Economic Co-operation and Development
OSB	Oriented Strand Board
PFT	Plant functional type
PIN	Production Index Number
Profetas	Protein Foods, Environment, Technology and Society
PSE	Producer Support Estimate
SAM	Social accounting matrix
SRES	Special Report on Emission Scenarios
STD	Sustainable Technology Development
TERI	Tata Energy Research Institute
Tg	10^{12} grammes
TSE	Total Support Estimate
UNCED	United Nations Conference on Environment and Development
UNDP	United Nations Population Division
UNFCC	United Nations Framework Convention on Climate Change
UNFPA	United Nations Fund for Population Activities
USDA	United States Department of Agriculture
Water-GAP	Water-Global Analysis and Prognosis
Yr	year

Preface

Agriculture is a major user of the available land resource and is both a source and sink of greenhouse gases. Patterns of land use may transform in the coming decades to meet food needs, but may also adjust in response to an effort to achieve reductions in greenhouse gas emissions. However, the international nature of agriculture implies that even local and regional agricultural developments and policies are no panacea for solving global-change related problems. This book offers a state-of-the-art overview of the interactions between agricultural development, future patterns of land use and emissions of greenhouse gases.

The book results from a workshop organised by LEI offering a broad overview of the key interactions between changes in agriculture, patterns of land use and efforts to reduce greenhouse gas emissions. The workshop was endorsed by the Land-Use and Cover Change (LUCC) Programme. The workshop was supported by the Ministry of Agriculture, Nature and Food Quality in the Netherlands and the Royal Netherlands Academy of Sciences (HDP Committee). Funds for finalising the book were obtained from the Ministry of Agriculture, Nature and Food Quality. This support is gratefully acknowledged.

The editors are grateful to the authors for preparing excellent contributions and for the secretarial assistance provided by Tessa van Dongen and Charlotte Khoe. They took responsibility for guiding the publication process, and prepared the several drafts of the chapters. Without the assistance and support given by Henny Hoogervorst and Esther Verdries (Springer Science) this volume would not have been in its present form.

Floor Brouwer and Bruce A. McCarl

Introduction

1

Floor Brouwer and Bruce A. McCarl

CLIMATE CHANGE, AGRICULTURE, FOOD DEMAND AND LAND USE

Interactions between agriculture, climate and patterns of land use are complex. Agriculture is a major user of the land, and patterns of land use are shaped through climatic conditions. The characteristics of agriculture in any location are largely determined by climatic factors. Evidence is amassing that increases in atmospheric concentrations of greenhouse gasses (GHG) like carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) cause increases in global temperature. The Intergovernmental Panel on Climate Change (IPCC) projects that the build-up of atmospheric GHGs will cause a moderate increase in temperature and altered patterns of precipitation are projected for large parts of the world. Accompanying changes in agricultural productivity are to be expected. In addition agriculture may play a role in managing the future GHG concentrations by switching land use from crops to forests, trees or biofuels and by managing energy use, rice lands, cattle and manures among other things. Thus agriculture is affected by both sides of the climate change issue and will feel influences on production patterns and land use.

There is an ongoing dialogue about agriculture as potentially manipulatable source or sink of greenhouse gas emissions. Major changes in agriculture, regional climate and land use patterns are foreseen in the next couple of decades. Society needs to be prepared to implement measures that contribute to transform agriculture in an environmentally effective, economically viable and socially acceptable manner.

Food demand will also influence future patterns of land use. Global population is projected to increase to about 9 billion by 2050. Global income per capita is likely to increase by a factor of three and more by 2050, and the share of animal calories in diet is projected to increase from about 15% today to about a third in 2050. Such changes increase the demand for food and put pressures on the available land resources.

F. Brouwer and B.A. McCarl (eds.), Agriculture and Climate Beyond 2015, 1-4

Experience is needed based on cross-disciplinary science and policy-science interactions to explore the way land use may aid in addressing the climate change and food demand influenced future.

KEY OBJECTIVES AND ORGANISATION OF THE BOOK

The objective of the book is threefold:

- establish linkages between land use and climate change;
- establish linkages between land use and greenhouse gas emissions control; and
- explore linkages with future patterns of food demand.

The perspective of the book is beyond the year 2015. The individual contributions draw on the experiences from cross-disciplinary approaches, and the interactions between policy and science. In this approach, the volume aims to identify existing gaps in scientific understanding. The book is divided into 4 parts.

Part 1 sets the scene and provides an overview of the key issues addressed in this book. The main interrelations between climate and societal factors as the influence land use change are explored. Chapter 2, by Peter Verburg and Jan Peter Lesschen, provides a discussion of different modelling approaches and the main challenges that are faced in exploring the interactions between land use policies, agriculture and the environment. A wide range of models of land use change is available. The authors argue in favour of a strong involvement of policy makers in the land use modelling process. Also, models could strongly support policy formulation. Chapter 3 identifies and explores important drivers and relationships of agricultural land use change under alternative scenarios of future development. Frank Ewert and his co-authors address linkages at the European scale between land use and agricultural productivity as affected by technological advances, climate change and atmospheric CO_2 concentrations. Agricultural land use changes are particularly sensitive to economic development, and technology development is a strong driver of productivity and land use change. Chapter 4, by Helmut Geist and his co-authors, aims to strengthen our understanding of the main driving forces, key actors and processes of agricultural change and land use patterns. The variety of key factors influencing land use transitions at the forest and dryland margins is explored. Also, a method is proposed for assessing the trade-offs and to draw implications for land use policies.

Part 2 looks at future forces shaping land use decisions and its sensitivity to climate change related issues. Chapter 5 offers an assessment of agricultural production systems in the coming decades and their implications for emissions of greenhouse gases. Lex Bouwman and his colleagues project a strong increase of global methane emissions, mainly in developing countries. Also, the projected concentration of agricultural activities will induce a further intensification of production. Chapter 6 examines main trends in agricultural land use in Central America over the past couple of decades, and how they point in the coming decades to changes in production patterns, patterns of agricultural land and forest cover. In this chapter, David Carr and his co-authors, notify strong intensification of agricultural production. Regional production to meet the demands of a growing population and international markets requires focus on sustainable development strategies. Such strategies require coping sustainability in agriculture and the trade-offs between intensification of labour, land and capital with extensification and reduction of forest cover. Chapter 7, by Hermann Lotze-Campen and his co-authors, puts agriculture as a crucial link between human society and the biosphere. In order to understand their interactions, they argue that an in-depth understanding of the links between food (both production and consumption), land use and climate change is indispensable. A grid-based global vegetation model is coupled with a non-spatial economic optimisation model, and applied for Germany. Neeraj Sharma, in Chapter 8, presents a perspective on the challenges that India faces in terms of population and economic growth. Here, land use patterns are likely to be decided by these factors in the coming decades.

Part 3 explores patterns of land use and the agricultural role in climate change mitigation. Edward Smeets and his co-authors, in Chapter 9, offer a methodology of global technical bioenergy production potential in 2050. A bottom-up approach is adopted and some results are presented as well. They conclude that the technical potential to increase crop yields and increase efficiency of animal production is sufficiently large to meet food demand and reduce the area needed for food production. Climate change mitigation policies promoting the production and use of bioenergy can have a major impact on global land use. The largest bioenergy potential comes from developing countries (e.g. sub-Saharan Africa, the Caribbean and Latin America). Chapter 10, by Harry Aiking and his co-authors, explore the land use implications of a transition from the consumption of meat to Novel Protein Foods (NPFs). The acceptance by the consumers is a crucial factor for a successful implementation. A switch to more NPFs by the wealthy part of society would be insufficient to overcome the projected increasing demand of meat in developing countries. NPFs could only offer a partial solution for reducing emissions to the environment. New tools are made operational in Chapter 11, to measure progress and identify indicators describing the process of change. Jan Ros and his co-authors, identify some options to reduce greenhouse gas emissions over time. They focus on agriculture in the fan meadow areas, food production and consumption, biomass and greenhouse production as a supply source of energy. The options are explored in close consultation with stakeholders and the conflicting viewpoints in society are addressed. Sanderine Nonhebel, in Chapter 12, identifies options to reduce emissions related to the production and consumption of food. The chain from food production to the consumer offers largest potential to decrease greenhouse gas emissions. However, a shift to organic production may increase emissions of CH_4 and N_2O. She also highlighted the reduction potential associated with intensive production methods relative to extensive production methods adopted with the production of milk. Chapter 13, by Heng-Chi Lee et al., explore management and land use practices to reduce greenhouse gas emissions in the agriculture and forestry sectors that offset fossil fuel emissions and enhance carbon sequestration. They argue that agricultural and forest carbon sequestration provides more time to find long-term technological solutions that halt the increasing ambient greenhouse gas concentrations. Also, power plant feedstock biofuels are likely to be an important long-term strategy under high greenhouse gas emission prices. Marie Boehm and her co-authors, in Chapter 14, explore possible changes in agriculture over the next decades. Farmers will still have to adapt to climate change. Innovation and experimentation at the farm level would be important to move from understanding to action. Management for mitigation and adaptation includes good land management, conservation of resources as well as careful management of the carbon and nitrogen cycles.

Finally, part 4 identifies policy and social responses to the new perspectives on future land use patterns. Wilfrid Legg, in Chapter 15, concentrates on the policy efforts to enhance the environmental dimension of sustainable agriculture in cost effective and efficient ways. He argues too little is yet known on the cause-effect linkages between policy measures and environmental outcomes. However, the policies may have been effective, but there have been trade-offs and in some case even inefficiencies. Murry Fulton and co-authors - in Chapter 16 - focus on institutional and organizational changes needed over the next 50-75 years to manage greenhouse gas emissions. The ability of the agricultural sector to respond to the new environment will depend on the new technologies that are developed, the institutional structures that are in place, and the manner in which the sector is organized. Finally, Chapter 17 reviews the different performance standards that are currently being used to evaluate a farmer's impact on the environment. Also, the appropriateness of legal rules for greenhouse gas mitigation in agriculture is evaluated. Patricia Farnese, in this Chapter, argues that it is desirable to adopt a range of policies aimed at bringing about the same outcome to ensure that farmers fully understand the performance standard they must satisfy in order to avoid liability.

Agriculture, Climate and Future Land Use Patterns: Potential for a Simulation-based Exploration

2

Peter H. Verburg and Jan Peter Lesschen

INTRODUCTION

The unprecedented rate of land cover conversion and changes in land management provides a major challenge to policy makers. Land Use and Land Cover change (LUCC) does not only change the landscapes in which we live, but also, more indirectly, components of our physical and social environment, such as climate, biodiversity and food security. Large scale deforestation has significant effects on regional and global climate (Cardoso et al., 2003; Cox et al., 2000). Fragmentation of ecosystems through agricultural expansion or infrastructure development causes changes in habitat conditions for many species, often leading to a decrease in biodiversity (Sala et al., 2002; White et al., 1997). Furthermore, ongoing urbanization results in a loss of recreation space and disconnection of urban populations from the rural hinterlands and natural areas. The global significance of land use and land cover change makes the study of LUCC of extreme importance in all discussions on the future of agriculture, land use and climate change.

LUCC is mostly seen as the result of the complex interaction between changes in social and economic opportunities in conjunction with the biophysical environment. Regionally LUCC leads to a modification or complete replacement of the cover of the earth surface (Lambin et al., 2003). The complexity of LUCC is largely due to the interaction of decision making at different levels: ranging from individual farmers that decide upon the land use management of individual plots to global organizations that argue for further liberalization of international trade markets in turn influencing market conditions faced by land owners. Furthermore, land use and land cover changes often show feedback and feed forward signals that can cause a relatively small change to trigger larger scale events (Lambin and Geist, 2003). A typical example of a feedback mechanism is the interaction between climate change and land use change. Climate change is an important driver for land use change while, at the same time, land use has

F. Brouwer and B.A. McCarl (eds.), Agriculture and Climate Beyond 2015, 5-32.

significant influence on climate conditions through the emission or sequestration of greenhouse gases.

For scientists, this complexity not only provides a major scientific challenge, but also the need to supply appropriate information to policy makers. Policy makers need to understand the trade-offs between different policy options and the mechanisms that steer the land use change processes. For that purpose, LUCC science can provide:

- insight into the driving factors and underlying processes that cause and modify land use change processes; and
- projections of plausible future land use change trajectories and land use patterns.

Insight into the processes of LUCC helps to identify policy measures that efficiently modify or mitigate the employment and use of land uses stimulating unfavourable effects. Projections can identify the implications of land use changes and can be used as early warning systems regarding hot-spots which are priority areas for in-depth analysis and policy intervention.

The analysis of complex systems is often assisted by simulation models that provide a conceptualisation of the functioning of the system under study (Carpenter et al., 1999; Scheffer, 1999). Since real-life experiments in land use change are difficult to perform, computer models are used to provide a computational laboratory in which hypothesis about the processes of and implications from land use change can be tested. Furthermore, models provide a structured way of analyzing complex interactions; scientists can make assumptions on the most important mechanisms of land use change and then test these hypotheses through sensitivity analysis. Once a functioning and validated model of the land use system is constructed, then projections of future developments can be made. The user can explore system functioning through 'what-if' scenarios and explore sensitivity regarding land use change projections and implications. Scenario simulations can provide insight toward alternative futures or allow the evaluation of the effects and trade-offs within different scenarios. Possible scenario simulations include the evaluation of the effect of changes in the agricultural sector (e.g., due to changes in market conditions or agricultural policies) on land use patterns.

This chapter provides a discussion of different LUCC modelling approaches and the main challenges that modellers are facing. An illustration of the possible use of LUCC models is given through an example of a scenario simulation to visualize the effects of different land use policies in the western part of the Netherlands. This area faces an increasing pressure due to urbanization and infrastructure construction. Agricultural lands are rapidly being replaced by residential and industrial areas. The model-based exploration of future land use patterns is used to visualize the effects of different land use policies that aim at protecting the recreational and ecological value of the remaining agricultural lands. The chapter concludes with a discussion of the constraints and challenges of using LUCC modelling to support land use policies.

A CLASSIFICATION OF LAND USE MODELS

Different authors have provided reviews of land use models using classification systems, often based on the dominant technique used in the model or the underlying disciplinary theory. For deforestation models an overview is provided by Lambin (1997) and Kaimowitz and Angelsen (1998) while Miller et al. (1999) present a review of integrated urban models. Lambin et al. (2000) review models for agricultural intensification, Bockstael and Irwin (2000) review a number of land use models in terms of economic theory foundations. Agarwal et al. (2001) review 19 models based on their spatial, temporal and human-choice complexity. Briassoulis (2000) give an extended overview of all types of land use models. An overview of more recent approaches is provided by the special issues edited by the LUCC focus 3 office (Veldkamp and Lambin, 2001; Veldkamp and Verburg, 2004; Verburg and Veldkamp, 2005). In this chapter, we will focus on a short typology of model classes relevant to policy makers and discuss a number of features of land use systems that are central to land use change modelling.

The first broad distinction that can be made between different models is the difference between descriptive and prescriptive models. Descriptive models aim at simulating the functioning of the land use system and the spatially explicit simulation of near future land use patterns. Prescriptive models, in contrast, aim at the calculation of optimised land use configurations that best match a set of goals and objectives. Descriptive models are based on the actual land use system and dominant processes that lead to changes in this system. The model output provides insights in the functioning of the land use system and gives projections of LUCC for scenario conditions. Prescriptive models mostly include the actual land use system solely as a constraint for more optimal land use configurations. The basic objective of most prescriptive or optimisation models is that any parcel of land, given its attributes and its location, is modelled as being used in the way that best matches a series of defined objectives (Lambin et al., 2000). Prescriptive models are relevant to policy makers as a spatial visualization of the land use pattern that is the optimal solution based on their preferred constraints and objectives (Van Ittersum et al., 1998). However, prescriptive models do not provide insights in the actual land use change trajectories and the conditions needed to reach the optimised situation. Optimisation models suffer from other limitations, such as the somewhat arbitrary definition of objective functions and non-optimal behaviour of people, e.g., due to differences in values, attitudes and cultures. While, at an aggregate level, these limitations are likely to be non-significant, they are more important as one looks at fine scale land-use change processes and is interested in the diversity between actors (Lambin et al., 2000).

Another major difference between broad groups of land use models is the role of theory. While there is no single all-compassing theory of land use change, there are different, disciplinary, theories that can be used to describe land use change processes. Deductive models are based on theories and the results of model simulations are compared to actual land use changes to test the validity of the theory. The most classical land use change model based on economic theory is the Von Thünen model. Von Thünen's work is based on the concept of land rents which are closely related to the potential profit a farmer can make from growing a crop. As this profit is related not just to the value of a crop at the market but also to the cost to transport the products to that market, rent for any particular crop falls off with distance from the market. When farmers have a choice of crops to grow they will, obviously, chose the most profitable one. Spatially, this will result in a series of concentric rings around the market, with crops with the highest transport costs relative to the market price growing nearest to the city. More recent deductive models for agricultural expansion are presented by Angelsen (1999) who compares four different model specifications based on economic theory.

Inductive models are based on observed processes of land use change rather than based on a theoretical model. Different types of inductive models exist, ranging from models in which decision-making by actors is specified in a range of decision rules and interactions (e.g., Parker et al., 2003) to models in which the relation between land use location and variability in the socio-economic and biophysical environment is captured by statistical techniques, often regression (Geoghegan et al., 2001; Nelson et al., 2001; Verburg and Chen, 2000). Both inductive and deductive modelling informs us about the processes that lead to land use change. Whereas deductive models are able to test theories and the actual importance of a number of driving factors, inductive models suggest which drivers empirically are associated with land use patterns.

A final distinction between model types to be discussed in this chapter is the difference between static and dynamic models. The calculation of the coefficients of a regression equation explaining the spatial distribution of land use changes as a function of a number of hypothesized driving factors can be seen as a static model of LUCC (Chomitz and Thomas, 2003; Nelson and Hellerstein, 1997; Overmars and Verburg, 2005). Dynamic models often include temporal dynamics, in land use systems represented by competition between land uses, irreversibility of past changes and fixed land use change trajectories. Static models can be used to test knowledge about the driving factors behind land use change while dynamic models are essential when projections for future land use change are needed.

Any further classification of models would disregard the large group of models that combine different techniques and paradigms to integrate the different dimensions of land use change. Therefore, in the next section we will discuss the current capacity of models to simulate land use change based on a number of aspects that are considered most important in the study of LUCC:

- level of analysis;
- cross-scale dynamics;
- driving factors;
- spatial interaction and neighbourhood effects;
- temporal dynamics; and
- level of integration.

These features have been mentioned frequently in a series of recent papers, reports and workshops by members of the LUCC research community (Geist et al., 2001; Lambin et al., 2000; McConnel and Moran, 2001; Moran, 2005;

Ojima and Moran, 2004; Turner II et al., 1995; van der Veen and Rotmans, 2001; Veldkamp and Lambin, 2001).

CHARACTERISTICS OF LAND USE MODELS

Level of analysis

Scientific discipline and tradition have caused two distinctly different approaches to emerge in the field of land use studies. Researchers in the social sciences have a long tradition of studying individual behaviour at the micro-level, some of them using qualitative approaches (Bilsborrow and Okoth Ogondo, 1992; Bingsheng, 1996) and others using the quantitative models of micro-economics and social psychology. Rooted in the natural sciences rather than the social, geographers and ecologists have focussed on land cover and land use at the macro-scale, spatially explicit approaches linking remote sensing and GIS, and using macro-properties of social organisation in order to identify social factors connected to the macro-scale patterns. Due to the poor connections between spatially explicit land use studies and the social sciences, the land use modellers have a hard time tapping into the rich stock of social science theory and methodology. This is compounded by the ongoing difficulties within the social sciences to interconnect the micro and macro levels of social organization (Coleman, 1990; Fox et al., 2002; Geoghegan et al., 1998; Watson, 1978).

Micro-level perspective

Models based on the micro-level perspective are based on the simulation of the behaviour of individuals and the up-scaling of this behaviour, in order to relate it to changes in the land use pattern. Two of the most important approaches will be discussed here: multi-agent simulation and micro-economic models.

Multi-agent models simulate decision-making by individual agents of land use change explicitly addressing interactions among individuals. The explicit attention for interactions between agents makes it possible for this type of model to simulate emergent properties of systems. Emergent properties are macro-scale attributes that are not predictable from observing the micro-units in isolation. Such properties 'emerge' if there are important interactions between the micro-units that feed back on the micro-behaviour. If the decision rules of the agents are set such that they sufficiently look like human decision-making they can simulate behaviour at the meso-level of social organisation, i.e., the behaviour of in-homogeneous groups of actors (Parker et al., 2003). Multi-agent models can shed light on the degree in which system-level properties simply emerge from local evolutionary forces and the degree to which those local processes are influenced and shaped by their effect on the persistence and continued functioning of ecosystems or the biosphere (Levin et al., 1998). Until recently, mathematical and computational capacity limited the operation of this type of models. Recently research teams have developed applicable simulation systems, most often for totally different purposes than land use change modelling (Cubert and Fishwick, 1998; DIAS, 1995; Lutz, 1997). The best known such system that is readily adaptable for ecological and land use simulation is the SWARM environment developed at the Santa Fe Institute (Hiebler et al., 1994).

Multi-agent models should be based on detailed information of socio-economic behaviour under different circumstances (Conte et al., 1997; Tesfatsion, 2001). This information can be obtained from extensive field studies by sociologists. The relevant importance of the different processes influencing land use change can be tested by sensitivity analysis and a link to higher levels of aggregation can be made. Simulated behaviour at the aggregate level can foster the development of new theories linking individual behaviour to collective behaviour. Meso-level studies typically show how individual people interact to form groups and organise collective action, and how such collective decisions vary with group size, collective social capital, and so on.

Most current multi-agent models are only able to simulate relatively simplified landscapes, as the number of interacting agents and factors that need to be taken into account, is still too large to comprehensively model (Kanaroglou and Scott, 2001). More recently a larger number of multi-agent modellers have begun to focus on land-use change processes and provide insights on the micro-level dynamics of these systems (Barreteau and Bousquet, 2000; Berger, 2001; Bousquet et al., 1998; Bura et al., 1996; Huigen, 2004; Manson, 2000; Polhill et al., 2001; Rouchier et al., 2001; Sanders et al., 1997; Vanclay, 1998).

A wide variety of land use models based on micro-economic theories exist as reviewed by Kaimowitz and Angelsen (1998) and Irwin and Geoghegan (2001). Most economic land use change models begin from the viewpoint of individual landowners who make land use decisions with the objective to maximize expected returns or utility. In turn such models use economic theory to guide model development, including choice of functional form and explanatory variables (Ruben et al., 1998). The assumptions on behaviour arise from the micro level. This limits these models to applications that are able to discern all individuals. Difficulties arise from scaling up these models, as they have primary been designed to work at the micro-level. Jansen and Stoorvogel (1998) and Hijmans and Van Ittersum (1996) have shown the problems of scale that arise when this type of models are used at higher aggregation levels.

Macro-level perspective

Studies that use the macro-level perspective are often based on macro-economic theory or apply the systems approach. A typical example of an economic model that uses the macro-perspective is the IIASA LUC model developed for China (Fischer and Sun, 2001). The model has a low spatial resolution (8 regions in China) and is very data demanding due to the multiple sectors of the economy that are taken into account. It is designed to establish an integrated assessment of the spatial and inter-temporal interactions among various socio-economic and biophysical forces that drive land use and land cover change. The model is based on recent advances in applied general equilibrium modelling. Applied general equilibrium modelling uses input-output accounting tables as the initial representation of the economy and applies a dynamic welfare optimisation model. In mathematical terms, the welfare optimum levels of resource uses and transformations are a function of the initial state of the economy and resources, of the parameterisation of consumer preferences and production relations, and of (exogenously) specified dynamics and constraints such as population growth and climate changes.

Other land use change models are based on an analysis of the spatial structure of land use; therefore, they are not bound to the behaviour of individuals or sectors of the economy. Among these models are the CLUE model (Verburg and Veldkamp, 2004; Verburg et al., 1999); GEOMOD2 (Pontius et al., 2001; Pontius and Malanson, 2005); LOV (White and Engelen, 2000) and LTM (Pijanowski et al., 2002).

Cross-scale dynamics

The above discussion on the micro- and macro-level research perspective referred to the issue of scale. Scale is the spatial, temporal, quantitative, or analytic dimension used by scientists to measure and study objects and processes (Gibson et al., 2000). All scales have extent and resolution. Extent refers to the magnitude of a dimension used in measuring (e.g., scope of area covered on a map) whereas resolution refers to the precision used in this measurement (e.g., grain size). For each process important to land use and land cover change, a range of scales may be defined over which it has a significant influence on the land use pattern (Dovers, 1995; Meentemeyer, 1989). These processes can be related to exogenous variables, the so-called ‘driving forces’ of land use change. Often, the range of spatial scales over which the driving forces and associated land use change processes act correspond to levels of organisation. Level refers to level of organisation in a hierarchically organised system and is characterised by its rank ordering in the hierarchical system. Examples of organizational levels include organism or individual, ecosystem, landscape and national or global political institutions. Many interactions and feedbacks between these processes occur at different levels of organisation. Hierarchy theory suggests that processes at a certain scale are constrained by the environmental conditions at levels immediately above and below the referent level, thus producing a constraint ‘envelope’ in which the process or phenomenon must remain (O’Neill et al., 1989).

Most land use models are based on one scale or level exclusively. Often, this choice is based on arbitrary, subjective reasons or scientific tradition (i.e., micro- or macro-level perspective) and not reported explicitly (Gibson et al., 2000; Watson, 1978). Models that rely on geographic data often use a regular grid to represent all data and processes. The resolution of analysis is determined by the measurement technique or data quality instead of the processes specified. Other approaches chose a specific level of analysis, e.g., the household level. For specific data sets optimal levels of analysis might exist where predictability is highest (Goodwin and Fahrig, 1998; Veldkamp and Fresco, 1997). Unfortunately these levels are not consistent, therefore, it might be better not to use a priori levels of observation, but rather extract the observation levels from a careful analysis of the data (Gardner, 1998; O’Neill and King, 1998).

The task of modelling socio-cultural forces is difficult because humans act both as individual decision makers (as assumed in most econometric models) and as members of a social system. Sometimes these roles have conflicting goals. Similar scale dependencies are found in biophysical processes. Often the aggregated result of individual processes cannot be straightforwardly determined. Rastetter et al. (1992) and King et al. (1989) point out that the simple spatial averaging of fine-scale non-linear functional forms of ecosystem relationships, or of the data required to compute the spatially aggregate versions of such functional forms, can lead to substantial aggregation errors. This is widely known as the 'fallacy of averages'.

Besides these fundamental issues of spatial scale, another scaling issue relates to scales of observation, and is, therefore, more related to practice. Due to our limited capacities for the observation of land use, extent and resolution are mostly linked. Studies at large spatial extent invariably have relatively coarse resolution, due to our methods for observation, data analysis capacity and costs. This implies that features that can be observed in small regional case studies are generally not observable in studies for larger regions. On the other hand, due to their small extent, local studies often lack information about the context of the case study area that can be derived from the coarser scale data. Scales of observation usually do not correspond with the scale/level at which the process studied operates, causing improper determination of the processes (Blöschl and Sivapalan, 1995; Schulze, 2000).

The discussion of scale issues can be summarised by the three aspects of scaling important for the analysis of land use change:

- Land use is the result of multiple processes that act over different scales. At each scale different processes have a dominant influence on land use.
- Aggregation of detailed scale processes does not straightforwardly lead to a proper representation of higher-level processes. Non-linearity, emergence and collective behaviour cause this scale-dependency.
- Our observations are bound by the extent and resolution of measurement causing each observation to provide only a partial description of the whole multi-scale land use system.

Although the importance of explicitly dealing with scaling issues in land use models is generally recognised, most existing models are only capable of performing an analysis at a single scale. Many models based on micro-economic assumptions tend to aggregate individual actions but neglect the emergent properties of collective values and actions (Riebsame and Parton, 1994). Approaches that implement multiple scales can be distinguished by the implementation of a multi-scale procedure in either the structure of the model or in the quantification of the driving variables. The latter approach acknowledges that different driving forces are important at different scales and takes explicit account of the scale dependency of the quantitative relation between land use and its driving forces. Two different approaches to quantifying the multi-scale relations between land use and driving forces are known. The first is based on data that are artificially gridded at multiple resolutions; where at each individual resolution the relations between land use and driving forces are statistically determined (de Koning et al., 1998; Veldkamp and Fresco, 1997; Verburg and Chen, 2000; Walsh et al., 2001; Walsh et al., 1999). The second approach uses multi-level statistics (Goldstein, 1995). The first applications of multi-level statistics were used in the analysis of social science data of educational performances in schools (Aitkin et al., 1981). More recently it was found that this technique could also be useful for the analysis of land use, taking different driving forces at different levels of analysis into account. Hoshino (2001) analysed the land use structure in Japan by taking different factors at each level into account using data for municipalities (level-1 units) nested within prefectures (level-2 units). A similar approach was followed by Polsky and Easterling (2001) for the analysis of the land use structure in the Great Plains of the USA. Also in this study administrative units at different hierarchical levels were used.

A number of land use change models are structured hierarchically, thus taking multiple levels into account. In its simplest form, the total amount of change is determined for the study area as a whole and allocated to individual grid-cells by adapting the cut-off value of a probability surface (Pijanowski et al., 2002). The demand-driven nature of land use change could be used as a rationale for this approach. Population and economic developments change the demand for different land use types at aggregate levels whereas the actual allocation of change is determined by regional and local conditions. This structure is also implemented in the CLUE modelling framework (Verburg et al., 1999). However, this framework uses three scales: the national scale for demand calculations and two spatially explicit scales to take driving forces at different scales into account. Apart from the top-down allocation a bottom-up algorithm is implemented to feed back local changes to the regional level.

Driving forces

A unifying hypothesis that links the ecological and social realms, and an important reason for pursuing integrated modelling, is that humans respond to cues both from the physical environment and from their socio-cultural context and behave to increase both their economic and socio-cultural well-being. Land use change is therefore often modelled as a function of a selection of socio-economic and biophysical variables that act as the so-called ‘driving forces’ of land use change (Turner II et al., 1993). Driving forces are generally subdivided in three groups (Turner II et al., 1995): socio-economic drivers, biophysical drivers and proximate causes (land management variables). Although biophysical factors mostly do not ‘drive’ land use change directly, they can cause land cover changes (e.g., through climate change) and they influence land use allocation decisions (e.g., soil quality). At different scales of analysis, different driving forces have a dominant influence on the land use system. At the local level this can be the local policy or the presence of small ecological valuable areas whereas at the regional level the distance to the market, port or airport might be the main determinant of the land use pattern.

Driving forces are most often considered exogenous to the land use system to facilitate modelling. However, in some cases this assumption hampers the proper description of the land use system, e.g., if the location of roads and land use decisions are jointly determined. Population pressure is often considered to be an important driver of deforestation (Pahari and Marai, 1999), however, Pfaff (1999) points out that population may be endogenous to forest conversion, due to unobserved government policies that encourage development of targeted areas, or that population may be collinear with government policies. If the former were the case, then including population as an exogenous 'driver' of land use change would produce a biased estimate and lead to misleading policy conclusions. If the latter were the case, then the estimates would be unbiased, but inefficient, leading to a potential false interpretation of the significance of variables in explaining deforestation. Other examples of endogeneity of driving forces in land use studies are given by Chomitz and Gray (1996), Mertens and Lambin (2000) and Irwin and Geoghegan (2001).

The temporal scale of analysis is important in deciding which driving forces should be endogenous to the model. In economic models of land use change, demand and supply prices and associated functions are the driving forces of land use change. However in the short term prices can be considered exogenous to land use change even though they are endogenous on longer time spans.

The selection of driving forces is very much dependent on the simplification made and the theoretical and behavioural assumptions used in modelling the land use system. In most economic approaches optimisation of utility is the assumed behaviour, leading to bid-rent models. Most economic models of land use change are, therefore, related to the land rent theories of Von Thünen and Ricardo. Any parcel of land, given its attributes and location, is assumed to be allocated to the use that earns the highest rent (e.g., Chomitz and Gray, 1996, Jones and O'Neill, 1992). In its most simple form, the monocentric model, the location of a central city or business district to which households commute, is the main factor determining the rent of a parcel. All other features of the landscape are ignored. Individual households optimise their location by trading off accessibility to the urban centre and land rents, which are bid up higher for locations closer to the centre. The resulting equilibrium pattern of land use is described by concentric rings of residential development around the urban centre and decreasing residential density as distance from the urban centre increases. In this case 'distance to urban centre' is the most important driving variable. The limitation of the monocentric model is partly due to its treatment of space, which is assumed to be a 'featureless plain' and is reduced to a simple measure of distance from the urban centre. Others explain spatial variability in land rent by differences in land quality that arise from a heterogeneous landscape, but abstract from any notion of relative location leading to spatial structure. Many models that try to explain land values, for example, hedonic models combine the two approaches by including variables that measure the distance to urban centre(s) as well as specific location features of the land parcel (Bockstael, 1996).

Models of urban and peri-urban land allocation are, generally, much more developed than their rural counterparts (Riebsame et al., 1994). More recent urban models are no longer solely based upon economic modelling using either equilibrium theory or spatial disaggregated intersectoral input-output approaches. Rather than utility functions they use discrete choice modelling through logit models (Alberti and Waddell, 2000; Landis, 1995). This also allows a greater flexibility in behavioural assumptions of the actors. Conventional economic theory makes use of rational actors, the *Homo economicus*, to study human behaviour. This powerful concept of the rational actor is not always valid and various modifications to this conception of human choice have been suggested (Janssen and Jager, 2000; Rabin, 1998). Examples of such modifications of the concept of the rational actor include the difficulty that people can have evaluating their own preferences, self-control problems and other phenomena that arise because people have a short-run propensity to pursue immediate gratification and the departure from pure self-interest to pursue 'other-regarding' goals such as fairness, reciprocal altruism and revenge.

Models that integrate the analysis of different land use conversions within the same model commonly use a larger set of driving forces. Apart from the drivers that determine urban land allocation, such as land value and transportation conditions, they need information on the suitability of the land for agricultural production (e.g., soil quality and climatic variables, market access). Also the extent of the study area influences the selection of variables. In larger areas it is common that a larger diversity of land use situations is found, which requires a larger variety of driving forces to be taken into account, whereas in a small area it might be only a few variables that have an important influence on land use.

Three different approaches to quantify the relations between land use change and its driving forces can be distinguished. The first approach tries to base all these relations directly on the processes involved, using theories and physical laws (deductive approach). Examples are economic models based on economic input-output analysis (Fischer and Sun, 2001; Waddell, 2000) or utility optimisation (Ruben et al., 1998). For integrated land use change analysis this approach is often not very successful due to the difficulty of quantifying socio-economical factors without the use of empirical data. Therefore, the second approach uses empirical methods to quantify the relations between land use and driving forces instead (inductive approach). Many econometric models rely therefore on statistical techniques, mainly regression, to quantify the defined models based on historic data of land use change (Bockstael, 1996; Chomitz and Gray, 1996; Geoghegan et al., 1997; Pfaff, 1999). Also other models, not based on economic theory, use statistical techniques to quantify the relationships between land use and driving forces (Mertens and Lambin, 2000; Mertens et al., 2000; Pontius et al., 2001; Pontius and Schneider, 2001; Serneels and Lambin, 2001; Turner et al., 1996; Veldkamp and Fresco, 1996; Wear and Bolstad, 1998 and many more). Most of these approaches describe historic land use conversions as a function of the changes in driving forces and location characteristics. This approach often results in a relatively low degree of explanation due to the short time-period of analysis, variability over this time period and a relatively small sample size (Hoshino, 1996; Veldkamp and Fresco, 1997). Cross-sectional analysis of the actual land use pattern, which reflects the outcome of a long history of land use changes, results in more stable explanations of the land use pattern (de Koning et al., 1998; Hoshino, 2001). A drawback of the statistical quantification is the induced uncertainty with respect to the causality of the supposed relations.

The third method for quantifying the relations between driving forces and land use change is the use of expert knowledge. Especially in models that use cellular automata, expert knowledge is often used. Cellular automata models define the interaction between land use at a certain location, the conditions at that location and the land use types in the neighbourhood (Clarke and Gaydos, 1998; Engelen et al., 1995; Silva and Clarke, 2002; Wu, 1998). The setting of the functions underlying these cellular automata is hardly ever documented and largely based upon the developer's knowledge and calibration.

Spatial interaction and neighbourhood effects

Land use patterns nearly always exhibit spatial autocorrelation. The explanation for this autocorrelation can be found, for a large part, in the clustered distribution of landscape features and gradients in environmental conditions that are important determinants of the land use pattern. Another reason for spatially autocorrelated land use patterns are the spatial interactions between land uses types itself: urban expansion is often situated right next to an already existing urban area, as is the case for business parks etc. Scale economies can provide an explanation for such patterns. In agricultural landscapes adoption of particular farming technologies or cultivation patterns might also exhibit observable spatial effects. Other land use types might preferably be located at some distance from each other, e.g., an airport and a residential area, causing a negative spatial autocorrelation. The importance of such structural spatial dependencies is increasingly recognized by geographers and economists. Spatial statistical techniques have been developed to quantify spatial dependencies when using econometrics (Anselin, 2002; Bell and Bockstael, 2000).

Spatial autocorrelation in land use patterns is scale dependent. At an aggregate level residential areas are clustered, having a positive spatial autocorrelation. However, Irwin and Geoghegan (2001) found that, at the scale of individual parcels in the Patuxent watershed, there was evidence of a negative spatial interaction among developed parcels, implying that a developed land parcel 'repels' neighbouring development due to negative spatial externalities that are generated from development, e.g., congestion effects. The presence of such an effect implies that, ceteris paribus, a parcel's probability of development decreases as the amount of existing neighbouring development increases. The existence of different causal processes at different scales means that spatial interactions should again be studied at multiple scales while relations found at a particular scale can only be used at that scale.

Spatial interactions can also act over larger distances: a change in land use in the upstream part of a river might affect land use in the downstream part through sedimentation of eroded materials leading to a functional connectivity between the two areas. Another example of spatial connectivity is the migration of companies from one part of the country to another part when all available land area is occupied at the first location. Analysis of these interactions is essential to understand the spatial structure of land use. Globalisation of the economy will cause these interactions to have a large spatial extent, leading to connectivity in land use between continents.

Cellular automata are a common method to take spatial interactions into account. They have been used in studies of urban development (Clarke and

Gaydos, 1998; Li and Yeh, 2002; White et al., 1997; Wu and Webster, 1998) but have now also been implemented in land use models that are able to simulate multiple land use types (White and Engelen, 2000). Cellular automata calculate the state of a pixel based on its initial state, the conditions in the surrounding pixels, and a set of transition rules. Although very simple, they can generate a rich behaviour (Wolfram, 1986).

The Urban Growth Model (Clarke and Gaydos, 1998), a classical cellular automata model for urban expansion was combined with so-called ‘deltatrons’ that enforce even more spatial interaction than achieved with cellular automata alone in order to achieve the desired degree of spatial and temporal autocorrelation (Candau, 2000; Herold et al., 2003).

Neighbourhood interactions are now also increasingly implemented in econometric models of land use change. Although this implementation can be done through advanced measures of autocorrelation (Bell and Bockstael, 2000; Brown et al., 2002; Walker et al., 2000), more often simple measures of neighbourhood composition, e.g., the area of the same land use type in the neighbourhood, are included as explanatory factors in regression models explaining land use change (Geoghegan et al., 1997; Munroe et al., 2001; Nelson and Hellerstein, 1997).

A different method for implementing spatial interaction, especially interaction over larger distances, is the use of network analysis. In many models, driving forces have been included that indicate travel times or distances to markets, ports and other facilities that are important to land use. Often models that are based on economic theory take travel costs to a market into account (Jones, 1983). Most often simple distance measures are used. However, it is also possible to use sophisticated techniques to calculate travel times/costs and use the results to explain the land use structure. This type of calculations are often included in combined urban-transportation models (Miller et al., 1999).

Spatial interactions can also be generated more indirectly through the hierarchical structure of the model. Multi-scale models like CLUE (Veldkamp and Fresco, 1996) and Environment Explorer (White and Engelen, 2000) can generate spatial interactions through the feedback over a higher scale. If a certain, regional, demand cannot be met at the local level (due to a location condition or policy, e.g., nature reserve), it will feedback to the regional level and allocation to another location will proceed. This type of modelling can indicate the trade-off of a measure at a certain location for the surrounding area.

Temporal dynamics: trajectories of change

The previous sections all dealt with spatial features of land use change. Many of the issues addressed are also relevant for the temporal dimension of land use change. Changes are often non-linear and thresholds play an important role. Non-linear behaviour requires dynamic modelling with relatively short time steps. Only then can land use change analysis take into account the path-dependency of system evolution, the possibility of multiple stable states, and multiple trajectories. Land use change cannot be simply explained as the equilibrium result of the present set of driving forces. In other words, land use change may be dependent on initial conditions, and small, essentially random events may lead to very different outcomes, making prediction problematic. Exemplary is the effect of transportation infrastructure on the pattern of development. Road expansion and improvement not only lead to more development but may also lead to a different pattern through a reorganisation of the market structure, which then feeds back to further infrastructure development. Thus, certain trajectories of land use change may be the result of ‘lock in’ that comes from systems that exhibit autocatalytic behaviour.

Connected to the temporal dimension of models is the issue of validation. Validation of land use change models is most often based on the comparison of model results for a historic period with the actual changes in land use as they have occurred. Such a validation exercise requires land use data for another year than the data used in model parameterisation. The time period between the two years for which data are available should be sufficient to actually compare the observed and simulated dynamics. Ideally this time period should be as long as the period for which future scenario simulations are made. Such data are often difficult to obtain and even more often data from different time periods are difficult to compare due to differences in the classification scheme of land use maps or the resolution of remote sensing data. Methods for validation of model performance should make a clear distinction in the model performance concerning the quantity of change and the quality of the spatial allocation of the land use changes. Appropriate methods for validation of land use change models are described by Pontius (2002), Costanza (1989), Pontius and Scheider (2001).

In a number of models, temporal dynamics are taken into account using initial land use as a criterion for the allowed changes. Cellular automata approaches do this explicitly by including decision rules that determine the conversion probability. In the CLUE-S model (Verburg et al., 2002) a specific land use conversion elasticity is given to each land use type. This elasticity will cause some land use types to be more reluctant to change (e.g., plantations of permanent crops) whereas others easily shift location (e.g., shifting cultivation). The SLEUTH urban growth model (Clarke and Gaydos, 1998) employ explicit functions to enforce temporal autocorrelation that also take the ‘age’ of a new urban development centre into account. The economic land allocation model of the Patuxent Landscape Model (Irwin and Geoghegan, 2001) also explicitly considers the temporal dimension. The land use conversion decision is posed as an optimal timing decision in which the landowner maximises expected profits by choosing the optimal conversion time. That time is chosen so that the present discounted value of expected returns from converting the parcel to residential use is maximized. These latter two model implementations of temporal dynamics already take account of a longer time span than most models, which only account for the initial state. However, most models are currently unable to account for land use change as influenced by land use histories over longer time scales. For a proper description of certain land use types, e.g., long fallow systems, or feedback processes such as nutrient depletion upon prolonged use of agricultural land, incorporation of land use histories could make an important improvement (Priess and Koning, 2001).

The combination of temporal and spatial dynamics often causes complex, non-linear behaviour. However, a large group of models do not account at all for temporal dynamics. These models are simply based on an extrapolation of the trend in land use change through the use of a regression on this change (Geoghegan et al., 2001; Mertens and Lambin, 2000; Schneider and Pontius, 2001; Serneels and Lambin, 2001). This type of model is therefore not suitable for scenario analysis, as they are only valid within the range of the land use changes on which they are based. The validity of the relations is also violated when confronted with a change in the competitive conditions between land use types, e.g., caused by a change in demand. This critique does not apply to all models based on statistical quantification. When these models are based on the analysis of the structure (pattern) of land use instead of the change in land use and are combined with dynamic modelling of competition between land use types, they have a much wider range of applications.

Land use change decisions are made within different time scales, some decisions are based on short term dynamics (such as daily weather fluctuations), and others are only based on long-term dynamics. Most land use models use annual time steps in their calculations. This means that short-term dynamics are often ignored or, when they can have an additive effect, are aggregated to yearly changes. However, this aggregation can hamper the linkage with the actual decision making taking at shorter time scales. The need for multi-scale temporal models was acknowledged in transportation modelling, where short-term decisions depend on the daily activity schedules and unexpected events (Arentze et al., 2001; Arentze and Timmermans, 2000). The link between this type of transportation models and land use is straightforward. If changes in the daily activity schedule are required on a regular basis, individuals will adjust their activity agenda or the factors affecting the agenda, for example by relocation. Such a decision is a typical long-term decision, evolving from regular changes in short-term decisions.

Level of integration

Land use systems are groups of interacting, interdependent parts linked together by exchanges of energy, matter, and information. Land use systems are therefore characterised by strong (usually non-linear) interactions between the parts, complex feedback loops that make it difficult to distinguish cause from effect, and significant time and space lags, discontinuities, thresholds, and limits (Costanza and Wainger, 1993). This complexity makes the integration of the different sub-systems one of the most important issues in land use modelling. Generally speaking, two approaches for integration can be distinguished. The first approach involves a rather loose coupling of sub-systems that are separately analysed and modelled. To allow the dissection of system components, it must be assumed that interactions and feedbacks between system elements are negligible or the feedbacks must be clearly defined and information between sub-systems must be achieved through the exchange of input and output variables between sub-system models. The second approach takes a more holistic view. Instead of focussing all attention on the description of the sub-systems explicit attention is given to the interactions between the sub-systems. In this approach, more variables are endogenous to the system and are a function of the interactions between the system components. The approach chosen is very much dependent on the time-scale (endogeneity assumptions) and the purpose for which the model is built. Generally speaking, integration only adds value as compared with disciplinary research when feedbacks and interactions between the sub-systems are explicitly addressed. An appropriate balance should be found, as the number of interactions that can be distinguished within the land use system is very large and taking all of those into account could lead to models that are too complex to be operational.

The group of models commonly referred to as integrated assessment models are models that attempt to portray the social, economic, environmental and institutional dimensions of a problem (Rotmans and van Asselt, 2001). In practice, most integrated assessment models are directed to the modelling of climate change and its policy dimensions (reviewed by Schneider, 1997). Some integrated assessment models, e.g., the IMAGE2 model (Alcamo et al., 1998) contain land use modules, but these are often much less elaborated than models that are specifically developed for land use studies. For integrated assessment models the same conclusions hold as for land use models: many large models consist of linked subsystems that are not fully integrated. This means that these models are complicated but not complex, as a result of which their dynamic behaviour is almost linear and does not adequately reflect real world dynamics (Rotmans and van Asselt, 2001).

An example of a fully integrated model is the IIASA-LUC model (Fischer and Sun, 2001). Although this model incorporates many sub-systems, interactions and feedbacks, it has become complex to operate and, above-all, difficult to parameterise due to the high data requirements (see Briassoulis, 2001 for a discussion of data needs). Another disadvantage of highly complex, integrated models is that the degree and type of integration often appears to be subjective based on the modeller's disciplinary background. As a fully integrated approach, qualitative modelling (Petschel-Held et al., 1999) allows a focus on the system as a whole, however, also this approach is completely based on the knowledge of the developer about the existence and importance of the feedbacks important to the studied system, so it is likely to be biased and incomplete.

An integrated approach that models the behaviour of the different subsystems individually but includes numerous connections between these sub-models is the Patuxent Landscape Model (Geoghegan et al., 1997; Voinov et al., 1999) that is designed to simulate fundamental ecological processes on the watershed scale, in interaction with a component that predicts the land use patterns. Land use change is dealt with in the economic module (Bockstael, 1996; Irwin and Geoghegan, 2001) whereas all hydrological and ecological processes in the watershed are simulated in the ecological module. The ecological module integrates all processes involved based on the General Ecosystem Model (Fitz et al., 1996). The coupling between the economic module and the ecological module is less elaborated. Output of the economic module, land use change patterns, is used as input in the ecological module whereas the possibility exists that output of the ecological module, e.g. water table depths, habitat health etc., should be used as inputs of the economic module, allowing for feedbacks within the system. Also in other integrated land use-ecosystem models, the ecological sub-models tend to be far more integrated than the associated land use models (McClean et al., 1995).

EXAMPLE FOR THE RANDSTAD REGION LAND USE MODEL

This example illustrates the possible use of LUCC models to support the discussion on land use policies and its effects for agriculture and future land use patterns. A representative LUCC model that allows the exploration of future land use patterns under different scenarios is applied to the Randstad region in the Netherlands. The term 'Randstad Holland' was launched to denote a group of towns and cities located relatively close together in the west of the Netherlands (see Figure 2.1A for the location). Surrounding by these cities is a rural area predominantly consisting of meadows, dairy farming, scattered villages and nature reserves. This area is commonly called 'the Green Heart' of the Randstad region and has important functions for agriculture, recreation and nature/landscape preservation. In the 90's emphasis was given to promoting compact urbanization by developing sites within and directly adjacent to cities. New business locations and residential areas were encouraged to be close to existing cities. This policy aimed at providing opportunities to keep the Green Heart open and green (Dieleman et al., 1999). These policies formed the basis for the so-called VINEX locations, designated areas for most of the Randstad's new housing up to 2005.

The Green Heart policy is an important part of the Dutch spatial planning doctrine, and in 1990 the area was given official borders by the Ministry responsible for land use planning. The Green Heart was appointed as national landscape to preserve and strengthen the cultural historic and ecological aspects and improve the visual coherence of built-up area and environment. Spatial policies have been relatively successful in keeping the Green Heart as a central open space surrounded by urban development. However, protection is no longer the sole objective of land use planning for the Green Heart. Apart from restrictive measures - in relation, for example, to businesses and new housing - policy largely focuses on developing the Green Heart's potential. It will be obvious from the above overview that a shift has occurred from a largely defensive approach to policies in which incentives play a key role.

The dynamic, spatially explicit, land use change model CLUE-S (Verburg et al., 2002, Verburg and Veldkamp, 2004) was used for the simulation of potential future land use changes in the Randstad region. The model structure is based on systems theory to allow the integrated analysis of land use change in relation to socio-economic and biophysical driving factors. In the CLUE-S model the complexity of land use systems is captured by a combination of dynamic modelling and empirical quantification of the relations between land use and its driving factors. The model allocates predefined demands to different locations within the study area. For each location, the possibilities for change are evaluated based on the actual land use and the competitive strength of the different land uses. Furthermore, areas where spatial land use policies apply can be indicated. Scenarios can be used to evaluate different land use change situations caused by differences in demographic change, land use requirements and spatial policies.

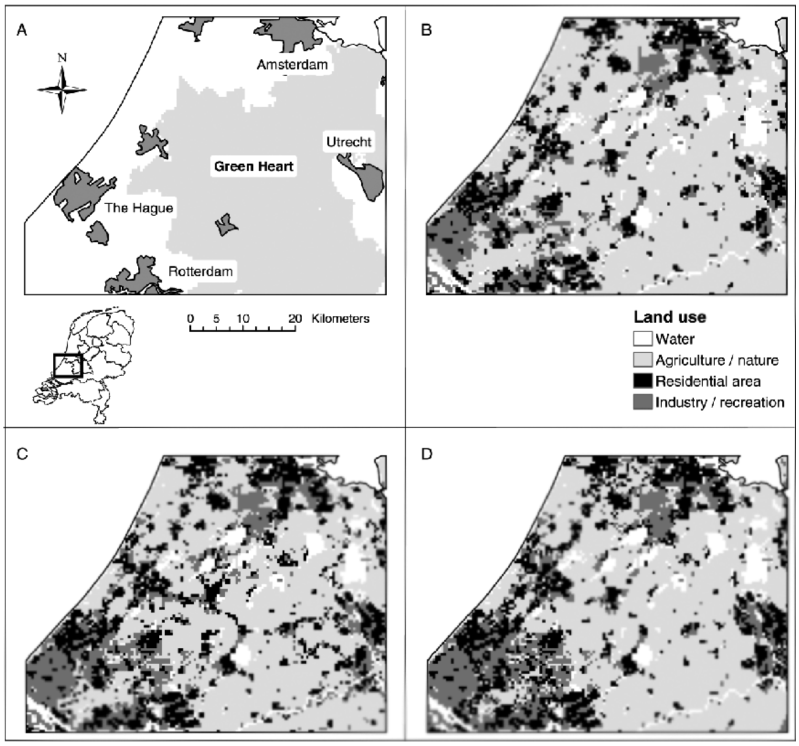


Figure 2.1 Location of the Randstad with its main cities, A: in light grey the Green Heart area is indicated, B: Initial land use in 1996, C: Land use in 2015 with the base scenario, D: Land use in 2015 with protection Green Heart scenario

A data set of maps representing land use, biophysical characteristics and socio-economic conditions at a resolution of 500 meter was used for the simulation (Verburg et al., 2004).

The model was run for two different scenarios for the period from 1996 to 2015 to explore the potential future changes of land use in the region. Two different scenarios are created based on different spatial policies. Both scenarios use the same claims for the different land use types, based upon the observed trends for the period 1989-1996. The claim for urban land uses (residential, industrial, commercial and recreational areas) increases by about 1.2% per year, while the claims for agricultural land use are expected to decrease 0.7% per year. In the base scenario, the model is run without specification of any spatial policy, which means that a certain land use will be allocated as a result of the 'preference' that the decision makers have for a certain location based on its biophysical, socio-economic, accessibility and other characteristics as well as on the competition between the land use types. The second scenario assumes a strict implementation of spatial policies aimed at the protection of the agricultural and natural areas within the Green Heart area. Expansion of urban land uses is under these conditions not allowed within the Green Heart area.

The maps of predicted land use in 2015 are given in Figure 2.1 for both scenarios. In the base scenario, without protection of the Green Heart, the small towns inside the Green Heart face a large expansion in residential areas. These towns are especially attractive for housing because of the rural environment and their proximity to the main cities. New industries (including greenhouses) and recreational areas arise at the outskirts of the cities and along highways. In the second scenario the Green Heart mainly remains under agricultural use (grassland and some arable land), while urban growth occurs mostly near to the four main cities. Especially the area between The Hague and Rotterdam almost completely changes into urban area.

The results of the two scenarios show the relevance of the ongoing discussion in the Netherlands about the implementation of spatial policies that restrict urban development in the Green Heart. Different implementations of spatial policies clearly result in different spatial patterns of land use with consequences for urban structure, openness of the rural hinterland and the role of agriculture within the landscape. The model results help to visualize these different policy options and structure the discussion by showing the potential consequences of land use planning decisions. This case study is a relatively simple representation of the changes the area might be facing in the future. Further analysis might include the land requirements for water retention and coastal protection under conditions of climate change as well as an in-depth analysis of the effects of changing agricultural policies on the future of agricultural practices in the area.

CONCLUSIONS

The discussion of the different issues relevant to modelling land use change presented in this chapter has shown that scientists have created a wide range of models of land use change. These models are used in various types of applications that relate to agriculture, climate change and future land use mostly within an academic environment. In order to adequately support policy makers, a lot of progress still needs to be made. The example presented in this chapter has illustrated the current capacity of land use models to simulate policy relevant scenarios. However, different studies have indicated that uncertainty in model predictions is still high (Pontius and Malanson, 2005; Walker, 2003) and the involvement of policy makers in scenario definition and interpretation of results is generally low (Uran and Janssen, 2003). Furthermore, results of simulation models are often difficult to communicate between scientists and policy makers; therefore presentation/visualisation issues might need more attention.

The lack of direct use of model results by policy makers should not (solely) be seen as a failure of land use modellers. The unravelling of the dynamics for a system as complex as land use has provided a magnitude of useful insights for local case studies as well as for the underlying processes in general (Geist and Lambin, 2002). These insights are of major importance to policy makers and helpful in defining appropriate interventions. Land use change modellers should aim at thorough validation of their models and demonstrations of the sensitivity of the model results to uncertainties in assumptions and data. Based on such a validation procedure appropriate techniques and levels of detail can be selected for presentation of results to policy makers. This will not only clarify the discussion about the validity of the scenario simulations but also help to identify the main target areas for future research to reduce the uncertainties.

Presentation issues are of extreme importance to enhance the implementation of scientific efforts in policy making. Land use modellers have the advantage that the results can easily be presented as maps rather than tables and texts that often go unnoticed by policy makers. Maps have the potential to identify the 'hotspots' of land use change and focus the attention of policy makers to priority issues. Indices can provide a means to summarize the effects of the simulated changes, e.g., by showing the change in 'open space' as a result of further urbanization such as in the example presented in this chapter.

Apart from the effort made by scientists to better link their work to the interests of policy makers, it is also necessary that policy makers are actively engaged in the land use modelling process and acknowledge the potential of using models in policy formulation. Incentives to actively engage policy makers in the process are the generation of policy relevant scenarios and joint sessions on the definition and interpretation of scenario conditions. If these challenges are met land use change models have the potential to become an important tool for both researchers and policy makers supporting assessments that deal with the future of agriculture, climate and land use patterns.

REFERENCES

Agarwal, C., G.M. Green, J.M. Grove, T.P. Evans and C.M. Schweik (2001) *A Review and Assessment of Land Use Change Models. Dynamics of Space, Time, and Human Choice*. Center for the Study of Institutions, Population, and Environmental Change, Indiana University and USDA Forest Service.

Aitkin, M., D. Anderson and J. Hinde (1981) Statistical modelling of data on teaching styles (with discussion). *Journal of the Royal Statistical Society A*, Vol. 144, pp. 148-161.

Alberti, M. and P. Waddell (2000) An integrated urban development and ecological simulation model. *Integrated Assessment*, Vol. 1 (3), pp. 215-227.

Alcamo, J., R. Leemans and E. Kreileman (1998) *Global Change Scenarios of the 21st Century. Results from the IMAGE 2.1 Model*. Elsevier, London.

Angelsen, A. (1999) Agricultural expansion and deforestation: modelling the impact of population, market forces and property rights. *Journal of Development Economics*, Vol. 58, pp. 185-218.

Anselin, L. (2002) Under the hood: Issues in the specification and interpretation of spatial regression models. *Agricultural Economics*, Vol. 27 (3), pp. 247-267.

Arentze, T.A., M. Dijst, E. Dugundji, C.-H. Joh, L. Kapoen, S. Krijgsman, K. Maat, H.J.P. Timmermans and J. Veldhuisen (2001) *The AMADEUS Program: Scope and Conceptual Development*, vol. WCTRS - 9th World Conference on Transportation Research, Seoul, Korea, 22-27 July 2001.

Arentze, T.A. and H.J.P. Timmermans (2000) *Albatross, A Learning Based Transportation Oriented Simulation System*. European Institute of Retailing and Service Studies, Eindhoven University, Eindhoven.

Barreteau, O. and F. Bousquet (2000) SHADOC: a multi-agent model to tackle viability of irrigated systems. *Annals of Operations Research*, Vol. 94, pp. 139-162.

Bell, K.P. and N.E. Bockstael (2000) Applying the generalized-moments estimation approach to spatial problems involvoing microlevel data. *The Review of Economics and Statistics*, Vol. 82 (1), pp. 72-82.

Berger, T. (2001) Agent-based spatial models applied to agriculture: a simulation tool for technology diffusion, resource use changes and policy analysis. *Agricultural Economics*, Vol. 25, pp. 245-260.

Bilsborrow, R.E. and H.W.O. Okoth Ogondo (1992) Population-driven changes in land use in developing countries. *Ambio*, Vol. 21, pp. 37-45.

Bingsheng, K. (1996) Regional inequality in rural development. In: R. Garnaut, G. Shutian and M. Guonan (Eds), *The Third Revolution in the Chinese Countryside.* Cambridge University Press, Cambridge, pp. 245-258.

Blöschl, G. and M. Sivapalan (1995) Scale issues in hydrological modelling: a review. *Hydrological Processes*, Vol. 9, pp. 251-290.

Bockstael, N.E. (1996) Modeling economics and ecology: the importance of a spatial perspective. *American Journal of Agricultural Economics*, Vol. 78 (5), pp. 1168-1180.

Bockstael, N.E. and E.G. Irwin (2000) Economics and the land use-environment link. In: H. Folmer and T. Tietenberg (Eds), *The International Yearbook of Environmental and Resource Economics 1999/2000.* Edward Elgar Publishing, UK and USA, pp. 1-54

Bousquet, F., I. Bakam, H. Proton and C. Le Page (1998) Cormas: common-pool resources and multiagent systems. *Lecture Notes in Artificial Intelligence*, Vol. 1416, pp. 826-837.

Briassoulis, H. (2000) Analysis of land use change: theoretical and modeling approaches. In: S. Loveridge (ed), *The Web Book of Regional Science at http://www.rri.wvu.edu/regscweb.htm.* West Virginia University, Morgantown.

Briassoulis, H. (2001) Policy-oriented integrated analysis of land-use change: an analysis of data needs. *Environmental Management*, Vol. 27 (1), pp. 1-11.

Brown, D.G., P. Goovaerts, A. Burnicki and M.Y. Li (2002) Stochastic simulation of land-cover change using geostatistics and generalized additive models. *Photogrammetric Engineering & Remote Sensing*, Vol. 68 (10), pp. 1051-1061.

Bura, S., F. Guerin-Pace, H. Mathian, D. Pumain and L. Sanders (1996) Multiagent systems and the dynamics of a settlement system. *Geographical Analysis*, Vol. 28 (2), pp. 161-178.

Candau, J. (2000) Calibrating a cellular automaton model of urban growth in a timely manner. In: B.O. Parks, K.M. Clarke and M.P. Crane (Eds), *Proceedings of the 4th International Conference on Integrating Geographic Information Systems and Environmental Modeling: Problems, Prospects, and Needs for Research.* September 2-8, CD-rom. University of Colorado. Boulder.

Cardoso, M.F., G.C. Hurtt, B. Moore III, C.A. Nobre and E.M. Prins (2003) Projecting future fire activity in Amazonia. *Global Change Biology*, Vol. 9, pp. 656-669.

Carpenter, S., W. Brock and P. Hanson (1999) Ecological and social dynamics in simple models of ecosystem management. *Conservation Ecology*, Vol. 3 (2) 4. [online] URL: http://www.consecol.org/vol3/iss2/art4.

Chomitz, K.M. and D.A. Gray (1996) Roads, land use and deforestation: a spatial model applied to Belize. *The World Bank Economic Review*, Vol. 10 (3), pp. 487-512.

Chomitz, K.M. and T.S. Thomas (2003) Determinants of land use in Amazonia: a fine-scale spatial analysis. *American Journal of Agricultural Economics*, Vol. 85 (4), pp. 1016-1028.

Clarke, K.C. and L.J. Gaydos (1998) Loose-coupling a cellular automaton model and GIS: long-term urban growth prediction for San Fransisco and Washington/Baltimore. *International Journal of Geographical Information Science*, Vol. 12 (7), pp. 699-714.

Coleman, J.S. (1990) *Foundations of Social Theory*. The Belknap Press of Harvard University Press, Cambridge.
Conte, R., R. Hegselmann and P. Terna (1997) *Simulating Social Phenomena*. Springer, Berlin.
Costanza, R. (1989) Model goodness of fit: a multiple resolution procedure. *Ecological Modelling*, Vol. 47, pp. 199-215.
Costanza, R. and L.A. Wainger (1993) Modeling complex ecological economic systems. *Bioscience*, Vol. 43 (8), pp. 545-556.
Cox, P.M., R.A. Betts, C.D. Jones, S.A. Spall and I.J. Totterdell (2000) Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature*, Vol. 408, pp. 184-187.
Cubert, R.M. and P.A. Fishwick (1998) OOPM: An object-oriented multimodeling and simulation application framework. *Simulation*, Vol. 70(6), pp. 379-395.
de Koning, G.H.J., A. Veldkamp and L.O. Fresco (1998) Land use in Ecuador: a statistical analysis at different aggregation levels. *Agriculture, Ecosystems and Environment*, Vol. 70, pp. 321-247.
DIAS (1995) The dynamic information architecture system: a high level architecture for modeling and simulation. *Advanced Computer Applications Center, Argonne National Laboratory* http://www.dis.anl.gov/DEEM/DIAS/diaswp.html.
Dieleman, F.M., M.J. Dijst and T. Spit (1999) Planning the compact city: the Randstad Holland experience. *European Planning Studies*, Vol. 7 (5), pp. 605-620.
Dovers, S.R. (1995) A framework for scaling and raming policy problems in sustainability. *Ecological Economics*, Vol. 12, pp. 93-106.
Engelen, G., R. White, I. Uljee and P. Drazan (1995) Using cellular automata for integrated modelling of socio-environmental system. *Environmental Monitoring and Assessment*, Vol. 34, pp. 203-214.
Fischer, G. and L.X. Sun (2001) Model based analysis of future land-use development in China. *Agriculture, Ecosystems and Environment*, Vol. 85 (1/3), pp. 163-176.
Fitz, H.C., E. DeBellevue, R. Costanza, R. Boumans, T. Maxwell, L.A. Wainger and F. Sklar (1996) Development of a general ecosystem model for a range of scales and ecosystems. *Ecological Modelling*, Vol. 88, pp. 263-295.
Fox, J., R.R. Rindfuss, S.J. Walsh and V. Mishra (2002) *People and the Environment; Approaches for Linking Household and Community Surveys to Remote Sensing and GIS*. Kluwer Academic Publishers, Boston.
Gardner, R.H. (1998) Pattern, process, and the analysis of spatial scales. In: D.L. Peterson and V.T. Parker (Eds), *Ecological Scale: Theory and Applications.* Columbia University Press, New York, pp. 17-34.
Geist, H.J. and E.F. Lambin (2002) Proximate causes and underlying driving forces of tropical deforestation. *Bioscience*, Vol. 52 (2), pp. 143-150.
Geist, H.J., E.F. Lambin, C. Vogel, M. Sharifa, B.L. Turner II, F.P. Lansigan, R. Reid, A. Veldkamp, R. Leemans, W. McConnel and S. Serneels (2001) LUCC's contribution for future IGBP research: a position paper of the IGBP-IHDP LUCC (Land-Use and Land-Cover Change) Project. *For use at the Scoping Team Meeting in Mainz, Germany, 26-27 October 2001, and in Fort Collins, USA, 21-23 January 2002*
Geoghegan, J., J.L. Pritchard, Y. Ogneva-Himmelberger, R.R. Chowdhury, S. Sanderson and B.L. Turner II (1998) 'Socializing the Pixel' and 'Pixelizing' the Social' in Land-Use and Land-Cover Change. In: D. Liverman, E.F. Moran, R.R. Rindfuss and P.C. Stern (Eds), *People and Pixels: Linking Remote Sensing and Social Science.* National Academy Press. Washington, pp. 51-69.
Geoghegan, J., S.C. Villar, P. Klepeis, P.M. Mendoza, Y. Ogneva-Himmelberger, R.R. Chowdhury, B.L. Turner II and C. Vance (2001) Modeling tropical deforestation in the Southern Yucat in Peninsular Region: comparing survey and satellite data. *Agriculture, Ecosystems and Environment*, Vol. 85 (1/3), pp. 25-46.

Geoghegan, J., L.A. Wainger and N.E. Bockstael (1997) Spatial landscape indices in a hedonic framework: an ecological economics analysis using GIS. *Ecological Economics*, Vol. 23, pp. 251-264.

Gibson, C.C., E. Ostrom and T.K. Anh (2000) The concept of scale and the human dimensions of global change: a survey. *Ecological Economics*, Vol. 32, pp. 217-239.

Goldstein, H. (1995) *Multilevel Statistical Models*. Halstaed, New York.

Goodwin, B.J. and L. Fahrig (1998) Spatial scaling and animal population dynamics. In: D.L. Peterson and V.T. Parker (Eds) *Ecological Scale: Theory and Applications*. Columbia University Press. New York, pp. 193-206.

Herold, M., N.C. Goldstein and K.C. Clarke (2003) The spatiotemporal form of urban growth: measurement, analysis and modeling. *Remote Sensing of Environment*, Vol. 86, pp. 286-302.

Hiebler, D., M. Strom and T.C. Daniel (1994) The SWARM Simulation System and Individual-based Modeling. In: *Decision Support 2001: 17th Annual Geographic Information Seminar and Resource Technology '94 Symposium*, Toronto, pp. 474-494.

Hijmans, R.J. and M.K. van Ittersum (1996) Aggregation of spatial units in linear programming models to explore land use options. *Netherlands Journal of Agricultural Science*, Vol. 44, pp. 145-162.

Hoshino, S. (2001) Multilevel modeling on farmland distribution in Japan. *Land Use Policy*, Vol. 18, pp. 75-90.

Hoshino, S. (1996) *Statistical analysis of land-use change and driving forces in the Kansai District, Japan*. International Institute for Applied Systems Analysis, Laxenburg.

Huigen, M. (2004) First principles of a multi actor framework for land use change and a preview regarding settlement in San Mariano, the Philippines. *Journal of Environmental Management,* Vol. 27, pp. 5-22.

Irwin, E. and J. Geoghegan (2001) Theory, data, methods: developing spatially-explicit economic models of land use change. *Agriculture, Ecosystems and Environment*, Vol. 85 (1-3), pp. 7-24.

Jansen, H. and J.J. Stoorvogel (1998) Quantification of aggregation bias in regional agricultural land use models: application to Guacimo County, Costa Rica. *Agricultural Systems*, Vol. 58 (3), pp. 417-439.

Janssen, M.A. and W. Jager (2000) The human actor in ecological-economic models: preface. *Ecological Economis*, Vol. 35 (3), pp. 307-310.

Jones, D.W. (1983) Location, agricultural risk, and farm income diversification. *Geographical Analysis*, Vol. 15 (3), 231-246.

Jones, D.W. and R.V. O'Neill (1992) Endogenous environmental degradation and land conservation: agricultural land use in a region. *Ecological Economis*, Vol. (6), pp. 79-101.

Kaimowitz, D. and A. Angelsen (1998) *Economic Models of Tropical Deforestation - A Review*. Center for International Forestry Research, Bogor, Indonesia.

Kanaroglou, P. and D. Scott (2001) Integrated urban transportation and land-use models for policy analysis. In: M. Dijst, W. Schenkel and I. Thomas (Eds), *Governing Cities on the Move*. Avebury, Aldershot UK, pp. 42-72.

King, A.W., A.R. Johnson, R.V. O'Neill and D.L. DeAngelis (1989) Using ecosystem models to predict regional CO_2 exchange between the atmosphere and the terrestrial biosphere. *Global Biogeochemical Cycles*, Vol. 3, pp. 337-361.

Lambin, E.F. (1997) Modelling and monitoring land-cover change processes in tropical regions. *Progress in Physical Geography*, Vol. 21 (3), 375-393.

Lambin, E.F., X. Baulies, N.E. Bockstael, G. Fischer, T. Krug, R. Leemans, E.F. Moran, R.R. Rindfuss, Y. Sato, D. Skole, B.L. Turner II and C. Vogel (2000) *Land-Use and Land-Cover Change (LUCC), Implementation Strategy*. IGBP, IHDP.

Lambin, E.F. and H.J. Geist (2003) Regional differences in tropical deforestation. *Environment*, Vol. 45 (6), pp. 22-36.
Lambin, E.F., H.J. Geist and E. Lepers (2003) Dynamics of land-use and land-cover change in tropical regions. *Annual Review of Environment and Resources*, Vol. 28, pp. 205-241.
Lambin, E.F., M.D.A. Rounsevell and H.J. Geist (2000) Are agricultural land-use models able to predict changes in land-use intensity? *Agriculture, Ecosystems and Environment*, Vol. 82, pp. 321-331.
Landis, J.D. (1995) Imaging land use futures. *Journal of the American Planning Association*, Vol. 61 (4), 438-458.
Levin, S.A., S. Barrett, S. Aniyar, W. Baumol, C. Bliss, B. Bolin, P. Dasgupta, P. Ehrlich, C. Folke, I.M. Gren, C.S. Holling, A.M. Jansson, B.O. Jansson, K.-G. Mäler, D. Martin, C. Perrings and E. Sheshinski (1998) Resilience in natural and socio-economic systems. *Environment and Development Economics*, Vol. 3, pp. 222-235.
Li, X. and A.G. Yeh (2002) Neural-network-based cellular automata for simulating multiple land use changes using GIS. *International Journal of Geographical Information Science*, Vol. 16 (4), pp. 323-343.
Lutz, R. (1997) HLA object model development: a process view, simulation interoperability workshop. *Simulation Interoperability Standards Organization*, Orlando, http://siso.sc.ist.ucf.edu/siw/97spring/papers/010.pdf.
Manson, S.M. (2000) Agent-based dynamic spatial simulation of land-use/cover change in the Yucatán peninsula, Mexico. In: B.O. Parks, K.M. Clarke and M.P. Crane (Eds) *Proceedings of the 4th international conference on integrating geographic information systems and environmental modeling: problems, prospects, and needs for research*. September 2-8. University of Colorado, Boulder.
McClean, C.J., P.M. Watson, R.A. Wadsworth, J. Blaiklock and J.R. O'Callaghan (1995) Land use planning: a decision support system. *Journal of Environmental Planning and Management*, Vol. 1, pp. 77-92.
McConnel, W. and E.F. Moran (2001) *Meeting in the Middle: The Challenge of Meso-Level Integration*. LUCC report Series 5. LUCC Focus 1 Office, Anthropological Center for Training and Research on Global Environmental Change, Indiana University, Bloomington.
Meentemeyer, V. (1989) Geographical perspectives of space, time, and scale. *Landscape Ecology*, Vol. 3 (3-4), pp. 163-173.
Mertens, B. and E.F. Lambin (2000) Land-cover-change trajectories in Southern Cameroon. *Annals of the Association of American Geographers*, Vol. 90 (3), pp. 467-494.
Mertens, B., W.D. Sunderlin, O. Ndoye and E.F. Lambin (2000) Impact of macroeconomic change on deforestation in South Cameroon: integration of household survey and remotely-sensed data. *World Development*, Vol. 28 (6), pp. 983-999.
Miller, E.J., D.S. Kriger and J.D. Hunt (1999) *TCRP Web Document 9: Integrated Urban Models for Simulation of Transit and Land-Use Policies: Final Report*. Toronto, University of Toronto Joint Program in Transportation and DELCAN Corporation.
Moran, E.F. (2005) Progress in the last ten years in the study of land use/cover change and the outlook for the next decade. In: A. Diekmann, T. Dietz, C.C. Jaeger and E.A. Rosa (Eds) *Studying the Human Dimensions of Global Environmental Change*. MIT Press, Cambridge, in press.
Munroe, D., J. Southworth and C.M. Tucker (2001) *The Dynamics of Land-Cover Change in Western Honduras: Spatial Autocorrelation and Temporal Variation*. Presented at the American Agricultural Economics Association. AAEA-CAES Annual Meeting. Chicago, IL, August 2001. Accessed on 5 June 2003 at: http://www. uncc.edu/dkmunroe/publications.htm.

Nelson, G.C., V. Harris and S.W. Stone (2001) Deforestation, land use, and property rights: empirical evidence from Darien, Panama. *Land Economics*, Vol. 77, pp. 187-205.

Nelson, G.C. and D. Hellerstein (1997) Do roads cause deforestation? Using satellite images in econometric analysis of land use. *American Journal of Agricultural Economics*, Vol. 79, pp. 80-88.

Ojima, D.S. and E. Moran (2004) *Global Land Project: Draft Science Plan*. Accessed: 5 August 2004 at: http://www.glp.colostate.edu.

O'Neill, R.V., A.R. Johnson and A.W. King (1989) A hierarchical framework for the analysis of scale. *Landscape Ecology*, Vol. 3, pp. 193-205.

O'Neill, R.V. and A.W. King (1998) Homage to St. Michael; or, why are there so many books on scale? In: D.L. Peterson and V.T. Parker (Eds), *Ecological Scale: Theory and Applications*. Columbia University Press, New York, pp. 3-16.

Overmars, K.P. and P.H. Verburg (2005) Analysis of land use drivers at the watershed and household level: Linking two paradigms at the Philippine forest fringe. *International Journal of Geographical Information Science,* Vol. 19 (2), pp. 125-152.

Pahari, K. and S. Marai (1999) Modelling for prediction of global deforestation based on the growth of human population. *ISPRS Journal of Photogrammetry & Remote Sensing*, Vol. 54, pp. 317-324.

Parker, D.C., S.M. Manson, M.A. Janssen, M. Hoffman and P. Deadman (2003) Multi-agent systems for the simulation of land-use and land-cover change: a review. *Annals of the Association of American Geographers*, Vol. 93 (2), pp. 314-337.

Petschel-Held, G., A. Block, M. Cassel-Gintz, J. Kropp, M.K.B. Ludeke, O. Moldenhauer, F. Reusswig and H.J. Schellnhuber (1999) Syndromes of global change; a qualitative modelling approach to assist global environmental management. *Environmental Modelling and Assessment*, Vol. 4, pp. 295-314.

Pfaff, A.S.P. (1999) What drives deforestation in the Brazilian Amazon? Evidence from satellite and socioeconomic data. *Journal of Environmental Economics and Management*, Vol. 37, pp. 25-43.

Pijanowski, B.C., D.G. Brown, B.A. Shellito and G.A. Manik (2002) Using neural networks and GIS to forecast land use changes: a land transformation model. *Computers, Environment and Urban Systems*, Vol. 26 (6), pp. 553-575.

Polhill, J.G., N.M. Gotts and A.N.R. Law (2001) Imitative versus nonimitative strategies in a land-use simulation. *Cybernetics and Systems*, Vol. 32, pp. 285-307.

Polsky, C. and W.E. Easterling III (2001) Ricardian climate sensitivities: accounting for adaptation across scales. *Agriculture, Ecosystems and Environment*, Vol. 85 (1-3), pp. 133-144.

Pontius, R.G. (2002) Statistical methods to partition effects of quantity and location during comparison of categorical maps at multiple resolutions. *Photogrammetric Engineering & Remote Sensing*, Vol. 68 (10), pp. 1041-1049.

Pontius, R.G., J.D. Cornell and C.A.S. Hall (2001) Modeling the spatial pattern of land-use change with GEOMOD2: application and validation for Costa Rica. *Agriculture, Ecosystems and Environment*, Vol. 85 (1/3), pp. 191-203.

Pontius, R.G. and J. Malanson (2005) Comparison of the accuracy of land change models: Cellular automata markov versus geomod. *International Journal of Geographical Information Science* Vol. 19 (2), pp. 243-266.

Pontius, R.G. and L.C. Schneider (2001) Land-use change model validation by an ROC method for the Ipswich watershed, Massachusetts, USA. *Agriculture, Ecosystems and Environment*, Vol. 85 (1-3), pp. 239-248.

Priess, J. and G. H. J. Koning (2001) Assessment of interactions between land use change and carbon and nutrient fluxes. *Agriculture, Ecosystems and Environment*, Vol. 85 (1-3), pp. 269-280.

Rabin, M. (1998) Psychology and economics. *Journal of Economic Literature*, Vol. 36 (1), pp. 11-46.
Rastetter, R.A., A.W. King, B.J. Cosby, G.M. Hornberger, R.V. O'Neill and J.E. Hobbie (1992) Aggregating fine-scale ecological knowledge to model coarse-scale attributes of ecosystems. *Ecological Applications*, Vol. 2, pp. 55-70.
Riebsame, W.E., W.B. Meyer and B.L. Turner II. (1994) Modeling land use and cover as part of global environmental change. *Climatic Change*, Vol. 28, pp. 45-64.
Riebsame, W.E. and W.J. Parton (1994) Integrated modeling of land use and cover change. *Bioscience*, Vol. 44 (5), pp. 350-357.
Rotmans, J. and M.B.A. van Asselt (2001) Uncertainty management in integrated assessment modeling: towards a pluralistic approach. *Envrionmental Monitoring and Assessment*, Vol. 69, pp. 101-130.
Rouchier, J., F. Bousquet, M. Requier-Desjardins and M. Antona (2001) A multi-agent model for describing transhumance in North Cameroon: Comparison of different rationality to develop a routine. *Journal of Economic Dynamics & Control*, Vol. 25, pp. 527-559.
Ruben, R., H. Moll and A. Kuyvenhoven (1998) Integrating agricultural research and policy analysis: Analytical framework and policy applications for bio-economic modelling. *Agricultural Systems*, Vol. 58 (3), pp. 331-349.
Sala, O.E., F.S. Chapin, J.J. Armesto, E. Berlow, J. Bloomfield, R. Dirzo, E. Huber-Sanwald, L. Huennek, R.B. Jackson, A. Kinzig, R. Leemans, D.M. Lodge, H.A. Mooney, M. Oesterheld, N.L. Poff, M.T. Sykes, B.H. Walker, M. Walker and D.H. Wall (2002) Global Biodiversity Scenarios for the Year 2100. *Science*, Vol. 287, pp. 1770-1774.
Sanders, L., D. Pumain, H. Mathian, F. Guerin-Pace and S. Bura (1997) SIMPOP: a multiagent system for the study of urbanism. *Environment and Planning B*, Vol. 24, pp. 287-305.
Scheffer, M. (1999) Searching explanations of nature in the mirror world of math. *Conservation Ecology*, Vol. 3 (2), p. 11. [online] URL: http://www.consecol.org/vol3/iss2/art11.
Schneider, L.C. and R.G. Pontius (2001) Modeling land-use change in the Ipswich Watershed, Massachusetts, USA. *Agriculture, Ecosystems and Environment*, Vol. 85 (1-3), pp. 83-94.
Schneider, S.H. (1997) Integrated assessment modeling of global climate change: Transparent rational tool for policy making or opaque screen hiding value-laden assumptions? *Environmental Modeling and Assessment*, Vol. 2, pp. 229-249.
Schulze, R. (2000) Transcending scales of space and time in impact studies of climate and climate change on agrohydrological responses. *Agriculture, Ecosystems and Environment*, Vol. 82, pp. 185-212.
Serneels, S. and E.F. Lambin (2001) Proximate causes of land use change in Narok district Kenya: a spatial statistical model. *Agriculture, Ecosystems and Environment*, Vol. 85 (1/3), pp. 65-81.
Silva, E.A. and K.C. Clarke (2002) Calibration of the SLEUTH urban growth model for Lisbon and Porto, Portugal. *Computers, Environment and Urban Systems*, Vol. 26 (6), pp. 525-552.
Tesfatsion, L. (2001) Introduction to the special issue on agent-based computational economics. *Journal of Economic Dynamics & Control*, Vol. 25, pp. 281-293.
Turner II, B.L., R.H. Ross and D.L. Skole (1993) *Relating Land Use and Global Land Cover Change*. GDP report no. 24; HDP report no. 5. Royal Swedish Academy of Sciences, Stockholm.
Turner II, B.L., D.L. Skole, S. Sanderson, G. Fischer, L.O. Fresco and R. Leemans (1995) *Land-Use and Land-Cover Change - Science/Research Plan*. IGBP Report 35, HDP Report 7. International Geosphere-Biosphere Programme, Stockholm.

Turner, M.G., D.N. Wear and R.O. Flamm (1996) Land ownership and land-cover change in the southern Appalachian Highlands and the Olympic Peninsula. *Ecological Applications*, Vol. 6 (4), pp. 1150-1172.
Uran, O. and R. Janssen (2003) Why are spatial decision support systems not used? Some experiences from the Netherlands. *Computers, Environment and Urban Systems*, Vol. 27, pp. 511-526.
van der Veen, A. and J. Rotmans (2001) Dutch perspectives on 'Agents, Regions and Land Use Change'. *Environmental Monitoring and Assessment*, Vol. 6, pp. 83-86.
van Ittersum, M.K., R. Rabbinge and H.C. van Latesteijn (1998) Exploratory land use studies and their role in strategic policy making. *Agricultural Systems*, Vol. 58, pp. 309-330.
Vanclay, J.K. (1998) FLORES: for exploring land use options in forested landscapes. *Agroforestry Forum*, Vol. 9 (1), pp. 47-52.
Veldkamp, A. and L.O. Fresco (1996) CLUE-CR: an integrated multi-scale model to simulate land use change scenarios in Costa Rica. *Ecological Modelling*, Vol. 91, pp. 231-248.
Veldkamp, A. and L.O. Fresco (1997) Reconstructing land use drivers and their spatial scale dependence for Costa Rica. *Agricultural Systems*, Vol. 55, pp. 19-43.
Veldkamp, A. and E.F. Lambin (2001) Editorial: Predicting land-use change. *Agriculture, Ecosystems and Environment*, Vol. 85 (1-3), pp. 1-6.
Veldkamp, A. and P.H. Verburg (2004) Modelling land use change and environmental impact: Introduction to the special issue. *Journal of Environmental Management,* Vol. 72 (1-2), pp. 1-3.
Verburg, P.H. and Y.Q. Chen (2000) Multi-scale characterization of land-use patterns in China. *Ecosystems*, Vol. 3, pp. 369-385.
Verburg, P.H., J. Ritsema van Eck, T. de Nijs, M.J. Dijst and P. Schot (2004) Determinants of land use change patterns in the Netherlands. *Environment and Planning B*, Vol. 31, pp. 125-150.
Verburg, P.H., W. Soepboer, R. Limpiada, M.V.O. Espaldon, M. Sharifa and A. Veldkamp (2002) Land use change modelling at the regional scale: the CLUE-S model. *Environmental Management*, Vol. 30 (3), pp. 391-405.
Verburg, P.H. and A. Veldkamp (2004) Projecting land use transitions at forest fringes in the Philippines at two spatial scales. *Landscape Ecology*, Vol. 19 (1), pp. 77-98.
Verburg, P.H. and A. Veldkamp (2005) Spatial modeling to explore land use dynamics. *International Journal of Geographical Information Science,* Vol. 19 (2), pp. 99-102.
Verburg, P.H., A. Veldkamp, G.H.J. de Koning, K. Kok and J. Bouma (1999) A spatial explicit allocation procedure for modelling the pattern of land use change based upon actual land use. *Ecological Modelling*, Vol. 116, pp. 45-61.
Visser, H. (2004) *The Map Comparison Kit: methods, software and applications*. Report 550002005/2004. National Institute for Public Health and Environment, Bilthoven.
Voinov, A., R. Costanza, L.A. Wainger, R. Boumans, F. Villa, T. Maxwell and H. Voinov (1999) Patuxent landscape model: integrated ecological economic modeling of a watershed. *Environmental Modelling & Software*, Vol. 14, pp. 473-491.
Waddell, P. (2000) A behavioral simulation model for metropolitan policy analysis and planning: residential location and housing market components of UrbanSim. *Environment and Planning B*, Vol. 27 (2), pp. 247-263.
Walker, R. (2003) Evaluating the performance of spatially explicit models. *Photogrammetric Engineering & Remote Sensing*, Vol. 69 (11), pp. 1271-1278.
Walker, R., E.F. Moran and L. Anselin (2000) Deforestation and cattle ranching in the Brazilian Amazon: External capital and household processes. *World Development*, Vol. 28 (4), pp. 683-699.
Walsh, S. J., T. W. Crawford, K. A. Crews-Meyer, and W. F. Welsh (2001) A multi scale analysis of land use land cover change and NDVI variation in Nang Rong District,

Northeast Thailand. *Agriculture, Ecosystems and Environment*, Vol. 85 (1-3), pp. 47-64.

Walsh, S.J., T.P. Evans, W.F. Welsh, B. Entwisle and R.R. Rindfuss (1999) Scale-dependent relationships between population and environment in northeastern Thailand. *Photogrammetric Engineering & Remote Sensing*, Vol. 65 (1), pp. 97-105.

Watson, M.K. (1978) The scale problem in human geography. *Geografiska Annaler*, Vol. 60B, pp. 36-47.

Wear, D.N. and P. Bolstad (1998) Land-use changes in southern Appalachian landscapes: spatial analysis and forecast evaluation. *Ecosystems*, Vol. 1, pp. 575-594.

White, D., P.G. Minotti, M.J. Barczak, J.C. Sifneos, K.E. Freemark, M.V. Santelmann, C.F. Steinitz, A.R. Kiester and E.M. Preston (1997) Assessing risks to biodiversity from future landscape change. *Conservation Biology*, Vol. 11 (2), pp. 349-360.

White, R. and G. Engelen (2000) High-resolution integrated modelling of the spatial dynamics of urban and regional systems. *Computers, Environment and Urban Systems*, Vol. 24, pp. 383-400.

Wolfram, S. (1986) *Theory and Applications of Cellular Automata*. World Scientific, Singapore.

Wu, F. (1998) Simulating urban encroachment on rural land with fuzzy-logic-controlled cellular automata in a geographical information system. *Journal of Environmental Management*, Vol. 53, pp. 293-308.

Wu, F. and C.J. Webster (1998) Simulation of land development through the integration of cellular automata and multicriteria evaluation. *Environment and Planning B*, Vol. 25, pp. 103-126.

Technology Development and Climate Change as Drivers of Future Agricultural Land Use

3

Frank Ewert, Mark Rounsevell, Isabelle Reginster, Marc Metzger and Rik Leemans

INTRODUCTION

Environmental, land cover and land use changes are closely interrelated (Lambin et al., 2000). Agriculture is the most important land use in Europe (Rounsevell et al., 2003) with about 27% and 18% of total land area used for crop production or as grassland respectively (FAO, 2003). Changes in agricultural land use may have substantial environmental implications including alterations in emissions of greenhouse gases. Guo and Gifford (2002) provide experimental data that suggests increases in soil carbon after land use changes from crop to pasture amount to 18%, while changes to forest plantations yield 19% and secondary forest (53%). In contrast, they report carbon stocks decline after land use changes from forest to crop (-42%) and from pasture to crop (-59%).

Agricultural land use may also be affected by environmental changes. In particular, changes in primary productivity through climate change and technology development are likely to determine future agricultural production and the use of land. However, the effects of socio-economic and bio-physical factors on crop productivity and land use are complex and not well understood with predictions remaining difficult. Previous attempts have developed qualitative descriptions of land use change with short time horizons and for small study regions. Consistent European quantitative information with spatial resolutions relevant to regional scale and ecosystem studies such as on greenhouse gas emissions are not yet available.

A useful technique for the exploration of uncertain futures is the application of comprehensive, alternative scenarios. A suitable concept for the development of alternative scenarios of land use change is provided by the IPCC Special Report on Emission Scenarios (SRES) (Nakićenović et al., 2000). The SRES scenarios are based on possible demographic, social economic, technological and environmental developments during the 21st century. The two-digit code of the four families (A1, B1, A2 and B2) locates them in a four-quadrant chart. The vertical axis represents a distinction between more economically (A) and more environmentally and equity (B) orientated futures. The horizontal axis represents

F. Brouwer and B.A. McCarl (eds.), Agriculture and Climate Beyond 2015, 33-51

the range between more globally (1) and more regionally orientated developments (2). The A1-set was further developed into three groups, depending on energy sources (A1FI: only fossil fuels; A1B: a balanced mix; A1T: non fossil fuels).

The present chapter aims to identify and explore important drivers and relationships of agricultural land use change under alternative scenarios of future development. The work is part of a larger project on the assessment of the vulnerability of ecosystems and ecosystem services in Europe (ATEAM, Advanced Terrestrial Ecosystem Analysis and Modelling). The present study specifically addresses land use changes of crops and livestock for food including meat and milk production. Main emphasis is on the linkages between land use and agricultural productivity as affected by technology advances, climate change and atmospheric CO_2 concentration. The approach is based on simple supply-demand relationships for food production. Effects of important drivers on changes in productivity and land use were evaluated for the four SRES basic scenarios (A1F1, A2, B1 and B2) and for three time-slices (2020, 2050 and 2080) with 2000 as the base-line year. Corresponding climate data were used from the HadCM3 general circulation model (Mitchell, et al., 2004). The present study emphasises the linkages between productivity and land use at the European scale, i.e. EU 15, Norway and Switzerland. The regional allocation of estimated land use changes is presented elsewhere (Rounsevell et al., 2005; Rounsevell et al., in review).

PAST CHANGES IN AGRICULTURAL LAND USE AND PRODUCTION

Data from the Food and Agriculture Organisation (FAO, 2003) indicate that the agricultural area of Europe (EU-15 member countries) declined by about 14% between 1961 and 2000 (Figure 3.1a). During the same period, population increased by nearly 20% and the economic power expressed in GDP per capita almost tripled (World Bank, 2002). Thus, agricultural production from a decreasing area of agricultural land had to satisfy the growing demand for food that resulted from increasing population and economic wealth.

At the beginning of the 1960s productivity of important crops in Europe increased significantly mainly due to advances in agricultural technology, known as the Green Revolution. For instance, yields of cereals in the EU 15 countries increased by about 150% in the last four decades (Figure 3.1b). Rates of yield increase were higher than increases in demand and production exceeded demand in the mid eighties (Figure 3.1c). Further, increases in crop productivity resulted in substantial oversupply in the late eighties/early nineties, with levels of self-sufficiency that reached 120% and more. In response, the EU reformed the Common Agricultural Policy (CAP) and introduced a substantial amount of set-aside land in the Arable Area Payment Scheme. However, while reduction in agricultural land use through set-aside resulted in reduced production, crop yields further increased and the reduction in oversupply was less than expected (Figure 3.1c). With the latest CAP reform at the beginning of the new century, the EU

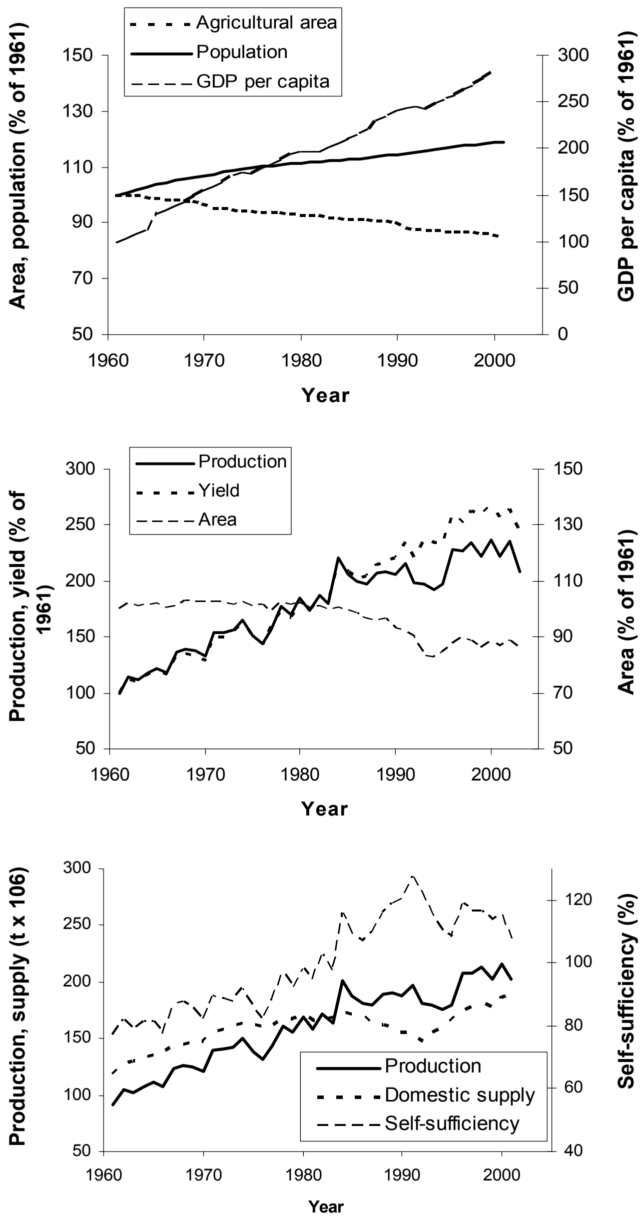


Figure 3.1 Changes in a) agricultural area, population and GDP per capita; b) harvested area, production and yields of cereals; and c) production, domestic supply and self-sufficiency for cereals in Europe (EU 15) between 1961 and 2000. Data in a) and b) represent relative changes compared to 1961

Source: Data were taken from FAO (2003) and World Bank (2002).

agricultural policy attempts to shift away from price support measures for production towards sustainable development and multifunctional agriculture. The potential implications of these policy measures for production, land use, rural development and the environment remain unclear.

Importantly, with the present study we do not aim to predict future changes in productivity and land use. Instead, alternative possible pathways of future development of important socio-economic and biophysical factors are used to explore changes in crop productivity and land use and discuss potential environmental implications.

MODELLING FUTURE LAND USE CHANGES

General method

The development of land use change scenarios was based on the following procedure (Figure 3.2). In a first step, important drivers of land use change were identified and interpreted at the European scale. Then, the future changes of the relevant drivers were estimated for the different scenarios and the corresponding total changes in land use were assessed. Finally, scenarios-specific rules were developed to allocate estimated land use changes across Europe. A more detailed description of the methodology is provided elsewhere (Rounsevell et al., 2005; Rounsevell et al., in review).

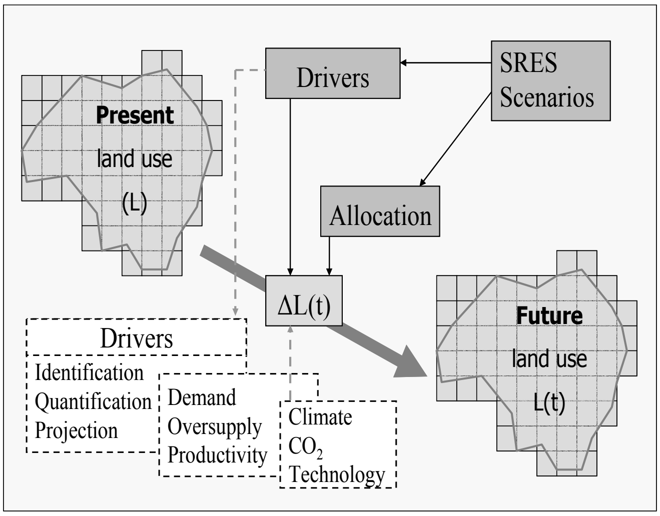


Figure 3.2 Schematic representation of the general methodology for the development of quantitative, spatially explicit and alternative scenarios of future agricultural land use in Europe. Stripped lines and boxes indicate drivers and relationships that are specifically emphasized in this study

Identification of drivers

SRES provides coarse scenarios for global scale applications, without guidelines to their application at the regional scale. Descriptions of likely sectoral changes, such as ones particularized for agriculture are not provided. Thus, in developing scenarios of future European agricultural land use change within the SRES framework, it is still necessary to both interpret regional scale and sectorally-based change drivers as well as to quantify the effects of these change drivers. Important drivers of agricultural land use change were identified and were related either to supply or demand for food or agricultural policy (Table 3.1).

Table 3.1 Important drivers of European agricultural land use change

Supply	Demand	Policy
Land use competition (e.g. urban)	Population (Europe, World)	Market intervention (subsidies, quotas)
Suitable areas	Consumer diet and preferences (meat, organic)	Rural development
Productivity (climate change, CO_2, research and technology)	Import/export regulations (World Trade Organisation)	Environmental protection (e.g. Nitrate Vulnerable Zones)

In order to quantify the impact of these drivers on land use change, we used an approach in which we estimated future land use from changes in supply and demand for food:

$$L_t = L_{t_0} r_{p_{t-t_0}} (\Delta S, \Delta D) \tag{3.1}$$

where L represents present (t_0) and future (t) land use, r is the land use change factor and S and D are food supply and demand. Policy measures may cause overproduction via market intervention. We have considered such effects via the introduction of an oversupply factor (see next section). In addition, alternative future policies were explicitly accounted for in the allocation rules for the different scenarios (Rounsevell et al., 2005; Rounsevell et al., in review).

Supply-demand model

We assumed that supply equals demand and that the relationship between supply and demand is constant and does not change in the future:

$$\frac{S_t}{D_t} = \frac{S_{t_0}}{D_{t_0}} \tag{3.2}$$

Supply can be calculated from the area used for production and the productivity per unit area. Since *S* may exceed *D* (see Figure 3.1c), overproduction needed to be considered and *S* was calculated from:

$$S = \frac{L \cdot P}{O_r} \tag{3.3}$$

where *P* is the productivity per unit land area and O_r the relative oversupply. Importantly, we first calculated land use change at the European level (Figure 3.2) so that regional differences in oversupply were not specifically considered. Thus, we assumed that even for the regional scenarios, economic integration of countries and regions within the EU will continue. The aspect of regional development was accounted for when estimated land use changes for Europe were allocated to individual regions applying scenario-specific allocation rules (Rounsevell et al., 2005; Rounsevell et al., in review). Substituting *S* in equation 3.2 with its formulation in equation 3 and solving it for L_t gives:

$$L_t = L_{t_0} \frac{D_t}{D_{t_0}} \frac{P_{t_0}}{P_t} \frac{O_{r,t}}{O_{r,t_0}} \tag{3.4}$$

Thus, agricultural land use at any time in the future was calculated from present land use and the relative changes in demand, relative oversupply and the inverse of the relative change in productivity. Estimation of parameters is described below (section parameterisation). However, for the estimation of changes in productivity an approach was required to account for the main factors that determine future productivity.

Modelling productivity changes

Drivers of productivity change

There is considerable evidence that changes in climatic conditions and atmospheric CO_2 concentrations will affect future crop productivity (Bender et al., 1999; Downing et al., 2000; Fischer et al., 2002; Jones et al., 2000; van Oijen and Ewert, 1999; Reilly et al., 2003; Rosenzweig and Parry, 1994). In addition, agricultural-technology development that has caused significant yield increases in the past decades may further increase future productivity (Borlaug, 2000; Evans, 1997). Accordingly, we calculated productivity changes from:

$$\frac{P_{t_0}}{P_t} = \frac{1}{1 + ((P_{t,Cl}/P_{t_0} - 1) + (P_{t,CO}/P_{t_0} - 1) + (P_{t,T}/P_{t_0} - 1))} \qquad (3.5)$$

where $P_{t,Cl}$, $P_{t,CO}$ and $P_{t,T}$ represent future productivity as affected by climate change, increasing CO_2 concentrations and technology development, respectively. Importantly, we assumed that the effects of these factors were additive. Although interactions between CO_2 elevation and changes in climatic conditions have been reported, experimental evidence at the field scale is still limited (Ewert et al., 2002; Tubiello and Ewert, 2002) and there is no evidence about the significance of such interactions at larger spatial scales such as regions, countries or even global.

Climatic effects

Process-based models are increasingly used to estimate changes in potential productivity under climate change (Amthor and Loomis, 1996, Boote et al., 1997, Tubiello and Ewert, 2002). However, prediction of responses in actual yields at the regional scale to climate change remains difficult since there are a number of important yield reducing factors involved that are currently not accounted for in process-based models (Figure 3.3). In addition, model validation for the range of crops grown in Europe is still unsatisfactory (Tubiello and Ewert, 2002). Alternatively, we used an approach that is based on an environmental stratification (EnS) developed by Metzger et al., (in press) in which Europe is grouped into 84 environmental strata (13 environmental zones) based on a number of climatic and other variables. Available NUTS 2 level yield statistics (Eurostat, 2000) were allocated to these strata. We calculated future productivity as affected by climate change from:

$$P_{t,CL} = P_t \cdot f_{Y,C(t)} \qquad (3.6)$$

where $f_{Y,C}$ is the climate related productivity change factor which was calculated from projected yield changes in the EnS strata. As EnS strata and corresponding yields changed their geographical location and size depending on time and SRES scenario a new yield was obtained for each ATEAM grid cell from which the climate change induced yield change was calculated:

$$f_{Y,C} = \sum_{i=1}^{n} \frac{Y_{G_i(t)}}{Y_{G_i(t_0)}} / n \qquad (3.7)$$

where Y_{Gi} is the actual yield of an ATEAM grid cell i at present and future times and n is the total number of grid cells considered.

Effects of increasing atmospheric CO_2 concentration

Substantial progress has been made in modelling crop responses to CO_2 elevation (Ewert, 2004; Tubiello and Ewert, 2002). However, state of European model validation under field conditions is still unsatisfactory (Tubiello and Ewert, 2002) and understanding of processes that determine yield responses to increasing CO_2 concentration at the regional scale is limited. Alternatively, we used a simple empirical relationship to estimate changes in productivity in response to CO_2 elevation that was derived from experimental investigations on crops (Amthor, 2001; Kimball et al., 2002; Oijen and Ewert, 1999). Effects of CO_2 on productivity were accounted for by a change factor ($f_{Y,CO}$):

$$P_{t,CO} = P_{t_0} \cdot f_{Y,CO(t)} \tag{3.8}$$

which was calculated from:

$$f_{Y,CO} = \frac{f_{CO,r} \cdot \Delta C_{t-t_0}}{100} + 1 \tag{3.9}$$

The relative change in productivity due to increasing CO_2 concentration (ΔC_{t-t_0}) was calculated assuming a relative yield increase per unit increase in CO_2 ($f_{CO,r}$) that was calculated based on experimental observations (see the section on parameter estimation).

Agricultural-technology development

Yields of crops in Europe have increased substantially since the Green Revolution (Calderini and Slafer, 1998; Cassman, 1999; Dyson, 1999; Evans, 1997; Reynolds et al., 1999). Improved crop management associated with fertilization, pest and weed control, tillage, water use and harvesting together with advances in conventional breeding have largely contributed to this development. The set of measures related to breeding and crop management that increased crop productivity in the past and are likely to increase it in the future are referred to as agricultural-technology development. In order to quantify the potential impacts of technology development on primary productivity we distinguished between actual and potential yields (Figure 3.3).

Potential yield is the maximum yield that could be reached in a given environment (Evans and Fischer, 1999). Limitations are only due to yield defining factors such as climatic conditions, temperature, radiation, CO_2 concentration and crop characteristics (Figure 3.3). Alternatively, actual yield is the harvested yield obtained in a given environment. It is lower than the potential

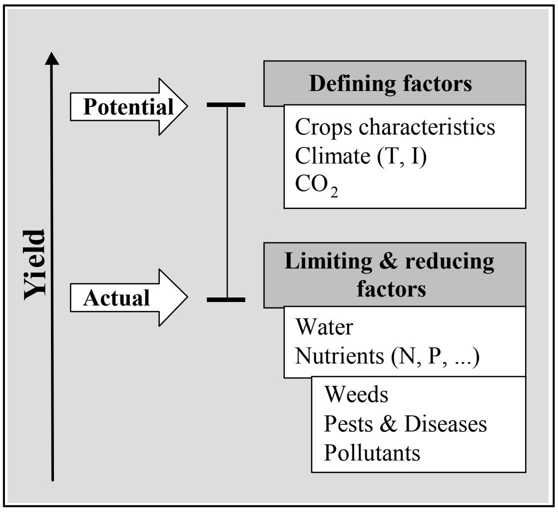


Figure 3.3 Schematic description of yield defining, limiting and reducing factors (after Goudriaan and Zadoks, 1995; van Ittersum et al., 2003)

yield due to a number of yield limiting and reducing factors (Figure 3.3). The difference between potential and actual yield, also called the yield gap, varies depending on regions and crops (Oerke and Dehne, 1997). Yield gaps for crops in Europe are about 20% which is smaller than in other parts of the world were application of pesticides is restricted to high-value crops only or were intensification of crop production is low (Oerke and Dehne, 1997). Agricultural-technology development has aimed at both increasing potential yield through improved crop characteristics and at reducing the yield gap through improved crop characteristics and crop management.

In the present study we calculated changes in productivity due to technology development as:

$$P_{t,T} = P_{t_0} \cdot f_{Y,T(t)} \tag{3.10}$$

where $f_{Y,T}$ represents the relative yearly change in productivity and was calculated as:

$$f_{Y,T} = f_{Y_r(t_0)} + \int_{2000}^{t=t_s} f_{T,r}\, dt \tag{3.11}$$

In order to project the linear historic yield trends into the future, we assumed that the relative yearly changes in productivity at the beginning of our scenario period,

$f_{Yr(t_0)}$, increased each year with a constant value of $f_{T,r}$ which is equal to ($f_{Yr(t_0)}$-1) over the scenario period t_s. We also assumed that yield trends might change in the future due to changes in technology. Following the concept of potential and actual yield we distinguished between technology developments specifically dedicated to increasing potential yield or to reducing the gap between potential and actual yield. This concept allowed consideration of different strategies for technology development with respect to the specific SRES scenario. Accordingly, changes in technology impacts on productivity were calculated from:

$$f_{T,r} = (f_{Y_r(t_0)} - 1) \cdot f_{T,P} \cdot f_{T,G} \tag{3.12}$$

in which $f_{T,P}$ accounts for changes in technology impacts on potential yields and $f_{T,G}$ for changes related to the yield gap. They are calculated from:

$$f_{T,P} = f_{T,P_b} \cdot f_{T,P_r} \tag{3.13}$$

$$f_{T,G} = \frac{f_{T,G_r}}{f_{T,G_b}} \tag{3.14}$$

assuming that future technology impacts on potential yield and yield gap change with f_{T,P_r} and f_{T,G_r}, respectively, relative to base-line assumptions, i.e. f_{T,P_b} and f_{T,G_b}, derived from historic data.

ESTIMATION OF PARAMETERS

Estimation of parameters that represent changes in demand and oversupply on land use change is described elsewhere (Rounsevell et al., 2005). Briefly, scenario specific estimations of future demand for food crops were derived from simulations with the IMAGE model v2.2 (IMAGE-team, 2001). Demand for food crops increased by between 5% and 50% depending on scenario and time-slice compared to 2000. Present oversupply of food in Europe was assumed to be about 10% (Figure 3.1c) although there are significant differences among countries (see section supply-demand model). Depending on the scenario future oversupply will be reduced to zero for the economic scenarios or will be further allowed for the environmental scenarios (Rounsevell et al., 2005; Rounsevell et al., in review).

Parameters that represent productivity responses to climate change were calculated from the climate change related shifts in the environmental strata. Estimated effects of climate change on productivity are presented in the results section. Increasing CO_2 concentration was calculated based on experimental observations in wheat (Amthor, 2001; Oijen and Ewert, 1999) and was assumed to increase productivity by 0.08 t/ppm CO_2, i.e. $f_{CO,r}$ in equation 3.9. The parameter refers to C3 crops and no further distinction was made for C4 crops which have a different photosynthetic pathway with a typically smaller response to increasing CO_2. However, the importance of C4 crops in Europe is relatively small compared to C3 crops and C4 crops were not specifically considered in the present analysis.

Different parameters had to be estimated to quantify the effects of technology development on productivity and land use change. We observed that historic relative yearly changes in productivity for major crops and countries within the EU tend to converge. Differences among crops and countries were surprisingly small, despite the fact that absolute differences among yields were substantial and tended to increase (Ewert et al., 2005) (Figure 3.4). Thus, a single value, representing a relative yield increase per year of about 1.75% was used for different crops and countries (Table 3.2). However, future yield increases will depend on increasing potential yields and/or reduction in the yield gaps. We set historic increases in potential yields to one (Table 3.2) and assumed that historic yield increases cannot be maintained in the future, so that future increases in potential yields will be less than in the past. This is consistent with a number of reports suggesting that on-farm yields have reached a plateau in recent years (Calderini and Slafer, 1998) and yield potential is likely to top out within the next 30 years (Cassman, 1999). However, other studies indicate that even though yield potential is already high in developed countries there is scope for further increase. Analysing data from recent wheat trials with candidate cultivars and F1 hybrids, Austin (1999) argued that further genetic yield gain will be achieved within the next decade. Modification of the photosynthetic enzyme rubisco to reduce its oxygenase activity might be a way to increase growth rates and biomass at maturity in the longer term (Austin, 1999). Improvement without changes in rubisco might also be achieved via the definition of optimal canopies of leaves having suitable acclimation and photoprotection (Loomis and Amthor, 1999) since actual radiation use efficiency of crops is less than potential with present rubisco kinetics (Loomis and Amthor, 1999). Several studies suggest that some new selection technologies have real potential to complete conventional wheat breeding programs in the area of biotechnology and physiology (Reynolds et al., 1999).

Thus, depending on the scenario we assumed that potential yield further increases particularly in the economic scenarios (A1FI and A2), though to a smaller extend than in the past. No further increase in potential yield was assumed after 2050 for the regional environmental scenario (B2). Present and future aims in research and technology development are also targeted towards closing the gap between potential and actual yield. Agronomic innovations and breeding to improve crop resistance to biotic and abiotic factors are likely to increase actual yields in the future (Borlaug, 2000; Evans, 1997). Thus, we assumed that except for the B2 scenario yield gaps will be reduced in the future. Our arguments that explain the derived scenario-specific parameter values in Table 3.2 are summarised in Table 3.3.

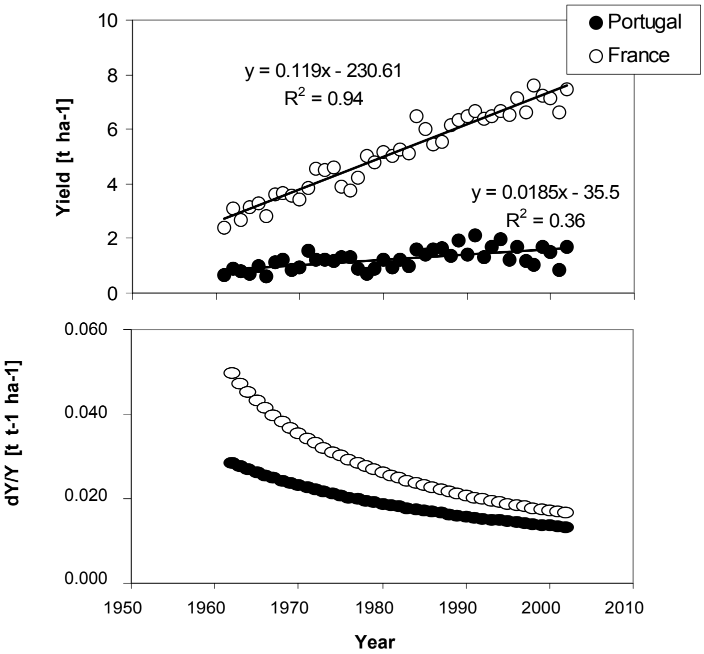


Figure 3.4 Changes in a) absolute and b) relative yields (dY/Y) of wheat over time for two selected countries in Europe

ESTIMATED CHANGES IN PRODUCTIVITY AND LAND USE

Productivity changes were calculated separately for the effects of climate change, increasing CO_2 concentration and technology development. Average yield changes across Europe due to climate change ranged between -3% and 1% depending on scenario and time period (Figure 3.5a). However, at the country and regional level, effects were more pronounced and differences among regions were evident (not shown). Average yields across Europe gradually increased due to increasing CO_2 concentration projected for the different scenarios. Yields were estimated to increase by 11% (B2) to 32% (A1FI) depending on the scenario in 2080 (Figure 3.5b). However, estimated changes in productivity were particularly high due to technology development. We estimated that yields will increase by 25% (B2) to 135% (A1FI) depending on the scenario in 2080 (Figure 3.5c).

The implications for changes in land use were substantial. Particularly for the scenarios A1FI and A2, we calculated that in 2080 the area used for crop production will be about 50% of present land use (Figure 3.6a). The estimated decline was smaller for the environmental scenarios B1 and B2 with 58% and 67% of present land use, respectively (Figure 3.6a). In these estimations, oversupply was not allowed. However, if present oversupply remains unchanged

Table 3.2 Parameter values as used in the present model for estimating effects of future technology development on crop productivity

Para-meter	Value						Description
		Scenarios					
		Year	A1FI	A2	B1	B2	
$f_{Yr(t_0)}$	1.0175						Base-line (historic) rate of productivity change
f_{T,P_b}	1						Base-line yield potential
f_{T,P_r}		2020	0.9	0.8	0.6	0.2	Correction factor for future yield potential
		2050	0.8	0.6	0.4	0	
		2080	0.7	0.4	0.2	0	
f_{T,G_b}	0.8						Base-line yield gap
f_{T,G_r}		2020	0.85	0.85	0.85	0.6	Correction factor for future yield gap
		2050	0.9	0.9	0.9	0.6	
		2080	0.95	0.95	0.95	0.6	

as we assumed for the B1 scenario (Rounsevell et al., 2005; Rounsevell et al., in review), the decrease in land use will be less (Figure 3.6b). Importantly, if agricultural land is fully protected as in the B2 scenario (Rounsevell et al., 2005; Rounsevell et al., in review) overproduction will increase to about 47% by 2080 (Figure 3.6c). There were regional differences in the allocation of these changes, which is not further discussed here (but see Rounsevell et al., 2005; Rounsevell et al., in review).

POTENTIAL IMPLICATIONS OF ESTIMATED LAND USE CHANGES

The estimated future decline in agricultural land use is likely to have substantial implications for rural development, agriculture and the environment. The potential reduction in future land areas required for agricultural production provides opportunities for alternative uses such as for bioenergy production (biofuels, woodlands), GHG emission reduction through conversion of crop land to forests (Guo and Gifford, 2002), biodiversity conservation and/or leisure and recreational purposes. The environmental and socio-economic benefits of such land use changes may be considerable, but are largely unknown. Alternatively, orientation towards sustainable agriculture with less emphasis on productivity increases, and agricultural protection policies will result in reduced changes (B1)

Table 3.3 Assumptions about effects of technology development on potential yield and yield gap of crops for different SRES scenarios

Scenario	Assumption
A1FI	In the global scenarios (A1FI and B1) food production has to meet the global demand. Since global population growth continues into the 21st century the pressure for food supply is high. The potential to increase productivity via closing the yield gap is relatively small and emphasis is largely placed on increasing potential yield. Globally organized breeding companies provide the required resources. Breeding activities will be concentrated in developed countries since it becomes too expensive to develop and introduce new technologies in developing countries. However, there are biophysical limits and increases in potential yield will gradually approach a ceiling. At the same time progress in reducing the yield gap continues largely due to improved varieties and crop management.
A2	In the regional scenarios (A2 and B2) food production has to meet the demand in Europe. Although the A2 scenario is the only scenario with a population increase in Europe the pressure of population growth on food supply is less than at the global level. Breeding is regionally oriented but emphasis is still on yield increase since it guaranties the largest economic return. Increases in potential yields gradually fall to 50% of what has been assumed in the A1FI scenarios by 2100.
B1	Again, pressure of global population growth on food supply is high. Breeding is globally organized with sufficient resources to invest in modern technologies. However, emphasis is not only on yield increase but also on yield quality, which correlates negatively with productivity. Also, agricultural production will be more sustainable and less intensive which limits breeding for high yielding varieties that require high inputs. Increases in potential yields gradually fall to about 25% of what has been assumed for the A1FI scenario by 2100.
B2	Pressure of population growth on food supply is relatively small. Breeding is regionally oriented and emphasis is on yield quality and sustainability of production. Increases in potential yields gradually fall to zero with no further increase in yield potential by 2050. Yield gap increases in the first year (and then stabilizes) due to the introduction of alternative, environmental friendly production methods for which appropriate crop management has not been developed yet.

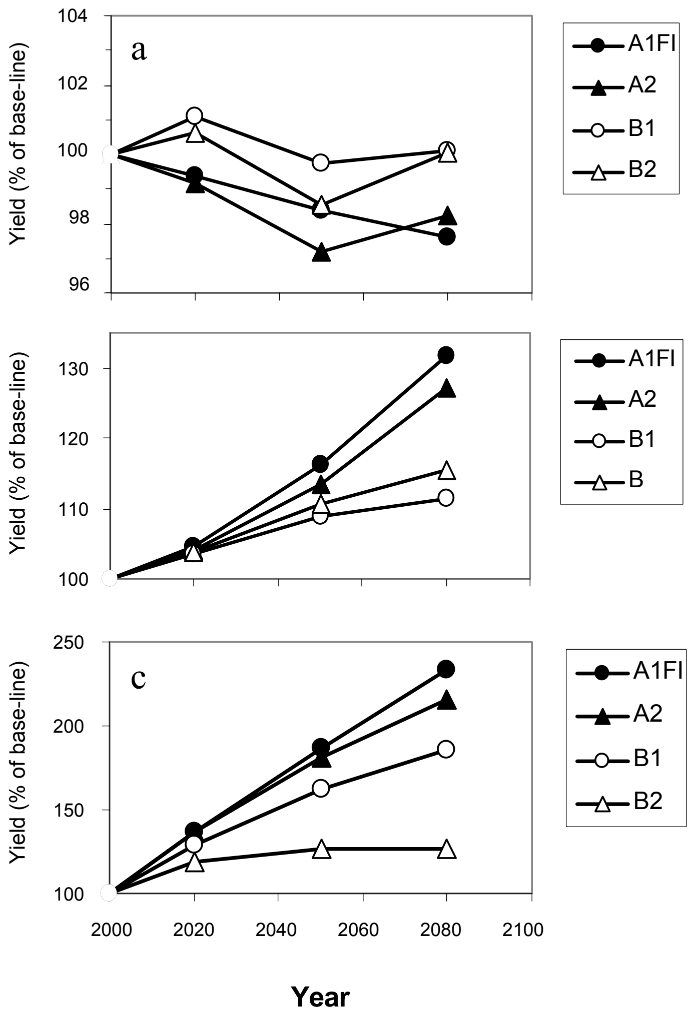


Figure 3.5 Estimated future yield changes of crops compared to the base-line year 2000 due to a) climate change, b) increasing CO_2 concentrations and c) technology development

or even prohibit changes (B2) in land use. Associated benefits for the environment including rural development and food quality have extensively been stressed. However, overproduction may be an inadvertent result of such developments. The costs are unknown but are likely to be high as is evident from the present EU agricultural experience. Clearly, the costs and benefits of the different pathways of changes in agriculture and land use remain unclear and await further evaluation. However, an integrated assessment of such complex

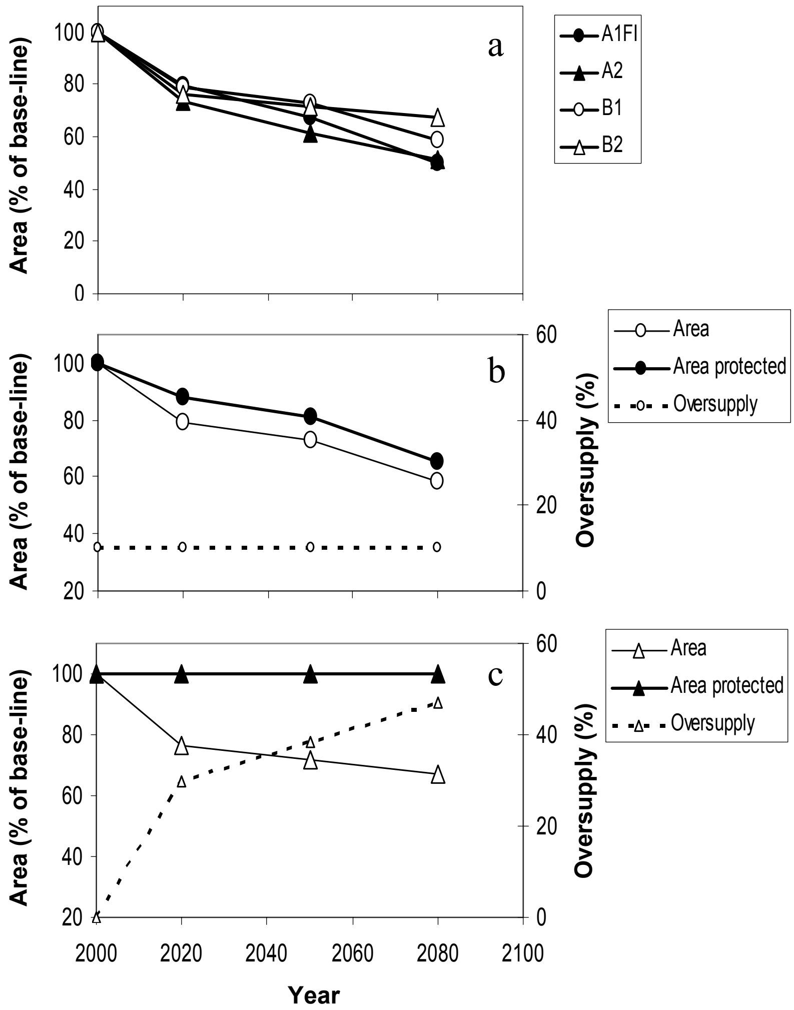


Figure 3.6 Estimated changes in agricultural land use of crops for different SRES scenarios compared to the base-line year 2000 assuming a) no oversupply, b) 10% oversupply (B1 scenario) and c) oversupply is allowed and land use changes were prohibited (B2 scenario)

systems remains difficult, which points to the need for adequate methods and tools. In addition, a debate among stakeholders of agriculture about the advantages and disadvantages of possible options for future development in productivity and land use, is required. The developed approach provides a helpful means of communicating relationships that are important in this respect.

SUMMARISING COMMENTS

We have used a relatively simple approach to assess impacts of changes in productivity as determined by climate change, increasing CO_2 concentration and technology development on future agricultural land use. Our results suggest that future land use changes can be substantial depending on the productivity of crops. Estimated decreases in agricultural land use were particularly high for the economic scenarios. Technology development was the most important driver of productivity and land use change. Effects of climate change and raising CO_2 concentration were comparably small at the European level, but might be more important for regions with marginal production conditions and a high sensitivity to climate change (e.g. southern and northern Europe). The socio-economic and environmental implications of the developed land use change scenarios remain unclear. Adequate tools and methodologies will be required to gain better understanding of the multi-dimensional implications of crop productivity and land use changes. This will provide valuable information to support the transformation of agriculture in an environmentally effective, economically viable and socially acceptable manner. Based on the present approach, important drivers and relationships that will determine future agricultural land use could be identified.

ACKNOWLEDGEMENTS

This work was funded by the Energy, Environment and Sustainable Development Programme of the European Commission via the project ATEAM (Advanced Terrestrial Ecosystem Analysis and Modelling, No. EVK2-2000-00075).

REFERENCES

Amthor, J.S. (2001) Effects of atmospheric CO2 concentration on wheat yield: review of results from experiments using various approaches to control CO2 concentration. *Field Crops Research*, Vol. 73 (1), pp. 1-34.

Amthor, J.S. and R.S. Loomis (1996) Integrating knowledge of crop responses to elevated CO_2 and temperature with mechanistic simulation models: model components and research needs. In: G.W. Koch and H.A. Mooney (Eds) *Carbon Dioxide and Terrestrial Ecosystems*. San Diego, USA, Academic Press, pp. 317-345.

Austin, R.B. (1999) Yield of wheat in the United Kingdom: Recent advances and prospects. *Crop Science*, Vol. 39 (6), pp. 1604-1610.

Bender, J., U. Hertstein and C.R. Black (1999) Growth and yield responses of spring wheat to increasing carbon dioxide, ozone and physiological stresses: a statistical analysis of ‘ESPACE-wheat’ results. *European Journal of Agronomy*, Vol. 10 (3-4), pp. 185-195.

Boote, K.J., N.B. Pickering, and L.H. Allen, Jr. (1997) Plant modeling: advances and gaps in our capability to predict future crop growth and yield in response to global climate change. In: L.H. Allen, Jr. et al. (Eds). Madison; USA, American Society of Agronomy, pp. 179-228.

Borlaug, N.E. (2000) Ending world hunger. the promise of biotechnology and the threat of antiscience zealotry. *Plant Physiology,* Vol. 124 (2), pp. 487-490.

Calderini, D.F. and G.A. Slafer (1998) Changes in yield and yield stability in wheat during the 20th century. *Field Crops Research*, Vol. 57 (3), pp. 335-347.

Cassman, K.G. (1999) Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. *PNAS*, Vol. 96 (11), pp. 5952-5959.

Downing, T.E., P.A. Harrison R.E. Butterfield and K.G. Lonsdale (2000) *Climate Change, Climatic Variability and Agriculture in Europe: An Integrated Assessment*. Environmental Change Unit, University of Oxford, Oxford.

Dyson, T. (1999) World food trends and prospects to 2025. *PNAS*, Vol. 96 (11), pp. 5929-5936.

Eurostat (2000) *Regio Database: User's Guide*. Commission des Communautés Européennes, Eurostat, Luxembourg.

Evans, L.T. (1997) Adapting and improving crops: the endless task. *Philosophical Transactions Royal Society London: Biological Sciences*, Vol. 352 (1356), pp. 901-906.

Evans, L.T. and R.A. Fischer (1999) Yield potential: its definition, measurement and significance. *Crop Science*, Vol. 39 (6), pp. 1544-1551.

Ewert, F. (2004) Modelling plant responses to elevated CO_2: how important is leaf area index? *Annals of Botany*, Vol. 93 (6), pp. 619-627.

Ewert, F., D. Rodriguez, P. Jamieson, M.A. Semenov, R.A.C. Mitchell, J. Goudriaan, J.R. Porter, B.A. Kimball, P.J. Pinter, Jr., R. Manderscheid, H.J. Weigel, A. Fangmeier, E. Fereres and F. Villalobos (2002) Effects of elevated CO_2 and drought on wheat: testing crop simulation models for different experimental and climatic conditions. *Agriculture, Ecosystems and Environment*, Vol. 93 (1-3), pp. 249-266.

Ewert, F., M.D.A. Rounsevell, I. Reginster, M. Metzger and R. Leemans (2005) Future scenarios of agricultural land use in Europe. II: Estimating changes in productivity. *Agriculture, Ecosystems & Environment,* Vol. 107 (2-3), pp. 101-116.

FAO (2003) Food and Agriculture Organization. Internet database: http://www.fao.org, Food and Agriculture Organization, Rome.

Fischer, G., H. van Velthuizen, M. Shah and F. Nachtergaele (2002) Global Agro-ecological Assessment for Agriculture in the 21st Century: Methodology and Results. International Institute for Applied Systems Analysis, Food and Agriculture Organization of the United Nations.

Goudriaan, J. and J.C. Zadoks (1995) Global climate change: modelling the potential response of agro-ecosystems with special reference to crop protection. *Environmental Pollution*, Vol. 87 (2), pp. 215-224.

Guo, L.B. and R.M. Gifford (2002) Soil carbon stocks and land use change: a meta analysis. *Global Change Biology*, Vol. 8 (4), pp. 345-360.

IMAGE-team (2001) The IMAGE 2.2 implementation of the SRES scenarios: A comprehensive analysis of emissions, climate change and impacts in the 21st century. National Institute of Public Health and Environment (RIVM), Bilthoven.

Jones, J.W., J.W. Hansen, F.S. Royce and C.D. Messina (2000) Potential benefits of climate forecasting to agriculture. *Agriculture, Ecosystems & Environment*, Vol. 82 (1-3), pp. 169-184.

Kimball, B.A., K. Kobayashi and M. Bindi (2002) Responses of agricultural crops to free-air CO_2 enrichment. *Advances in Agronomy*, Vol. 77, pp. 293-368.

Lambin, E.F., M.D.A. Rounsevell and H.J. Geist (2000)Are agricultural land-use models able to predict changes in land-use intensity? *Agriculture, Ecosystems & Environment*, Vol. 82 (1-3), pp. 321-331.

Loomis, R.S. and J.S. Amthor (1999)Yield potential, plant assimilatory capacity, and metabolic efficiencies. *Crop Science,* Vol. 39 (6), pp. 1584-1596.

Metzger, M.J., R.G.H. Bunce, R.H.G. Jongman, C.A. Mücher and J.W. Watkins (in press) A climatic stratifaction of the environment in Europe. *Global Ecology and Biogeography*, in press.

Mitchell, T.D., T.R. Carter, P.D. Jones, M. Hulme and M. New (2004) A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901-2000) and 16 scenarios (2001-2100). Tijndall Centre for Climate Change Research, Working Paper 55.

Nakićenović, N., J. Alcamo, G. Davis, B. de Vries, J. Fenhann, and others (2000) *Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge.

Oerke, E.C. and H.W. Dehne (1997) Global crop production and the efficacy of crop protection-current situation and future trends. *European Journal of Plant Pathology*, Vol. 103 (3), pp. 203-215.

Reilly, J., F. Tubiello, B. McCarl, D. Abler, R. Darwin, K. Fuglie, S. Hollinger, C. Izaurralde, S. Jagtap, J. Jones, L. Mearns, D. Ojima, E. Paul, K. Paustian, S. Riha, N. Rosenberg and C. Rosenzweig (2003) U.S. agriculture and climate change: new results. *Climatic Change*, Vol. 57 (1-2), pp. 43-69.

Reynolds, M.P., S. Rajaram and K.D. Sayre (1999) Physiological and genetic changes of irrigated wheat in the post-green revolution period and approaches for meeting projected global demand. *Crop Science*, Vol. 39 (6), pp. 1611-1621.

Rosenzweig, C. and M.L. Parry (1994) Potential impact of climate change on world food supply. *Nature*, Vol. 367, pp. 133-138.

Rounsevell, M.D.A., J.E. Annetts, E. Audsley, T. Mayr and I. Reginster (2003) Modelling the spatial distribution of agricultural land use at the regional scale. *Agriculture, Ecosystems & Environment*, Vol. 95 (2-3 SU), pp. 465-479.

Rounsevell, M.D.A., I. Reginster , M.B. Araújo, T.R. Carter, N. Dendoncker, F. Ewert, J.I. House, S. Kankaanpää, R. Leemans, M.J. Metzger, C. Schmit, P. Smith and G. Tuck (in review) A coherent set of future land use change scenarios for Europe. *Agriculture, Ecosystems & Environment.*

Rounsevell, M.D.A., F. Ewert, I. Reginster, R. Leemans and T. Carter (2005) Future scenarios of agricultural land use in Europe. *Agriculture, Ecosystems & Environment,* Vol. 107 (2-3), pp. 117-135.

Tubiello, F.N. and F. Ewert (2002) Simulating the effects of elevated CO2 on crops: approaches and applications for climate change.*European Journal of Agronomy*, Vol. 18 (1-2), pp. 57-74.

van Ittersum, M.K., P.A. Leffelaar, H. van Keulen, M.J. Kropf, L. Bastiaans and J. Goudriaan (2003) On approaches and applications of the Wageningen crop models. *European Journal of Agronomy*. Vol. 18 (3-4), pp. 201-234.

van Oijen, M. and F. Ewert (1999) The effects of climatic variation in Europe on the yield response of spring wheat cv. Minaret to elevated CO2 and O3: an analysis of open-top chamber experiments by means of two crop growth simulation models. *European Journal of Agronomy*, Vol. 10 (3-4), pp. 249-264.

World Bank (2002) World Development Indicators 2002, http://www. worldbank. org/search.htm.

Agricultural Transitions at Dryland and Tropical Forest Margins: Actors, Scales and Trade-offs

4

Helmut Geist, Eric Lambin, Cheryl Palm and Thomas Tomich

INTRODUCTION

Concerns about land-use/cover change emerged in the research agenda on global environmental change several decades ago with the realization that land surface processes influence climate. In the mid-1970s, it was recognised that land-cover change, especially in drylands, modifies surface albedo and thus surface-atmosphere energy exchanges, with an impact on regional climate. In the early 1980s, humid forest zones were highlighted as sources and sinks of carbon, which underscored the impact of land-use/cover change on the global climate via the carbon cycle (Lambin et al., 2003; Palm et al., 2005). Be it dryland or humid forest ecosystems, they constitute global agricultural frontier zones which hold a large, if not the last, source of potentially cultivable land for agricultural use. Given the large variety of ecosystems and land use histories involved in these zones, universal assessments and policies to guide the design of future land use patterns must necessarily fail. To achieve sustainable agricultural management, any policy intervention has to be regionally specific, and sometimes even adapted to local particularities of 'real world' pathways of land change, involving trade-offs between economic gains and conservation (Tomich et al., 2005). Therefore, understanding the main driving forces, key actors and processes of agricultural change and land use patterns is vital to improve assessments of the long-term change occurring in rural lands at the global agricultural frontiers. Two meta-analytical databases are used in this chapter to explore the variety of key actors influencing land use transitions at the forest (Geist and Lambin, 2001; 2002) and dryland margins (Geist and Lambin, 2004; Geist, 2005). In addition, a matrix, developed through the Alternatives to Slash-and-Burn (ASB) Programme, is put forward as a method for assessing the trade-offs and to draw implications for land use policies (Tomich et al., 2005; Palm et al., 2005).

In the first part of the chapter, results of a region-by-region analysis of causative factors of land-use/cover change are presented, disaggregated by broad geographical regions such as continents, or subsets of continents. By doing so, we

F. Brouwer and B.A. McCarl (eds.), Agriculture and Climate Beyond 2015, 53-73

adhere to the notion that no ‘one-size-fits-all’ approach is adequate to explain the complex phenomenon of agricultural trajectories in tropical forest and dryland regions. This is due to the high variability in time and space exhibited by biophysical environments, socio-economic activities, and cultural contexts that are associated with land use change. In fact, the pathways of deforestation and desertification are nearly as diverse as the histories, cultures, and ecosystems of the regions themselves. Nonetheless, there is no irreducible complexity inherent to it, and a few dominant ‘stories‘ can be identified which explain the succession of causes and events leading to land change, despite of their substantial variation by regions (Lambin and Geist, 2003a).

Understanding the pathways of land change is crucial for designing appropriate policy interventions. To achieve sustainable management of humid forest and dryland ecosystems, interventions need to address the region-specific causes of land-use/cover change. Proximate causes generally operate at the local level (of individual farms, households, or communities), while underlying causes may originate from the regional (districts, provinces, or country) or even global levels, with complex interplays between different levels of organization. Underlying causes are often exogenous to the local communities managing land and are thus often uncontrollable by these communities. Only some local-scale factors are endogenous to decision makers (Lambin and Geist, 2003b). Thus the second part of this chapter considers variable interactions and important interacting hierarchical scales.

If land use patterns at the last remaining agricultural frontiers are to be sustainable, i.e., balancing the legitimate interests of development and equally legitimate global concerns over the environmental consequences of land cover change, trade-offs need to be considered between what is to be sustained, and what is to be developed. From the viewpoint of managing agricultural transitions, there must be an incentive structure introduced for various actors operating at different scales influencing negotiations about outcomes that suit the various interests involved. The ASB matrix (Tomich et al., 1998, 2005; Palm et al., 2005) provides an approach to assess the degree of trade-offs (and complementarities) global environmental objectives served by rain forest conservation and national and local objectives, often involving conversion of natural forest to other uses and to identify innovative policies and institutions needed to reconcile ecosystems and human well-being at the local level. The ASB matrix is also a powerful tool for looking at specific trade-offs between provisioning and regulating services in various tropical ecosystems under human uses, i.e., losses of certain ecosystem functions of global importance such as carbon stocks, affecting central functions of the climate system, *versus* provision of food, fiber and feed services for local livelihoods as well as national economic development. The matrix also provides a basis for policymakers and stakeholders to assess trade-offs across land use systems regarding development options and ecosystem services. Principally, the ASB matrix could be applied to other ecoregions and land use systems outside the humid tropics. Therefore, the final part of the chapter presents examples of indicators of environmental and developmental objectives for a selection of ASB benchmark sites.

CAUSES OF LAND-USE/COVER CHANGE: ACTIVITIES AND ACTORS

Using a configurational comparative design for meta-analytical research (Ragin, 1989; Matarazzo and Nijkamp, 1997), in this chapter a generalized understanding is gained of activities and actors associated with land-use/cover change, while preserving the descriptive richness of case studies. We analyzed the frequency of occurrence of proximate causes and underlying driving forces, including their cross-scalar interactions and feedbacks upon land use, as reported in 152 subnational cases deforestation (Geist and Lambin, 2002) and in 132 subnational cases of desertification (Geist and Lambin, 2004). The cases were taken from articles published in journals covered by the citation index of the Institute for Scientific Information (www.isiwebofknowledge.com). Four broad clusters of proximate causes were identified, with each category of proximate causation further subdivided into more specific activities and actors. Underlying driving forces of deforestation and desertification were categorized into five and six broad clusters, respectively, with further subdivivions into specific factors. The complete lists of case studies and details of the method are given in Geist and Lambin (2001) and Geist (2004), including a discussion of the limitations of a meta-analysis. Tables 4.1 and 4.2 below provide a breakdown of proximate causes and underlying driving forces by broad geographical regions (or continents). As for drylands, European, Australian and North American cases were not considered here (but see Geist and Lambin, 2004). The tables show the absolute number as well as the relative percentage of the frequency of causative variables reported in the case studies. They provide a detailed breakdown of the broad clusters by specific factors, with factors occurring in less than 25% of the cases not reported. The relative percentages of the frequency of occurrence of specific factors do not add up to 100% as multiple counts exist because of causal factor synergies. Robust causes, or generic land uses, are those which show low geographical variation in their frequency of occurrence, i.e., they have more or less equal and high frequencies.

Proximate causes

At the proximate level of causation, both tropical deforestation and desertification are best explained by multiple factors and various actors. Dominating the broad clusters of proximate causes of deforestation is the combination of agricultural expansion, wood extraction, and infrastructure extension, with clear regional variations. Dominating the broad clusters in desertification is the combination of agricultural activities, increased aridity, infrastructure extension, and wood extraction, or related extractional activities, again with regional variations. In both land change classes, a limited and recurrent set of variables is involved. However, different from humid forest zones, more coupled biophysical and socio-economic factors can be found in drylands. There, agricultural activities and increased aridity form a robust combination with low geographical variation – see Table 4.1.

Table 4.1 Frequency of specific proximate factors in tropical deforestation and desertification

	Latin America				Africa				Asia			
	Humid forests		Drylands		Humid forests		Drylands		Humid forests		Drylands	
	abs	rel	abs	rel	abs	rel	abs	rel	abs	rel	abs	rel
Agricultural activities	**75**	**96**	**14**	**100**	**16**	**84**	**36**	**86**	**146**	**96**	**51**	**100**
Livestock production												
… extensive grazing[a]	64	82	7	50	3	16	26	62	3	6	23	45
… nomadic grazing	0	-	0	-	0	-	10	24	0	-	28	55
Crop production												
… shifting cultivation	31	40	0	-	8	42	0	-	24	44	0	-
… sedentary cultivation[b]	39	50	2	14	10	53	17	40	24	44	24	47
Increased aridity[c]	**5**	**6**	**9**	**64**	**4**	**21**	**39**	**93**	**9**	**16**	**42**	**82**
Infrastructure extension	**65**	**83**	**6**	**43**	**9**	**47**	**20**	**48**	**36**	**66**	**36**	**71**
… (Road) transport	62	80	6	41	9	47	0	-	26	47	12	24
… settlements/markets	26	33	0	-	3	16	14	31	12	22	26	52
… watering technology[d]	0	-	5	36	0	-	17	40	0		24	48
Wood extraction	**40**	**51**	**6**	**43**	**13**	**68**	**17**	**41**	**49**	**89**	**31**	**61**
… commercial (for trade)	31	40	0	-	5	26	0	-	43	78	0	-
… fuelwood (domestic)[e]	14	18	6	43	10	53	17	41	18	33	29	57

[a] Cattle ranching only in deforestation cases; [b] Annual cropping only in dryland cases; [c] Mostly drought-induced forest fires in deforestation cases; [d] Hydrotechnical installations (boreholes, dams, etc.) for irrigation agriculture; [e] Including domestic polewood uses in desertification cases.

Agricultural activities are, by far, the leading land uses associated with deforestation (96% of all cases) and desertification (95%) (Table 4.1). At tropical forest margins, they include permanent cultivation (or sedentary cropping), cattle ranching, and shifting cultivation as robust or generic land uses. Further subdivisions reveal striking differences. In sedentary cropping, the expansion of food-crop cultivation for subsistence is three times more frequently reported than the expansion of commercial farming (less than 25% for all regions). In shifting cultivation, cases which are driven by slash-and-burn agriculture are more widespread in upland and foothill zones of Asia than elsewhere, whereas the activities of colonizing migrant settlers are mainly limited to lowland areas, especially in Latin America. Pasture creation for cattle ranching is a striking cause of forest conversion reported almost exclusively for lowlands in mainland South America. In drylands, agricultural activities include extensive grazing, nomadic pastoralism and annual cropping. Only extensive grazing, carried out as sedentary or transhumant livestock husbandry, is a generic land use. Further subdivisions again reveal striking differences. The activities of pastoral nomadic groups are two times less frequently reported than extensive grazing activities by transhumant pastoralists, mainly featuring African and Asian cases. Annual rainfed cropping has low importance in Latin America, and shifting cultivation does not matter at all. Perennial cropping and irrigation (including wetland) farming are four times less frequently reported than annual rainfed cropping (15% for all regions). Livestock activities slightly outweigh crop production, but both activities are intricately interlinked in most of the cases. This means that cropland expansion onto areas previously used for pastoral activities triggers land degradation through overstocking on the remaining rangeland. In addition, expansion of cropping leads to soil mining at dryland sites which are generally not suitable for permanent agriculture, in particular.

Increased aridity is a widespread factor of desertification (86%), but far less important at the humid forest margins (12%), where some drought-induced forest fires are important only in Amazonia or Indonesia.

Among all forms of infrastructure expansion (deforestation: 75%, desertification: 55%), road construction as a proximate cause of deforestation is by far the most frequently reported, mainly in Latin America, and partly in combination with human settlement extension. Differently, road extension plays a minor role in dryland regions where the spread of watering technology in the form of irrigation infrastructure for both cropping and livestock raising is most dominant. Mainly in Africa and Asia, the build-up of irrigation infrastructure (reservoirs, dams, canals, boreholes, pump stations, etc.) is related to expanding human settlements and related market or service infrastructures.

Wood extraction or related extractional activities are frequent causes of land-cover change (deforestation: 67%, desertification: 45%). In humid forest areas, commercial wood extraction is widespread in both mainland and insular Asia, whereas in Africa the harvesting of fuelwood and poles by individuals for domestic uses dominates cases of deforestation associated with wood extraction. In drylands, wood extraction is less important, except for cases of fuelwood extraction.

Among the detailed categories of proximate causes for all humid forest regions, the extension of overland transport infrastructure, followed by commercial wood extraction, permanent cultivation, and cattle ranching, are the leading proximate causes of deforestation. Contrary to widely held views, shifting cultivation is not the primary cause of deforestation. Among the detailed categories of proximate causes for all dryland regions, extensive livestock production, annual rainfed cropping, and the extension of irrigation infrastructure, always in combination with increased aridity, are the leading proximate causes of dryland degradation. Also contrary to widely held views, nomadic pastoralism is not the chief agent of degradation, and overstocking is not the sole cause of desertification.

Underlying driving forces

At the underlying level, tropical deforestation and desertification are explained by regionally distinct combinations of multiple – and in the case of drylands, coupled social and biophysical – factors and drivers acting synergistically. Statistically, we find that deforestation of lands at the forest margin is driven by the full interplay of economic, technological, cultural, and demographic variables in more than one third of the cases. More than half of the desertification cases are driven by the interplay of four to six variables, including climatic factors. These variables exhibit a limited and recurrent set of drivers, though. In deforestation, public and individual decisions were found to largely respond to changing economic opportunities and/or policies. Such effects were mediated by local scale and institutional factors, with some of these combinations being robust geographically (such as the development of market economies and the expansion of permanently cropped land for food). In desertification, a recurrent, generic broad factor combination – though differing widely in the specific factors involved – reveals the importance of climatic factors (leading to reduced rainfall), agricultural growth policies, newly introduced land use technologies, and land tenure arrangements which are no longer suited to dryland ecosystem management – see Table 4.2.

Economic factors are prominent underlying forces behind tropical deforestation (in 81% of the cases), less so in desertification (60%), except in Central Asia. In deforestation, commercialisation and the growth of mainly timber markets as well as market failures are frequently found to drive forest removal. Special economic variables such as low domestic costs (for land, labour, fuel, or timber), product price increases (mostly for cash crops), and the ecological footprint of remote urban-industrial centers underpin about one third of the cases, whereas the requirement to generate foreign exchange earnings enters in a quarter of the cases. With few exceptions, factors related to economic development through a growing cash economy constitute robust underlying driving forces. Poverty-driven forest conversion, relating to the marginalization of farmers who have lost their resource entitlements, mostly happens in conjunction with capital-driven deforestation, relating to public or private investments to develop the frontier for political, economic, or social reasons. For dryland alterations, market growth and commercialisation are important, mainly export-oriented market production, industrialisation, and urbanisation, but less so

Table 4.2 Frequency of specific underlying driving forces in tropical deforestation and desertification

	Latin America				Africa				Asia			
	Humid forests		Drylands		Humid forests		Drylands		Humid forests		Drylands	
	abs	rel	abs	rel	abs	rel	abs	rel	abs	rel	abs	rel
Economic factors	**68**	**87**	**9**	**64**	**16**	**84**	**15**	**36**	**39**	**71**	**45**	**88**
Market growth[a]	58	74	9	64	15	79	8	19	30	55	37	74
Urban-industrial growth	30	39	0	-	5	26	0	-	23	42	8	16
Market failures[b]	24	31	1	7	6	32	2	5	22	40	2	4
Foreign exchange[c]	17	22	0	-	5	26	0	-	16	29	0	-
Special variables[d]	34	44	1	7	5	26	2	5	9	16	5	10
Institutional/policy factors	**57**	**73**	**12**	**86**	**9**	**47**	**20**	**48**	**53**	**96**	**45**	**88**
Formal (growth) policies[e]	52	67	0	-	7	37	17	2	46	84	27	53
Property rights issues[f]	29	37	6	43	5	26	11	27	33	60	21	42
Policy failures[g]	32	41	0	-	1	5	0	-	31	56	0	-
Technological factors	**44**	**56**	**7**	**50**	**14**	**74**	**20**	**48**	**49**	**89**	**42**	**82**
Agrotechnical change[h]	34	44	7	50	8	42	12	28	28	51	35	70
Deficient applications[i]	22	28	3	21	8	42	17	41	39	71	31	60
Cultural/sociopolitical factors	**48**	**62**	**6**	**43**	**7**	**37**	**12**	**29**	**46**	**84**	**26**	**51**
Public attitudes, values[j]	46	59	5	36	5	26	10	24	45	82	30	59
Individual behaviour[k]	36	46	6	43	6	32	10	24	38	69	18	35
Demographic factors	**41**	**53**	**2**	**14**	**18**	**95**	**21**	**50**	**34**	**62**	**43**	**84**
In-migration	37	47	0	-	9	47	2	5	12	22	12	24
Growing density	20	26	0	-	6	32	12	29	12	22	3	6
Unspecified increase in size	17	22	2	14	15	79	3	7	28	51	21	41
Biophysical factors	**17**	**22**	**9**	**64**	**6**	**32**	**39**	**93**	**11**	**20**	**42**	**82**
Climatic factors[l]	5	6	3	21	4	21	21	50	9	16	21	42

Table 4.2 (continued)

[a)] In deforestation, export-oriented commercialisation of wood (timber products), agricultural products, and minerals; in desertification, of cotton, beef, rice, and oil/gas (including urban-industrial growth). [b)] Including insufficient mechanisms to properly internalise externalities such as harmful effects on the environment; in drylands, poor distribution systems, excessive subsidisation, and unjust credit systems. [c)] Generation of foreign exchange earnings. [d)] Low cost conditions (production factors) and price change (increases as well as decreases). [e)] In deforestation, related to land, credits/subsidies, and economic growth, especially agricultural and infrastructure development policies; in desertification, growth- and reform-oriented policies such as agrarian reforms, land (re)distribution, and rural development projects, including market liberalization policies. [f)] In deforestation, land races, land tenure insecurity, quasi open access conditions, maladjusted customary rights, titling/legalization, and low empowerment of local user groups; in desertification, common property regulations, newly introduced land tenure regimes, and land zoning measures. [g)] Corruption, lawlessness, clientelism, and the operation of vested interest and ‘growth coalitions’, besides mismanagement or poor performance. [h)] In deforestation, intensification as well as extensification measures, changes in market versus subsistence orientation, in intensity of labour versus capital, and in holding size; in desertification, new innovative developments and introductions mainly, i.e., new land and water management technology (new crop varieties, hydrotechnical installations, etc.), new transport and earth movement technology, and improvements in research and veterinary services. [i)] In deforestation, poor logging performance, wastage in timber processing, and poor domestic or industrial furnace performance; in desertification, poor efficiency of watering infrastructure, mainly. [j)] Including beliefs; dominant frontier mentalities, prevailing attitudes of nation-building, modernization and development (goal of catching up in terms of living standard, self-sufficiency in food, etc.), and low (public) morale, including violent conflicts about land. [k)] Including household behaviour; mainly, situation-specific behaviour (e.g., rent-seeking) and unconcern by individuals (e.g., about natural resources as reflected in increasing levels of demand, aspiration, and consumption, commonly associated with increased income). [l)] In causal synergy or concomitant occurrence with socio-economic drivers in drylands, and droughts but also high humidity (floods) in humid forest zones.

in Africa. Farmers usually respond to market signals due to external demands for mainly cotton, beef, and grain, with increasingly more land put under production. Market failures, special economic variables, and foreign exchange earnings matter less or are not found to have an influence. Like Latin American deforestation, Asian dryland changes are mainly influenced by economic factors such as market growth, chiefly. In contrast, farmers in Latin American drylands, namely Patagonia, respond to an unfavourable economic situation such as declining prices in the export-oriented sheep sector (leading to indebtedness of their economically no longer viable farms) by overusing rare natural resources.

Institutional or policy factors are also found to drive many cases of deforestation (78%) and desertification (65%). In humid forest cases, these factors mainly include pro-deforestation measures such as policies on land use and economic development as related to colonization, transportation, or subsidies for land-based activities. Land tenure arrangements and policy failures (such as corruption or mismanagement in the forestry sector) are also important drivers. Property rights issues, though much discussed as a general cause of deforestation, are mainly a characteristic in only Asian cases. In addition, they tend to have ambiguous effects upon forest-to-agriculture conversion, i.e., insecure ownership, quasi-open access conditions, and maladjusted customary rights, on the one hand, as well as the legalization of land titles. On the other hand, all are reported to influence deforestation in a similar manner. At dryland margins, the weight of formal, mainly agricultural growth policies (e.g., land distribution, agrarian reforms, propagation of agricultural intensification) is not generally important, excepting in Asia. The same holds true for related policy failures. Property right issues often relate to traditional land tenure which turns out to be badly adjusted to changing economic and demographic conditions. Examples are the equal sharing of land, splintering of herds, and traditional succession law, reducing flexibility in management and increasing the pressure upon constant land units. The introduction of new land tenure arrangements, be it private (individual) or state (collective) management, is another important factor associated with degradation of drylands.

Technological factors are found important in many cases of deforestation (70%) and desertification (69%). Important processes for both land change classes are agro-technical change through improved technologies, mainly fostering agricultural intensification, and poor technological applications, largely in the wood sector (forest zones) leading to wasteful logging practices, and in the irrigation sector (drylands) leading to excessive use of scarce water and, hereby, reinforcing salinization, for example.

Cultural or sociopolitical factors are found important in deforestation cases (66%) and somewhat less frequently in desertification cases (42%), more or less operating in the same direction. They are mainly associated with economic and policy factors in the form of public (state, government) attitudes of indfference towards forest or dryland environments. In Asia and Latin America, land use change often is found to be strongly driven by state motivations in the form of frontier mentality. Linked to it are beliefs or perceptions such as that water or forests constitute ‘free goods’, and that indigenous forest use or traditional nomadic grazing are ‘inefficient’ land uses. These factors also shape rent-seeking behaviour and a lack of concern on behalf of individual agents toward causing deforestation and desertification.

Demographic factors are important driving forces, both in deforestation (61%) and desertification cases (55%). In deforestation, only in-migration of colonizing settlers into sparsely populated forest areas associated with rising population densities there, shows a notable influence on forest-to-agriculture conversion. Contrary to a common misconception, population increase due to high fertility rates is not a primary driver of deforestation at the local scale and is infrequently found over a time period of a few decades (8% of the cases only). In desertification, African and especially Asian cases are found to be mostly related to human population dynamics. Most widespread are situations in which population growth, overpopulation, or population pressure stemming from distant urban populations, triggers out-migration of cultivators and/or herders from these zones onto marginal dryland sites. Consequently, the sometimes rapid increases in the size of local human populations are often linked to in-migration of cultivators onto rangelands or large-scale irrigation schemes, or of herders onto previously unused, marginal sites, with the consequence of rising population densities there. Similarly, population increase due to high fertility rates is not found to be a primary driver of short run desertification at a local scale, and is only infrequently found in the longer run over a few decades (3% of the cases only). However, there are some uncertainties with regard to the impact of specific demographic variables, since they are blurred into notions such as ‘population pressure’.

Biophysical factors are less important in deforestation (entering less than 20% of the cases), but of overriding relevance in desertification (86%). In humid forest zones, biophysical factors include pre-disposing environmental factors such as soil quality or topography, which sometimes attain driver or shaping factor qualities, and triggering events such as droughts leading to increased fire intensity causing deforestation. In drylands, mainly climatic factors trigger transformations, principally decreases in rainfall. They operate either through indirect impacts of rainfall oscillations or by directly impacting upon land cover in the form of prolonged droughts. Although many cases fail to explicitly describe climatic impact (apart from its mention), the most widespread mode of causation are reported to be climatic conditions operating in concomitant occurrence or synergistically with other, socio-economic driving forces such as agro-technological change.

SCALES AND INTERACTION OF VARIABLES

Not only are multiple causal factors at work, but their interactions across several scales also lead to deforestation and desertification, which is why it is important to understand cross-scale systems dynamics. The analysis reveals that regardless of the type of land-use/cover change, three to five underlying causes are driving two to three proximate causes. The analysis also reveals that the local-global interplay of factors are the principal drivers for tropical deforestation, while local-national interactions are prevalent in desertification.

Tropical forest margins

At tropical forest margins, a frequent pattern of causal interaction stems from the necessity for road construction that is associated with wood extraction or agricultural expansion. Such expansions are mostly driven by policy and institutional factors (e.g., infrastructure projects of international development agencies), but also involve economic and cultural factors (e.g., frontier mentality, state consolidation). Pro-deforestation state policies aimed at land use and economic development (e.g., credits, low taxation, incentives for cash cropping, legal land titling) lead to the expansion of commercial crops and pastures in combination with an extension of the road network. Another pattern, seen mostly in Africa, comes from insecure ownership related to uncertainties of land tenure, which drives the shift from communal to private property and underlies cases in which traditional shifting cultivation is a direct cause of deforestation. Involvement of policies facilitating the establishment of state agricultural and forestry plantations with deforestation is a special feature of both insular and continental Asia. Agricultural colonization in Latin America is often associated with land policies which are directed towards the transfer of public forest land to private holdings and towards state regulations in favour of large individual land holdings (similar factors also drive wood extraction). In-migration and, to a much lesser degree, natural population growth drive the expansion of cropped land and pasture in many cases in Africa and Latin America, concomitantly with other underlying drivers. The extension of permanently cropped land for subsistence farming to meet the needs of a growing population is reported particularly for African cases. In contrast, expansion of pastures emerges exclusively from mainland South America, in association with processes of both planned colonization and spontaneous settlement by colonist agriculturalists.

Not all of these factors are important at the same level of hierarchical organisation, and individual scales are far less important than scalar interplays – see Table 4.3. Mostly demographic factors, and, to a lesser extent, technological and cultural factors are relevant at the individual local scale. National and global scales are not important if considered in isolation, excepting the importance of a few economic factors. Most cases of deforestation are best explained by the interplay of causative factors at local to global scales in 74 to 94% of the cases (Lambin and Geist, 2003b).

Dryland margins

At dryland margins, a frequent, contemporary pattern of causal interactions stems from the necessity for water-related infrastructure. This need is associated with the expansion of irrigated croplands and pastures, which is mostly driven by policy, economic, and technological factors. Typically, newly introduced irrigation infrastructures induce accelerated in-migration of farm workers into formerly dryland regions, accompanied by commercial-industrial developments and the growth of settlements and service economies. Commonly, road extension and availability of earthmoving equipment for dam construction pave the way for the subsequent extension of grazing, irrigation, and (semi)urban land uses. In the developing world, underlying these factors are policies aimed at consolidating territorial control over remote, marginal areas, and policies destined for attaining self-sufficiency in food and clothing, with rice and cotton as key irrigation products. Irrigation scheme examples stem from arid river and lake basin ecosystems worldwide, but notably from Central Asia. There, the establishment during the second half of the 20th century of large hydrotechnical installations with mainly low water use efficiency disrupted fragile hydrographic ecosystems which have sustained flexible nomadic grazing or small-scale settled (oasis) farming for centuries. Paramount examples of expanding pastures and livestock industries (cattle and sheep, mainly), based on artificial watering points and roads, arise in all major rangeland zones in the world. Another pattern, seen mostly in Africa and northern China, comes from growth-oriented development policies that favour cropping at the expense of herding. Often, the changing opportunities created by markets and policies involve the introduction of new, mostly private land tenure in conjunction with the zoning of land. The mix of agricultural commercialisation and outside policy intervention sends powerful market signals to local farmers. Customary land management institutions, such as inherited succession law or flexible common property regulations, conflict with the new requirements. In herding, low investments in labour occur and livestock mobility gets reduced, thus triggering overstocking on the remaining pasture land. In cropping, inappropriate or 'unwise' land management practises are carried out such as the undue extension of cereals onto marginal lands, despite oscillating rainfall and poor land suitability. Uncertainties of land tenure may arise, often in conjunction with violent conflicts about land, thus reducing the adaptive capacity of herding as well as farming populations. In Asia and Africa, rapidly growing local population densities add to the interaction of underlying driving forces, stimulating the harvest of wood from natural forests, woodlands and shrubs for construction and fuel.

Like in tropical deforestation, not all causative factors are important at all scales – see Table 4.4. Individual scales are less important, explaining between 4 and 29% of the cases only, while multiple scales dominate in 29 to 80% of the cases. The cross-scalar interactions of underlying factors are significant, but differ from the dynamics found in the deforestation cases. In contrast to humid forest zones where global-local interplays dominate (e.g., signals coming from the world timber or soybean markets to local farmers), national-local interplays are most important at dryland margins (e.g., state frontier policies driving the increasing profitability of hitherto marginal drylands) (Geist, 2005; Geist and Lambin, 2004).

Table 4.3 Driving forces of tropical deforestation by scale of influence (in %)

	All factors (range) N=152 cases	Demo-graphic factors (n=93)[a]	Economic factors (n=123)	Techno-logical factors (n=107)	Policy and institution-al factors (n=119)	Cultural or socio-political factors (n=101)
Local	2-88	88	2	23	4	16
National	1-14	1	14	3	2	7
Global	0-1	-	1	-	-	-
Several scales: Global-local interplays	11-94	11	82	74	94	77

[a]6 cases of unspecified population pressure could not be attributed to scales.

Table 4.4 Driving forces of desertification by scale of influence (in %)

	All factors (range) N=132	Demo-graphic factors[a] (n=73)	Econo-mic factors (n=79)	Techno-logical factors (n=91)	Policy and institu-tional factors (n=86)	Cultural or sociopo-litical factors (n=55)	Climatic factors[a] (n=114)
Local	12-29	23	18	29	12	16	-
National	4-20	-	13	-	20	4	-
Global	4-12	-	4	-	6	-	12
Several scales: national-local interplays	29-80	29	66	71	63	80	60

[a]35 demography-driven and 32 climate driven cases could not be attributed to scales.

INTERVENTION POINTS ALONG PATHWAYS: ASSESSING TRADE-OFFS

The exact future of land-use/cover change is often unpredictable, because land use is emergent rather than predetermined. However, transitional thinking applied to place-based research reveals a repertoire of pathways of land change where associated risk factors can be identified, and thus intervention points for actions arise (Lambin et al., 2003; Lambin and Geist, 2003a; Lambin et al., 2001). Technologies, and to a much larger extent, institutional capacities and policies are key instruments to affect the rate and pattern of land-use/cover change. The ASB Programme allocates its location-specific studies in active zones of deforestation such as the Western Amazon, the Congo Basin and Sumatra (Tomich et al., 2005). At ASB sites, current forces often swamp local conservation efforts, i.e., the area of forest cleared by successive waves of migrants, whose arrival is driven by the lack of opportunities elsewhere and facilitated by the building of roads, vastly exceeds the area ‘saved’ by projects. A major weakness of past conservation efforts is that they have routinely limited their activities to technical interventions at the local level while failing to tackle the larger policy and institutional issues that also determine success or failure. A careful identification of the factors at work in a given location will be a prerequisite for getting the mix right while minimizing the cost to local peoples’ livelihood opportunities and other legitimate development objectives. Policy makers need accurate, objective information regarding the private and social costs and benefits of alternative land use systems on which to base their inevitably controversial decisions. To help them weigh up the difficult choices they must make, ASB researchers developed a tool known as the ASB matrix – see Table 4.5 for an example from the forest margin of Sumatra (Tomich et al., 1998; Tomich et al., 2005).

Table 4.5 ASB matrix of trade-offs at the agriculture/forest margin in Sumatra

Land use	Global environment		Agronomic sustainability	National policymakers' concerns		Smallholders: Adoptability by smallholders	Smallholders: Smallholder concerns
	Carbon sequestration (aboveground, time-averaged MT/ha)	Biodiversity (aboveground species per standard plot)	Plot-level production sustainability (overall rating)	Potential profitability at social prices (returns to land (US$/ha)	Employment (average labour input; days/ha/yr)	Production incentives at private prices (returns to labour; US$/day)	Household food security (entitlement paths)
Natural forest	306	120	1	0	0	0	NA
Community-based forest management	120	100	1	5	0.2-0.4	4.77	food + income
Commercial logging	94	90	0.5	1,080	31	0.78	income
Rubber agroforest	66-79	90	0.5	0.7-878	111-150	1.67-2.25	income
Oil palm monoculture	62	25	0.5	114	108	4.74	income
Upland rice / bush fallow rotation	37	45	0.5	-62	15-25	1.47	food
Continuous cassava degrading to Imperata	2	15	0	60	98-104	1.78	food + income

In the ASB matrix, natural forest and the land use systems that replace it are scored against different environmental, socio-economic and institutional criteria reflecting the objectives of different interest groups. To enable results to be compared across sites, the systems specific to each site are grouped according to broad categories, ranging from forests and agroforests to grasslands and pastures. The criteria may be adjusted to specific locations, but the matrix always comprises indicators for:

- two major global environmental concerns: carbon storage and biodiversity;
- agronomic sustainability, assessed according to a range of soil, nutrient, and pest trends;
- policy objectives: employment opportunities and economic growth, with the latter expressed in social prices (i.e., adjusted for trade policy distortions and capital market failures, but not for environmental externalities such as carbon sequestration);
- smallholders' concerns: returns to their labour and land, their workload, food security for their family, and start-up costs of new systems or techniques; and
- policy and institutional barriers to adoption by smallholders, including the availability of credit, and improved technology, and access to and the performance of input and product markets.

As with all the indicators used in the matrix, agronomic sustainability is a plot level indicator. It refers specifically to yield levels over time as a result of continuation of that particular land use. If yields under continued land use would be stable or increasing, then the land use is considered to be agronomically sustainable. If yields would be decreasing, it is considered unsustainable. The reference point is farmer's ability to manage the resources. In the matrix (Table 4.5), '1' indicates no problem, '0.5' indicates most farmers likely can manage the problem, and a '0' indicates that farmers are not able to manage the problem, either because of high costs (it's uneconomic) or lack of technical information. This indicator is based on expert panel assessment of each land use regarding a range of soil characteristics, including trends in nutrients and organic matter over time.

Over the past eight years, ASB researchers have filled in such matrices for representative benchmark sites across the humid tropics. The social, political and economic factors at work at these sites vary greatly, as also does their current resource endowment. The sites range from the densely populated lowlands of the Indonesian island of Sumatra (Table 4.5), through a region of varying population density and access to markets south of Yaoundé in Cameroon, to the remote forests of Acre State in the far west of the Brazilian Amazon, where settlement by small-scale farmers is relatively recent and forest is still plentiful. At each site, ASB researchers have evaluated land use systems both as they are currently practiced and in the alternative forms that could be possible through policy, institutional and technological innovations. A key question addressed was whether the intensification of land use through technological innovation could reduce both poverty and deforestation. Like with Tables 4.1 and 4.2 on the causes of land-use/cover change, it has to be noted that Table 4.5 is a summary matrix, and that the complete matrix covers a lot more information on social and economic issues (Tomich et al., 2001).

The ASB matrix allows researchers, policymakers, environmentalists and others to identify and discuss trade-offs among the various objectives of different interest groups, and/or to discuss ways of promoting land use systems that could provide a better balance among trade-offs without making any group worse off, but that still were not broadly adopted. The studies in Indonesia and Cameroon have revealed the feasibility of a ‘middle path’ of development involving smallholder agroforests and community forest management for timber and other products. In Brazil, small-scale managed forestry poses the same potential benefits. Such a path could deliver an attractive balance between environmental benefits and equitable economic growth. ‘Could’ is the operative word, however, since whether or not this balance is struck in practice will depend on the ability of these countries to deliver the necessary policy and institutional innovations (Vosti et al., 2003).

Exploring in more detail the examples of Sumatran rubber agroforests (as well as their cocoa and fruit counterparts in Cameroon), these systems offer levels of biodiversity which, though not as high as those found in natural forest, are nevertheless far higher than those in monocrop tree plantations or annual cropping systems (Gillison, 2005). Like any tree-based system, they also offer substantial levels of carbon storage (Palm et al., 2005), thus illustrating the value of the ASB matrix. Crucially, technological innovations have the potential to increase yields of the key commodities in these systems, thereby raising farmers’ incomes substantially, to levels that either outperform or at least compete well with virtually all other systems. However, to realize this potential, it is vital to find ways of delivering improved planting material—the key input needed. Other obstacles to more widespread adoption of these agroforestry systems are the higher labour requirements compared to other systems, the costs of establishment and the number of years farmers must wait for positive cash flow.

The case in Lampung Province of southwest Sumatra provides an encouraging example where policy action has taken place to assure the continuation of productive and sustainable agroforestry. The Krui people of the area grow rice in permanently irrigated plots as their staple crop, while in the uplands they cultivate a succession of crops, building to a climax that mimics mature natural forest. The tall-growing timber species they plant includes the damar tree *(Shorea javanica),* a source of valuable resin that provides a steady flow of income over the long term. The Krui system is able to deliver broad-based growth in which the poor can participate. Combining environmental and economic benefits, the Krui system offers considerable advantages over many other systems that replace or exploit natural forest. In 1991 the Krui system came under threat. The Suharto government declared large areas of the Krui agroforests to be State Forest Land – a classification that would allow logging followed by conversion to oil palm plantations. A forestry company was awarded the right to harvest an estimated 3 million trees – trees that had been planted by the local people. The Krui stopped planting trees, saying that they would not resume until they were certain they would be able to reap the benefits of their work. A consortium of research institutions, NGOs, and universities was able to provide support through scientific evidence on the social and environmental benefits of the Krui system. This helped to legitimise the Krui system in the eyes of professional foresters and to refute arguments by vested interests intent on taking the land. The consortium conveyed requests to the government from village leaders for dialogue on the status of their land, arranged field visits for key government officials and organised a workshop to present research results and discuss the tenure issue. In 1998, the Minister of Forestry signed a new decree reversing the official position that declared the Krui system to be a unique form of forest use, recognised the legitimacy of community-managed agroforests in Lampung Province, and restored the rights of the Krui to harvest and market timber and other products from the trees they plant. The decree is a powerful instrument for restoring social justice and promoting sustainable development. This principle of local management could be extended to benefit hundreds of thousands of rural Indonesians in similar areas (Tomich et al., 2005).

CONCLUSIONS AND IMPLICATIONS

The concept of land use transition has been applied in land change studies at different spatial and temporal scales. A forest transition has occurred at a national scale in Europe and North America during the last 100 years, constituting a change from decreasing to expanding national forest areas. This transition has involved afforestation and natural regeneration mostly on abandoned marginal agricultural land and occurred as societies industrialized and urbanized (Mather et al., 1999). The transition came fairly far along in the structural transformation process with a key turning point arising when the rural labour force peaked in absolute numbers and then began a gradual decline, thereby reducing the number of people directly dependent on the natural resource base for their main source of livelihood (Tomich et al., 1995). Forests in the Mediterranean basin did not make this transition, while some regions in the tropics currently show signs of some significant reforestation (Rudel et al., 2000, 2002). The predominantly national focus in forest transition studies has been increasingly complemented by analyses at the subnational scale. Case studies from the Amazon basin have identified transition-like trajectories that suggest, over a decade or so, households undertake management of already cleared areas following a period of rapid deforestation, stop deforesting, and even undertake afforestation within their individual parcels (Moran et al., 2002). The pattern of a U-shaped curve of degradation followed by restoration (Mather and Needle, 1998) is immediately relevant to future land use patterns and the issue of carbon storage. Looking beyond 2015, it can reasonably be assumed that the structural transformation process will lead to continued and later on reversed deforestation, with eventually more tree cover in the developing world, just as it has in many industrial and post-industrial countries.

Our analysis of agricultural transitions at tropical forest margins shows which are the most important cause interactions to be directly influenced and which are the most important feedbacks to be enforced or turned around. It further shows that global-local interplays of causative factors are important drivers (while national-local interplays are characteristic for dryland margins). This leaves some opportunities for interventions at multiple scales, given that universal applications or mitigating policies will not work. The question arises which mix of local and national initiative combined with global support (e.g., incentives, sanctions) could work.

At the level of underlying driving forces, actions to foster the transition towards sustainable land use in tropical forest regions need to be directed towards improving governance, fighting corruption, decentralizing forest management with a concomitant increase in the local capacity to enforce law, developing public participation in environmental planning, and creatively designing new institutional instruments, including market-based ones, as an outcome of the meta-analysis of deforestation causes (Lambin and Geist, 2003a). Other actions need to relate to environmental service payments or other mechanisms to create incentives for forest conservation that are sufficient to offset the powerful incentives for forest conversion, as a conclusion of the ASB matrix analysis of trade-offs between global environmental objectives such as carbon sequestration and local/national development opportunities (Tomich et al., 2005).

At the proximate level, some assert the best opportunities for dealing with trade-offs among the concerns of poor households, national development objectives and global environmental concerns lie in the harvest of various products from community-managed forests. In practice, such extensive systems require low population densities plus effective mechanisms for keeping other groups out if they are to prove sustainable. Where forests are converted, agroforests often represent the 'next best' option for conserving biodiversity and storing carbon, while also providing attractive livelihood opportunities for smallholders. However, for both economic and ecological reasons, no single land use system should predominate at the expense of all others. Mixes of land uses increase biodiversity at a landscape level, if not within individual systems, and also can enhance economic and ecological resilience.

Where the productivity of the natural resource base has already sunk to low levels, concentrating development efforts on the simultaneous environmental and economic restoration of degraded landscapes is an option well worth exploring. The precise mix of interventions needed – hence the benefits and costs of restoration – varies from place to place. In Cameroon, improved cocoa and fruit tree systems could be a win-win proposition in place of unsustainably short-fallow rotations (Gockowski et al., 2005). In Indonesia, millions of hectares of *Imperata* grasslands are the obvious starting point (Purnomosidhi et al., 2005; Garrity, 1997), as are the millions of hectares of degraded pastures in Brazil. The direction of change in land use systems determines the environmental consequences. For example, if farmers replace unsustainable cassava production with an improved rubber agroforest, they help restore habitats and carbon stocks. But if such a system replaces natural forest, the environment loses.

Intensification of land use through technological change is a two-edged sword. It has great potential to increase the productivity and sustainability of existing forest-derived systems, thereby raising incomes. By the same token, however, these higher incomes attract more landless people to the agricultural frontier in search of a better living. Therefore, technological innovation to intensify land use will not be enough to stop deforestation (Angelsen and Kaimowitz, 2001). Indeed, it often will accelerate it. If both objectives are to be met, policy measures intended to encourage intensification will need to be accompanied by measures to protect those forest areas that harbour globally significant biodiversity.

With regard to agricultural transitions at dryland margins, both land use options and necessary policy and institutional reforms are less clear since the process of dryland degradation is not really well understood (Reynolds and Stafford Smith, 2002). A critical point seems that pressures might not derive so much from changes in intensity and magnitude of resource extraction (grass, water), but in *how* resources are extracted (Geist, 2005). This would leave some prospect, at least, to increase, for example, (re)investments in herding labour, mediating the often disturbed social relations between herding and farming populations, and safeguarding land use practices in dryland ecosystems which are based upon multiply constrained land productivity, i.e., linked to the oscillations of rainfall and biomass, and constrained by a nested system of seasonally differentiated use rights to a piece of land by various farming as well as pastoral groups, such as in the West African Sudan-Sahel (Turner, 1999). In principle, the ASB matrix approach could be applied to and modified for dryland areas, thus helping to reveal the mechanisms to create incentives for ecosystem conservation that are sufficient to offset the powerful incentives for dryland modification or conversion.

ACKNOWLEDGEMENTS

This chapter has greatly benefited from ideas developed within the Land-Use and Land-Cover Change (LUCC) project, which is a joint activity of the International Geosphere-Biosphere Programme (IGBP) and the International Human Dimensions Programme on Global Environmental Change (IHDP), and within the Alternatives to Slash-and-Burn (ASB) Programme, which is a systemwide programme of the Consultative Group on International Agricultural Research (CGIAR) hosted by the World Agroforestry Centre (ICRAF). Most fruitfully, the collabouration of ASB and LUCC was made possible through subglobal joint activities for the Millenium Ecosystem Assessment (MEA). Helmut Geist is grateful for the support from the Belgian Federal Science Policy Office.

REFERENCES

Angelsen, A. and D. Kaimowitz (Eds) (2001) *Agricultural Technologies and Tropical Deforestation*. CAB International, Wallingford, UK.

Garrity, D.P. (ed) (1997) *Agroforestry Innovations for Imperata Grassland Rehabilitation*. Kluwer Academic Publishers, Dordrecht.

Geist, H. (2005) *The Causes and Progression of Desertification*. Ashgate Publishing Ltd., UK and Ashgate Publishing Co., USA, Aldershot, Brookfield.

Geist, H.J. and E.F. Lambin (2001) *What Drives Tropical Deforestation? A Meta-Analysis of Proximate and Underlying Causes of Deforestation Based on Subnational Case Study Evidence*. LUCC Report Series 4. CIACO Press, Louvain-la-Neuve.

Geist, H.J. and E.F. Lambin (2002) Proximate causes and underlying driving forces of tropical deforestation. *BioScience*, Vol. 52 (2), pp. 143-150.

Geist, H.J. and E.F. Lambin (2004) Dynamical causal patterns of desertification. *BioScience*, Vol. 54 (9), pp. 817-829.

Gillison, A.N. (2005) The potential role of aboveground biodiversity indicators in assessing best-bet alternatives to slash and burn. In: C.A. Palm, P.A. Sanchez, S.A. Vosti and P.J. Ericksen (Eds) *Slash and Burn. The Search for Alternatives*. Columbia University Press, New York, pp. 83-118.

Gockowski, J., J. Tonyé, C. Diaw, S. Hauser, J. Kotto-Same, A. Moukam, R. Nomgang, D. Nwaga, T. Tiki-Manga, J. Tondoh, Z. Tschondeau, S. Weise and L. Zapfack (2004) The forest margins of Cameroon. In: C.A. Palm, P.A. Sanchez, S.A. Vosti and P.J. Ericksen (Eds) *Slash and Burn. The Search for Alternatives*. Columbia University Press, New Yrok, pp. 305-331.

Lambin, E.F. and H.J. Geist (2003a) Regional differences in tropical deforestation. *Environment*, Vol. 45 (6), pp. 22-36.

Lambin, E.F. and H.J. Geist (2003b) The land managers who have lost control of their land use. Implications for sustainability. *Tropical Ecology*, Vol. 44 (1), pp. 15-24.

Lambin, E.F., B.L. Turner II, H.J. Geist, S. Agbola, A. Angelsen, J.W. Bruce, O. Coomes, R. Dirzo, G. Fischer, C. Folke, P.S. George, K. Homewood, J. Imbernon, R. Leemans, X. Li, E.F. Moran, M. Mortimore, P.S. Ramakrishnan, J.F. Richards, H. Skånes, W. Steffen, G.D. Stone, U. Svedin, T. Veldkamp, C. Vogel and J Xu (2001) The causes of land-use and land-cover change. Moving beyond the myths. *Global Environmental Change*, Vol. 11 (4), pp. 261-269.

Lambin, E.F., Geist, H.J. and E. Lepers (2003) Dynamics of land-use and land-cover change in tropical regions. *Annual Review of Environment and Resources*, Vol. 28, pp. 205-241.

Matarazzo, B. and P. Nijkamp (1997) Meta-analysis for comparative environmental case studies. Methodological issues. *International Journal of Social Economics*, Vol. 24 (7-9), pp. 799-811.

Mather, A.S. and C.L. Needle (1998) The forest transition. A theoretical basis. *Area*, Vol. 30 (2), pp. 117-124.

Mather, A.S., J. Fairbairn and C.L. Needle (1999) The course and drivers of the forest transition. The case of France. *Journal of Rural Studies*, Vol. 15 (1), pp. 65-90.

Moran E.F., E.S. Brondizio and S.D. McCracken (2002) Trajectories of land use. Soils, succession, and crop choice. In: C.H. Wood and R. Porro (Eds) *Deforestation and Land Use in the Amazon*. University of Florida Press, Gainesville, pp. 193-217.

Palm, C.A., M. van Noordwijk, P.L. Woomer, J.C. Alegre, L. Arévalo, C.E. Castilla, D.G. Cordeiro, K. Hairiah, J. Kotto-Same, A. Moukam, W.J. Parton, A. Ricse, V. Rodrigues and S.M. Sitompul (2005) Carbon losses and sequestration following land use change in the humid tropics. In: C.A. Palm, P.A. Sanchez, S.A. Vosti and P.J. Ericksen (Eds) *Slash and Burn. The Search for Alternatives*. Columbia University Press, New York, pp. 41-63.

Purnomosidhi, P., K. Hairiah, S. Rahayu and M. van Noordwijk (2005) Smallholder options for reclaiming and using *Imperata cylindrica* (Alang-Alang) grasslands in Indonesia. In: C.A. Palm, P.A. Sanchez, S.A. Vosti and P.J. Ericksen (Eds) *Slash and Burn. The Search for Alternatives*. Columbia University Press, New York, pp. 248-262.

Ragin, C.C. (1989) *The Comparative Method: Moving Beyond Qualitative and Quantitative Strategies*. University of California Press, Berkeley.

Reynolds, J.F. and D.M. Stafford Smith (Eds) (2002) *Global Desertification: Do Humans Cause Deserts?* Dahlem Workshop Report No. 88. Dahlem University Press, Berlin.

Rudel, T.K., M. Perez-Lugo and H. Zichal (2000) When fields revert to forest. Development and spontaneous reforestation in post-war Puerto Rico. *Professional Geographer*, Vol. 52, pp. 386-397.

Rudel, T.K., D. Bates and R. Machinguiashi (2002) A tropical forest transition? Agricultural change, out-migration, and secondary forests in the Ecuadorian Amazon. *American Association of American Geographers*, Vol. 92 (1), pp. 87-102.

Tomich, T.P., P. Kilby and B.F. Johnston (1995) *Transforming Agrarian Economies: Opportunities Seized, Opportunities Missed*. Cornell University Press: Ithaca, NY.

Tomich, T.P., M. van Noordwijk, S.A. Vosti and J. Witcover (1998) Agricultural development with rainforest conservation. Methods for seeking best bet alternatives to slash-and-burn, with applications to Brazil and Indonesia. *Agricultural Economics*, Vol. 19 (1-2), pp. 159-174.

Tomich, T.P., M. van Noordwijk, S. Budidarsono, A. Gillison, T. Kusumanto, D. Murdiyarso, F. Stolle and A.M. Fagi (2001) Agricultural intensification, deforestation, and the environment. Assessing tradeoffs in Sumatra, Indonesia. In: D.R. Lee and C.B. Barrett (Eds) *Tradeoffs or synergies? Agricultural Intensification, Economic Development and the Environment*. CAB International, Wallingford, UK, pp. 221-244.

Tomich, T.P., A. Cattaneo, S. Chater, H.J. Geist, J. Gockowski, E.F. Lambin, J. Lewis, C. Palm, F. Stolle, J. Valentim, M. van Noordwijk and S.A. Vosti (2005) Balancing agricultural development and environmental objectives. Assessing tradeoffs in the humid tropics. In: C.A. Palm, P.A. Sanchez, S.A. Vosti and P.J. Ericksen (Eds) *Slash and Burn. The Search for Alternatives*. Columbia University Press, New York, pp. 415-440.

Turner, M.D. (1999) Labour process and the environment. The effects of labour availability and compensation on the quality of herding in the Sahel. *Human Ecology*, Vol. 27 (2), pp. 267-296.

Vosti, S.A., J. Witcover and C. Carpentier (2003) *Agricultural Intensification by Smallholders in the Western Brazilian Amazon. From Deforestation to Sustainable Use*. IFPRI Research Report No. 130. International Food Policy Research Institute, Washington, D.C.

World Livestock and Crop Production Systems, Land Use and Environment between 1970 and 2030

5

Lex Bouwman, Klaas van der Hoek, Gerard van Drecht and Bas Eickhout

INTRODUCTION

The world population may increase from about 6 billion current inhabitants to 8.2 to 9.3 billion between now and 2030 (Nakićenović et al., 2000). Food production will have to increase to meet the increasing population-induced demand, while with increasing prosperity dietary patterns may shift towards a higher share of meat and milk. There is major concern about the environmental consequences of such increases for a number of reasons:

- Forest clearing and other land transformations may be necessary for expansion of grazing land and arable land for the production of crops for feeding animals. Moreover, a significant part of arable and grazing land may consist of marginal unproductive land with low carrying capacity and high risk of land degradation due to soil erosion, soil nutrient depletion and overgrazing, especially in the arid and semi-arid tropics and subtropics (Delgado et al., 1999; Seré and Steinfeld, 1996). Loss of productivity in such areas may be compensated for by expansion of the agricultural area by forest clearing.
- A further concern is that livestock production systems and rice cultivation are major global sources of methane (CH_4). Ruminants produce CH_4 during enteric fermentation in their digestive tract contributing about 15% of the global source, while animal waste is also a source of CH_4. Most of the global production for rice, one of the major cereal crops, comes from wetland systems (paddies) that contribute about 6% to the global CH_4 source.
- Moreover, most of the anthropogenic NH_3 and N_2O emissions come from food production, while accelerated cycling of nitrogen in agricultural systems leads to increasing NO emissions. N_2O is one of the so-called greenhouse gases, constituting 6% of the anthropogenic greenhouse effect, and also contributes to the depletion of stratospheric ozone (IPCC, 2001). NO is an important player in atmospheric chemistry for its role in regulation of the oxidant balance. The global production of N in animal manure exceeds the

F. Brouwer and B.A. McCarl (eds.), Agriculture and Climate Beyond 2015, 75-89.

global amount of fertilizer N used in agriculture, and its contribution is 40% of the global NH_3 source.

- Apart from the overall increase in fertilizer use and livestock production, there is also a global trend towards concentration of agricultural activities related to livestock and intensive crop production and horticulture in peri-urban areas (FAO, 1997). This will lead to large local surpluses of N and P from animal manure and associated losses to aquatic systems and atmosphere.

The aim of this chapter is to describe the observed changes in agricultural production systems in recent decades, and assess the changes that may occur in the coming decades. The focus is on consequences of changing livestock production systems for the use of grassland and arable land, feed resource use, N fertilizer inputs and animal manure management, and consequences of changing production systems for emissions of greenhouse gases. More details on agriculture, climate change effects on future land use patterns and agricultural transitions can be found elsewhere in this volume (Chapters 2, 3 and 4).

CHANGES IN LIVESTOCK PRODUCTION SYSTEMS

Livestock production systems differ in their ability to respond to increasing demand for livestock products. Generally poultry and pork (white meat) production systems respond quickly to increasing demand, since they are commonly industrial with have fast reproduction cycles and adaptable feeding systems. Also, the feed conversion efficiency in poultry and pork production is higher than in most other systems.

Compared to white meat, the production of red meat (beef, mutton and goat meat) has longer reproduction cycles, a relatively low feed conversion efficiency and generally a lower degree of specialization than in white meat production. Therefore, transformations in red meat production systems are slower than in pork and poultry production systems (Seré and Steinfeld, 1996).

Traditional mixed livestock production systems also respond more slowly to increasing demand than modern poultry and pork production systems, mainly because livestock has other functions within the farm system than meat and milk production alone. This may explain why traditional mixed systems are unable to increase their production sufficiently. As a consequence, the supply of modern livestock production systems is increasing with larger shares of poultry and pork, particularly in developing countries (Bruinsma, 2003).

In this chapter we distinguish two livestock production systems according to a model described elsewhere (Bouwman et al., 2005a). These are pastoral-based and mixed/industrial livestock production systems (Figure 5.1). In the pastoral production systems grazing is dominant and not integrated with cropping systems.

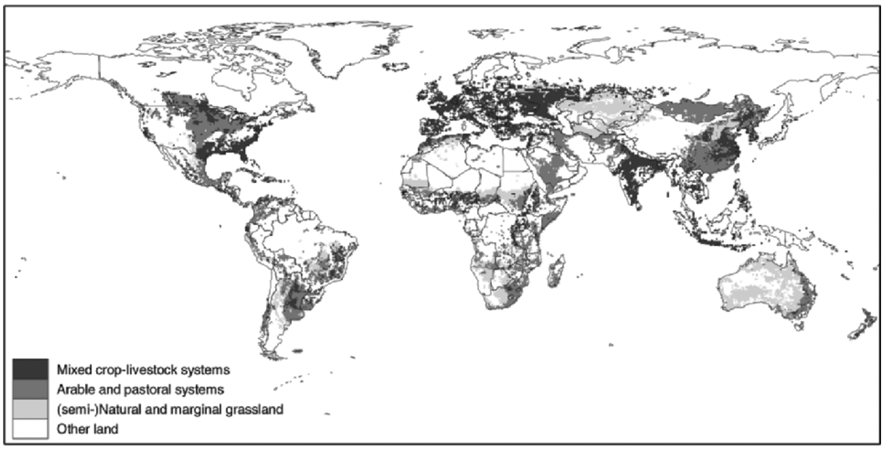


Figure 5.1 Distribution of crop and livestock production systems for 1995

Mixed/industrial systems have integrated cropping and livestock production, in which livestock production relies on a mix of food crops, crop by-products and roughage, consisting of grass, fodder crops, crop residues, and other sources of feedstuffs. In these mixed systems the by-products of one activity (crop by-products, crop residues, and manure) often serve as inputs for another.

This model for describing livestock production systems is part of the Integrated Model to Assess the Global Environment (IMAGE) (Alcamo et al., 1998; IMAGE-team, 2001). The livestock model was developed by Bouwman et al. (2005a) using historical data for the period 1970-1995 based on FAO (2001) and data Bruinsma (2003). All calculations are geographically distributed compiled for a 0.5 by 0.5 degree resolution.

Changes in the demand for agricultural products is largely determined by population growth and changing human diets. According to the FAO population projection used in this assessment, the world population growth will gradually slow down from 1.5% per annum now to 0.9% per annum between 2015 and 2030 reaching a world total of 8,270 million inhabitants in 2030 (Table 5.1). However, the population growth in developing countries will be much faster than in industrialized countries, while the projected growth in transition countries (Eastern Europe and the former USSR) will be negative in the coming 3 decades. Simultaneously, the per capita meat consumption shows a strong worldwide increase with a very fast growth in developing and transition countries. More details on food demand (Chapter 7) and consumption patterns (Chapter 10) can be found elsewhere in this volume.

The growth of animal populations and the production in each production system in the period 1980-1990 from Seré and Steinfeld (1996) were used by Bouwman et al. (2005a) to calculate the population numbers and the production within the pastoral and mixed/industrial production systems for the period 1970 to 1995 based on Seré and Steinfeld (1996). For the development of the distribution of the production over the two production systems for 1995-2030,

Table 5.1 Projections for total population (million inhabitants) and per capita meat consumption (kg/person/yr) for developing, industrial and transition countries

	Year	Developing	Industrialized	Transition	World
Population	1998	4,572	892	413	5,900
	2030	6,869	979	381	8,270
Meat consumption	1998	26	88	46	36
	2030	37	100	61	45

Source: Bruinsma (2003).

Bouwman et al. (2005a) assumed a continuation of the 1970-1995 trend in total production for pastoral and mixed/industrial systems.

As a result of the changing demand, the production of all livestock products strongly increased between 1970 and 1995, with larger in the production of pork and poultry meat than in that of beef and sheep and goat meat (Figure 5.2). The data for ruminants for the two major production systems, i.e. pastoral and mixed/industrial systems indicate an increase between 1970 and 1995 of global beef production of 16 Tg/yr. About 80% of this gain has been achieved in the mixed/industrial systems. For milk 94% of the total increase of 145 Tg has been achieved in mixed/industrial systems, while for mutton and goat meat this is 93% of the 4 Tg production growth.

In the same period, the productivity of all animal categories has increased, most strongly in mixed/industrial systems (Figure 5.3). Farmers not only increased the productivity per animal, but also achieved important increases in the productivity per hectare of grassland (Figure 5.4), particularly in the mixed/industrial systems.

In the coming three decades the production of pork and poultry will likely increase more strongly than that of ruminant meat. In the developing countries the white meat production is projected to grow from 99 to 196 Tg/yr, while ruminant meat production increases from 11 to 14 Tg/yr in pastoral systems and from 21 to 53 Tg/yr in mixed/industrial systems (Figure 5.2). In the industrialized countries growth of white meat production (65 to 74 Tg/yr) will slow down somewhat compared to the 1970-1995 period (38 to 65 Tg/yr), while the ruminant meat production in pastoral systems will not change substantially, and that in mixed/industrial systems will increase only slightly from 24 to 26 Tg/yr. In the transition countries the ruminant meat production will increase from 8 to 10 Tg/yr and that of white meat from 16 to 19 Tg/yr in mixed/industrial systems (Figure 5.2).

The growth in the production of milk shows similar changes. As in the 1970-1995 period (13 to 20 Tg/yr), in the developing countries milk production will slowly increase in pastoral systems in the coming three decades (20 to 26 Tg/yr). The increase in mixed/industrial systems will increase much faster in the coming three decades (176 to 413 Tg/yr) than in the period 1970-1995 (73 to 176 Tg/yr). In the industrialized countries the milk production in pastoral systems is insignificant compared to that in the mixed/industrial systems, where the

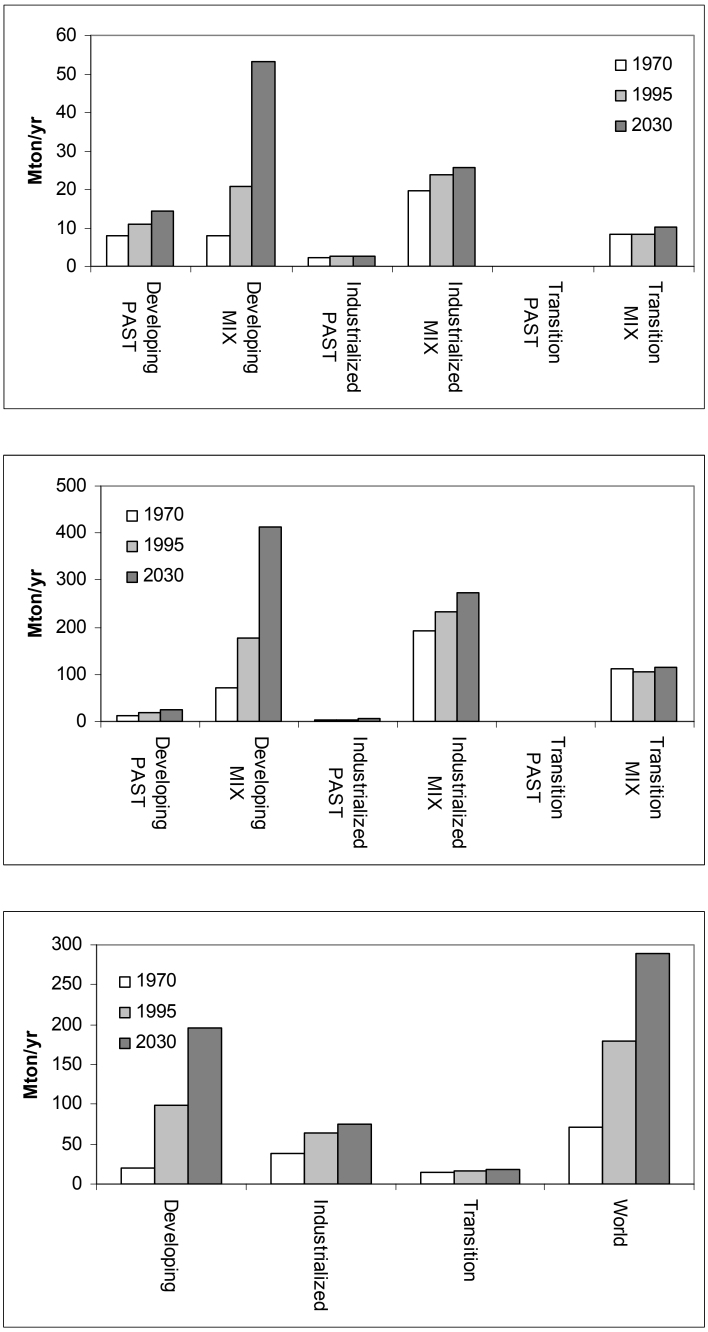


Figure 5.2 Total production of ruminant meat (cattle, sheep and goats) (top panel) and milk (middle panel) for pastoral (PAST) and mixed/industrial production systems (MIX), and production of poultry and pork (bottom panel) for developing, industrialized and transition countries for 1970, 1995 and 2030

production increased from 194 Tg/yr (1970) to 231 (1995) and will increase further to 272 Tg/yr in the coming three decades. The changes in milk production over the whole period 1970-2030 in the transition countries are only minor. The development of the productivity of the animals and the production per hectare in the coming three decades shows a continuation of that in the period 1970-1995 (Figure 5.3; Figure 5.4).

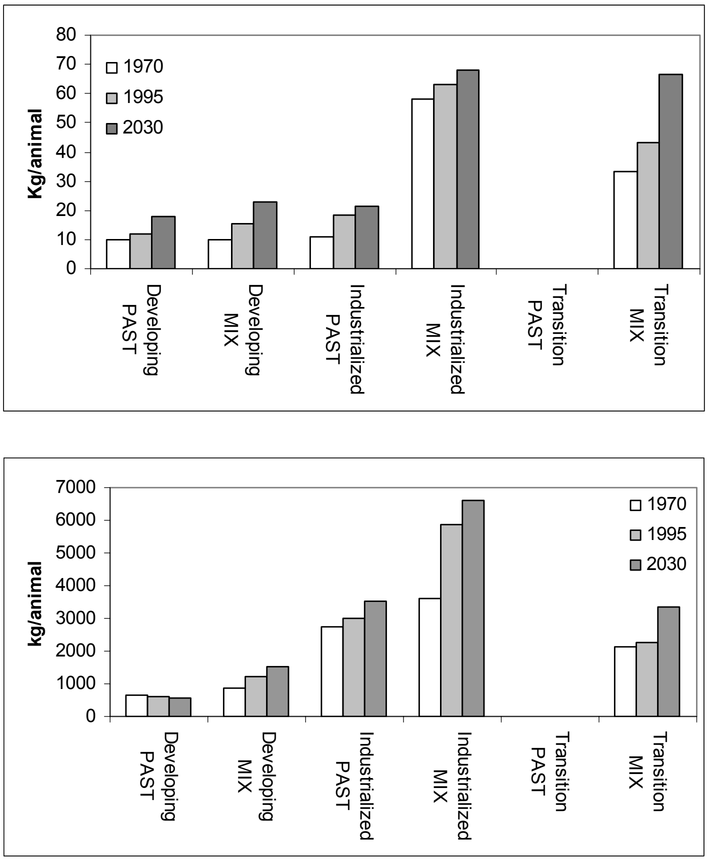


Figure 5.3 Annual meat (top panel) and milk (bottom panel) production per animal for pastoral and mixed/industrial production systems for all ruminants in developing, industrialized and transition countries for 1970, 1995 and 2030

CHANGES IN LAND USE

Most of the world's ruminant production comes from only one-sixth of the global area of grassland. The estimated global area of grassland in mixed/industrial systems is 565 Mha for 1995, which in pastoral systems ~1,600 Mha, while about

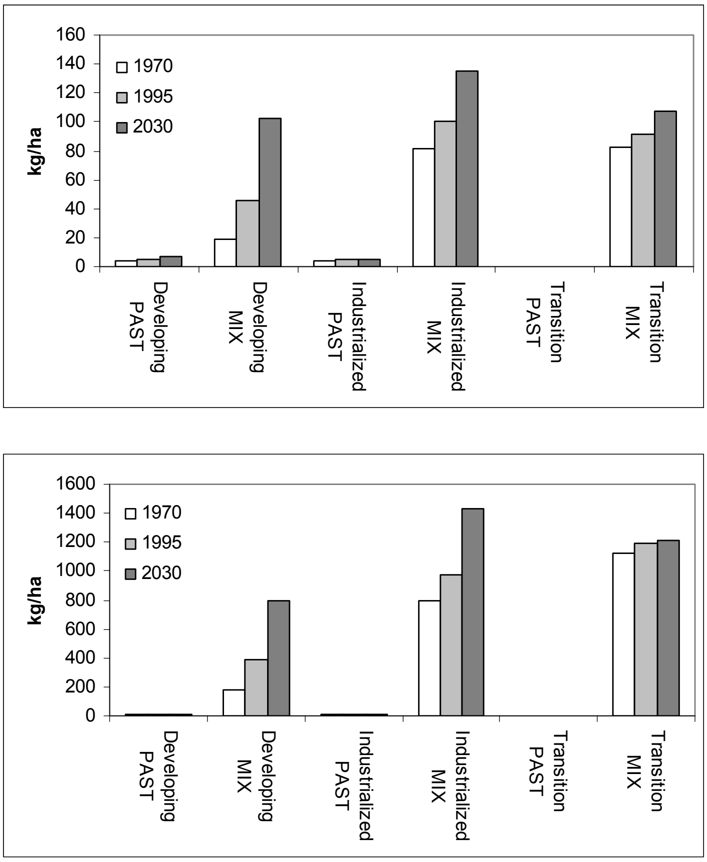


Figure 5.4 Annual meat (top panel) and milk (bottom panel) production per hectare of grassland for pastoral and mixed/industrial production systems for all ruminants in developing, industrialized and transition countries for 1970, 1995 and 2030

1,250 Mha is semi-natural or marginal land used for nomadic grazing (Figure 5.1; Table 5.2).

Changes in the distribution of ruminant production over pastoral and mixed/industrial production systems have led to small changes in the grassland area between 1970 and 1995 (Table 5.2). This is because the increase in ruminant meat and milk production during the past three decades has primarily been achieved by increasing the production in mixed/industrial production systems and much less so in pastoral systems. Despite the fast increase of ruminant production by 40% in the 1970-1995 period, the global area of grassland has, therefore, increased by only 4% (Table 5.2).

The global arable land area has increased from 1,405 to 1,495 Mha between 1970 and 1995 (Table 5.2). Since in the industrialized and transition countries the arable land areas have slightly decreased during this period, there has been a considerable expansion in the developing countries. According to the projection used the global arable land area will increase from 1,495 to 1,611 Mha between 1995 and 2030 (Table 5.2). While in industrialized (from 367 to 377 Mha) and transition countries (from 266 to 273 Mha) the arable land area will increase only slightly during this period, there will be a major expansion from 861 to 963 Mha in the developing countries.

Table 5.2 Areas of grassland (in pastoral, mixed/industrial, (semi-) natural and marginal systems) and arable land (in Mha) for different world regions and the world for 1970, 1995 and 2030

	Developing	Industrialized	Transition	World
1970				
Pastoral	1,281	175	0	1,456
Mixed/industrial	209	242	100	551
(semi-)natural and marginal	616	371	273	1,261
Total grassland	2,106	788	373	3,268
Arable land	742	381	282	1,405
1995				
Pastoral	1,451	147	0	1,599
Mixed/industrial	239	236	90	565
(semi-)natural and marginal	618	372	261	1,251
Total grassland	2,308	756	351	3,415
Arable land	861	367	266	1,494
2030				
Pastoral	1,437	157	0	1,594
Mixed/industrial	297	190	96	584
(semi-)natural and marginal	618	373	248	1,239
Total grassland	2,353	720	344	3,416
Arable land	963	372	273	1,609

The global increase in food production between 1995 and 2030 calculated from data provided by (Bruinsma, 2003) is about 1,600 Tg/yr (in dry matter). The contribution of yield increase to the total growth of production is about 70% (Bruinsma, 2003). Hence, crop yield increase alone would be sufficient to produce the extra amount of 1,200 Tg/yr (in dry matter) of crops for direct human consumption. The remaining production increase of 300-400 Tg/yr (in dry matter) equals the increase in production of food crops used to feed animals. This implies that most of the projected arable land expansion is needed for increasing the production of animal feedstuffs.

CHANGES IN FEED USE

The above simple calculation shows the importance of livestock production for determining land use through its feed demand. Ruminant production (cattle, buffaloes, sheep and goats) takes place under very diverse conditions. However, the general direction of change is towards a gradual intensification to meet the increasing demand for livestock products. This intensification also influences the composition of the animal feed required by ruminant production systems. In general, intensification is accompanied by decreasing dependence on open range feeding and increasing use of concentrate feeds, mainly feed grains, to supplement other fodder.

At the same time improved and balanced feeding practices and improved breeds in both monogastric and ruminant systems enabled more of the feed to go to the produce (meat and milk) rather than to maintenance of the animals. This has led to increasing overall feed conversion efficiency (Seré and Steinfeld, 1996). The calculated total feed intake shows large differences between regions, and also a considerable improvement in feed conversion efficiency in the period 1970-1995 (Figure 5.5).

This improvement is related to the increased production per animal as a result of increasing carcass weight, off-take rates and milk production per animal (Bouwman et al., 2005a). In addition, the use of animal traction providing draft power for about 28% of the world's arable land (Delgado et al., 1999) has decreased in recent decades (Bruinsma, 2003), leading to important decreases in the feed energy requirements, for example in East Asia. Regarding the feed use for ruminants and pigs and poultry, our results indicate an increase of about 44% for all feed categories between 1995 and 2030.

Total use of food crops for pigs and poultry increases by 55%, while the increase for cattle is 28%. Total grass consumption increases by 33% between 1995 and 2030 (Figure 5.6).

Only slight changes in the global extent of grassland in mixed/industrial and pastoral systems are projected for the period 1995 to 2030, which is consistent with the trends in recent decades (Table 5.2). In many industrialized regions, the extent of grassland in the mixed/industrial systems shows a slight decrease, while grassland is expanding in some developing regions. This implies that increased grass consumption will come from intensification, as illustrated by increasing production per hectare (Figure 5.4). The considerable increase of 33% in grassland productivity can only be achieved by increasing inputs of fertilizers, use of grass-clover mixtures and improved management (Bouwman et al., 2005a).

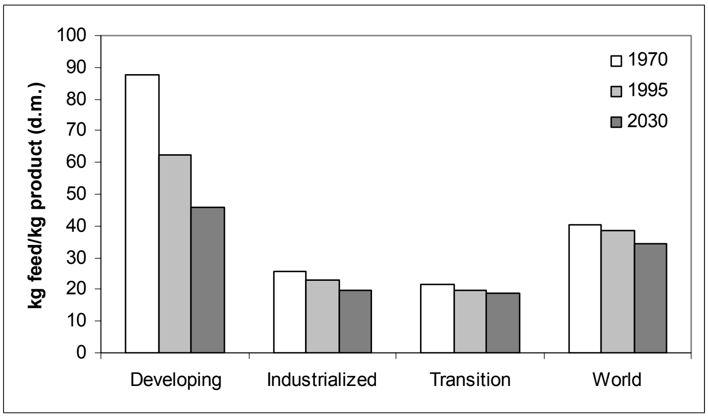


Figure 5.5 Feed conversion for total ruminant production in developing, transition and industrialized countries for 1970, 1995 and 2030

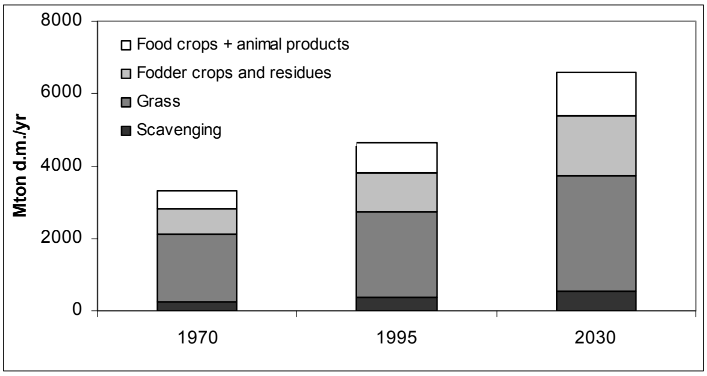


Figure 5.6 Global feed use by category for total livestock production (including monogastric production) for 1970, 1995 and 2030

CHANGES IN ANIMAL MANURE MANAGEMENT AND FERTILIZER USE

The changes in livestock production and land use portrayed above also have important repercussions for the production, management and use of animal manure and fertilizers. Bouwman et al. (2005b) distinguished large ruminants (dairy and non-dairy cattle, buffaloes), small ruminants (sheep and goats), pigs, poultry, horses, asses, mules and camels for calculating the animal manure N production. The approach for distributing of animal manure over the two production systems, and within each system over different animal manure management systems (grazing, storage, etc.), and calculation of ammonia volatilization in each system, are described elsewhere (Bouwman et al., 2005b).

The results show that the total N inputs from animal manure varied from less than 10 kg/ha/yr to more than 50 kg/ha/yr in 1995, and were highest in Western Europe and East Asia and much lower in world regions dominated by crop production systems and with less intensive livestock production. Inputs from animal manure will grow in all world regions in the coming three decades, except for Western Europe.

Within the latter region EU regulations for animal manure regarding usage of nitrogen inputs used will be bound to a maximum rate. Such rules have consequences in some countries with current high inputs, such as The Netherlands and Denmark. Atmospheric N deposition is generally highest in world regions with intensive livestock production (Bouwman et al., 2005b).

Global total N inputs from fertilizers and production of animal manure in agricultural systems have almost doubled between 1970 and 1995 from about 114 Tg/yr to 188 Tg/yr, whereby N manure contributed 83 Tg/yr or about 73% in 1970 and 104 Tg/yr (55%) in 1995. Bouwman et al. (2005b) estimated a total N input from fertilizers and animal manure of 238 Tg/yr, animal manure N being 127 Tg/yr (53%) and N fertilizer 110 Tg/yr (estimate for 2030) (Table 5.3).

Currently 22 Tg/yr of the total global amount of N in the animal manure production is not part of the agricultural system (16 Tg/yr) or is lost as NH_3 from stored manure (7 Tg/yr). Stored manure may not be used, such as in many lagoon systems in North America, and manure is also used as a fuel or for other purposes in other, primarily developing countries. For example, for India a large part of the total amount of animal manure is excreted in forests, during roadside grazing or scavenging in villages and urban areas (Bouwman et al., 2005b; Van der Hoek, 2001), and is not part of the agricultural system.

Hence, the total amount of animal manure in agricultural systems has steadily increased between 1970 and 1995 and will continue to do so in the coming decades, but its share in total inputs has decreased from more than 70 to 55% in the past three decades, and will decrease at a slower rate in the coming three decades. The total quantity of nitrogen in animal manure that is available for spreading in mixed/industrial agricultural systems increased from 19 to 24 Tg/yr during the 1970-1995 period and according to the projection used it will increase further to 27 Tg/yr in 2030. The data show that the increase in the volume of animal manure N production increased less rapidly than the livestock production (Table 5.3). This is caused primarily by increasing productivity (Figure 5.3), mainly in the mixed/industrial systems, resulting in increasing nitrogen efficiency of the production system as a whole.

CHANGES IN EMISSIONS TO THE ATMOSPHERE

Finally, the technological development in agricultural production systems induce changes in the emissions of greenhouse gases and ammonia, and nitrate leaching to groundwater. Here we concentrate on the gaseous emissions, which are suitable indicators of climate-change effects of agricultural production.

Table 5.3 Disposal of animal manure on grazing land and application in pastoral and mixed/industrial systems, and N fertilizer use for 1970, 1995 and 2030 (N in Tg/yr)

Region	Year	Grazing		Application		Total[a]	Fertilizer
		Pastoral	Mixed/ industrial	Pastoral	Mixed/ industrial		
Developing	1970	20.8	10.9	0.8	7.8	53.0	8.6
	1995	23.2	17.5	0.9	13.0	73.5	52.7
	2030	28.8	24.7	1.4	15.0	96.5	73.1
Industrialized	1970	2.3	8.2	0.0	7.3	19.5	14.9
	1995	3.0	8.9	0.0	7.2	20.9	25.6
	2030	3.2	8.6	0.0	7.0	20.6	31.0
Transition	1970	0.0	4.6	0.0	4.4	10.1	7.2
	1995	0.0	4.0	0.0	4.3	9.4	4.7
	2030	0.0	4.1	0.0	4.5	9.7	5.9
Global	1970	23.1	23.8	0.8	19.5	82.6	30.7
	1995	26.2	30.3	1.0	24.5	103.7	82.9
	2030	32.0	37.4	1.4	26.6	126.8	110.0

Source: Bouwman et al. (2005b).
[a] Total manure N includes, apart from grazing and application, NH_3 volatilization from stored and collected manure, and animal manure that is not part of the agricultural system, such as manure excreted in urban areas, and stored but unused manure.

We use the approach described by Alcamo et al. (1998) to calculate CH_4 emissions from enteric fermentation in the digestive tract of ruminants. In this approach, the emissions depend on the type and quality of the feed consumed by ruminants. Methane emissions from enteric fermentation have increased between 1970 and 1995 mainly as a result of increases in livestock herds in developing countries (Table 5.4). There has been a fast growth in ruminant production (Figure 5.2) which was not balanced by a simultaneous decrease in the feed conversion (Figure 5.5). In contrast, meat and milk production by ruminants grew much less rapidly in industrialized and transitional countries, and with a slow decrease of feed conversion rates the CH_4 emissions have not changed considerably. The global annual CH_4 emission from enteric fermentation is projected to increase from 94 to 131 Tg between 1995 and 2030 (Table 5.4).

The CH_4 emission from wetland rice fields has increased only slightly during the 1970-1995 time period (Table 5.4), and is projected to stabilize in the coming three decades. This development is the result of a strong increase in paddy rice production (from 550 to 770 Tg/yr in the 1995-2030 period), a nearly constant harvested area due to strongly increasing yields, and decreasing organic

Table 5.4 Regional and global CH_4 emissions from livestock production (enteric fermentation + animal waste) and wetland rice systems expressed as emission of CH_4 in Tg/yr and % of total emission from all sources for 1970, 1995 and 2030

Year	Developing countries		Industrialized countries		Transition countries		World	
	(Tg/yr)	(%)	(Tg/yr)	(%)	(Tg/yr)	(%)	(Tg/yr)	(%)
	Livestock							
1970	39	36	24	34	10	28	73	16
1995	60	36	25	32	8	20	94	18
2030	98	31	24	28	8	14	131	19
	Wetland rice							
1970	26	24	1	2	0	0	28	6
1995	31	18	1	1	0	0	32	6
2030	30	9	1	1	0	0	31	4

amendments which are (partly) responsible for CH_4 generation (IMAGE-team, 2001).

Global direct emissions of N_2O from animal manure calculated according to (IMAGE-team, 2001) strongly increased from 1.2 to 1.4 Tg N_2O-N/yr between 1970 and 1995 (Table 5.5). For the coming three decades a further increase to 1.7 Tg is projected. In the period 1970 to 1995 the N_2O emission from N fertilizers increased rapidly from 0.4 to 1.0 Tg N_2O-N/yr, and a further 30% increase to 1.4 Tg N_2O-N/yr 2030 is projected for 2030.

Ammonia emissions are calculated with different approaches for stable and grazing emissions (Bouwman et al., 1997) and manure and fertilizer application (Bouwman et al., 2002). Emissions increased from 21 Tg/yr in 1970 to 38 Tg/yr in 1995, based on calculations of (Bouwman et al., 2005b). For the coming three decades an increase to 48 Tg/yr is projected. This increase is less than that for the period 1970-1995, mainly due to increasing N use efficiencies in livestock production.

CONCLUSIONS

A number of conclusions can be drawn from the analyses discussed in this chapter for the historical period 1970-1995 and the projection towards 2030 for global crop and livestock production systems. The primary findings relate to livestock production characteristics and feed resources, consequences for land use, the global N cycle and emissions of greenhouse gases.

Regarding livestock production, it is clear that while the extensively used pastoral grassland and the area of intensively used grassland in mixed/industrial systems show gradual changes, the production characteristics change with trends towards intensification and integration of a growing part of livestock production in mixed crop and livestock production systems.

Turning to land-use aspects of livestock production, we see that the dependence of ruminant production on grassland resources is declining, and the

Table 5.5 Regional and global fertilizer-induced N_2O emissions from N fertilizers and animal manure expressed as emission of N_2O-N in Tg/yr and % of total emission from all sources for 1970, 1995 and 2030

Year	Developing countries (Tg/yr)	(%)	Industrialized countries (Tg/yr)	(%)	Transition countries (Tg/yr)	(%)	World (Tg/yr)	(%)
	N fertilizer							
1970	0.1	2	0.2	8	0.1	12	0.4	3
1995	0.7	7	0.3	13	0.1	10	1.0	7
2030	0.9	8	0.4	16	0.1	9	1.4	8
	Animal manure							
1970	0.7	11	0.3	13	0.1	20	1.2	9
1995	1.0	11	0.3	13	0.1	22	1.4	10
2030	1.3	11	0.3	13	0.1	16	1.7	10

Note: Calculations are based on IPCC (1997).

importance of food crops and other feedstuffs is increasing. Despite this decreasing importance of grass as a feed resource, a fast grass production increase of 33% is needed. This increase will have to come from improved management. In addition, vast increases in arable land are required to produce the food crops needed for both ruminant and pork and poultry production.

The global production of N in animal manure has increased strongly in the 1970-1995 period from 83 to 104 Tg/yr and will continue to grow to reach a level of 127 Tg/yr in the coming three decades. Most of this increase is the result of expanding livestock production in the developing countries, while in other countries the animal manure N production stabilizes (industrialized countries) or will show a slight increase (transition countries). The use of N fertilizers will also strongly increase in the developing countries (from 53 to 73 Tg/yr) and less so in the industrialized countries (26 to 31 Tg/yr).

An important environmental consequence of ruminant production is the emission of methane, one of the major greenhouse gases. Our projection suggests that the global annual methane emission will strongly increase from 85 Tg now to 120 Tg in 2030, mainly as a result of a fast growth in developing countries. Enteric fermentation will thus have a growing contribution to the global CH_4 emission. Similar developments are expected for N_2O and NH_3. Global direct emissions of N_2O from animal manure strongly increased from 1.2 to 1.4 Tg N_2O-N/yr between 1970 and 1995. For the coming three decades a further increase to 1.7 Tg is projected. Similar increases for emissions of NH_3 are foreseen. The N_2O emissions from N fertilizer use increased from 0.4 Tg N_2O-N/yr in 1970 to 1 Tg in 1995 and will rapidly increase in the coming three decades to 1.4 Tg N_2O-N/yr.

Furthermore, increasing production and further intensification in mixed/industrial livestock production systems means a concentration of activities, particularly of manure availability, which may lead to local losses to the environment (emissions to air and groundwater). In addition, there is concern about animal well-being, particularly in landless systems, which will gain importance in all world regions in the projection used.

REFERENCES

Alcamo, J., E. Kreileman, M. Krol, R. Leemans, J. Bollen, J.V. Minnen, M. Schaeffer, S. Toet and B. de Vries (1998) Global modelling of environmental change: an overview of IMAGE 2.1. In: J. Alcamo, R. Leemans and E.Kreileman (Eds), *Global Change Scenarios of the 21st Century. Results from the IMAGE 2.1 model*. Elsevier Science Ltd., Oxford, pp. 3-94.

Bouwman, A.F., L.J.M. Boumans and N.H. Batjes (2002) Estimation of global NH3 volatilization loss from synthetic fertilizers and animal manure applied to arable lands and grasslands. *Global Biogeochemical Cycles*, Vol. 16 (2), pp. 8-1 to 8-14 (1024, doi:10.1029/2000GB001389).

Bouwman, A.F., D. Lee, W.A.H. Asman, F.J. Dentener, K.W. van der Hoek and J.G.J. Olivier (1997) A global high-resolution emission inventory for ammonia. *Global Biogeochemical Cycles*, Vol. 11, pp. 561-587.

Bouwman, A.F., K.W. van der Hoek, B. Eickhout and I. Soenario (2005a) Exploring changes in world ruminant production systems. *Agricultural Systems,* Vol. 84, pp. 121-153.

Bouwman, A.F., G. van Drecht and K.W. van der Hoek (2005b) Nitrogen surface balances in intensive agricultural production systems in different world regions for the period 1970-2030. *Pedosphere*, Vol. 15(2), pp. 137-155.

Bruinsma, J.E. (2003) *World Agriculture: towards 2015/2030. An FAO perspective*. Earthscan, London, 432 pp.

Delgado, C., M. Rosegrant, H. Steinfeld, S. Ehui and V. Courbois (1999) *Livestock to 2020. The next food revolution*. Food, Agriculture and the Environment Discussion paper 28, International Food Policy Research Institute, Food and Agriculture Organization of the United Nations, International Livestock Research Institute, Washington, D.C.

FAO (1997) Long-term scenarios of livestock-crop-land use interactions in developing countries, *FAO Land and Water Bulletin No. 6*. Food and Agriculture Organization of the United Nations, Rome, Italy, pp. 144.

FAO (2001) *FAOSTAT database collections (*www.apps.fao.org), Food and Agriculture Organization of the United Nations, Rome.

IMAGE-team (2001) *The IMAGE 2.2 implementation of the SRES scenarios. A comprehensive analysis of emissions, climate change and impacts in the 21st century*. CD-ROM publication 481508018, National Institute for Public Health and the Environment, Bilthoven.

IPCC (1997) *Guidelines for national greenhouse gas inventories*, Intergovernmental panel on Climate Change/Organization for Economic Cooperation and Development, Paris.

IPCC (2001) *Third assessment report. Working Group I*. Cambridge University Press, Cambridge.

Nakićenović, N., J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Grübler, T.Y. Jung, T. Kram, E. Emilio la Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K. Riahi, A. Roehrl, H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. van Rooyen, N. Victor and Z. Dadi (2000) *Special Report on emissions scenarios*. IPCC Special Reports. Cambridge University Press, Cambridge.

Seré, C. and H. Steinfeld (1996) *World livestock production systems. Current status, issues and trends*. Animal Production and Health Paper 127, Food and Agriculture Organization of the United Nations, Rome.

Van der Hoek, K.W. (2001) Nitrogen efficiency in agriculture in Europe and India. In: J.M. Galloway, E. Cowling, J.W. Erisman, J. Wisniewski and C. Jordan (Eds), *Optimizing Nitrogen Management in Food and Energy Production and Environmental Protection*. Balkema Publishers, Lisse, pp. 148-154.

Agricultural Change and Limits to Deforestation in Central America

6

David Carr, Alisson Barbieri, William Pan and Heide Iravani

INTRODUCTION

In this chapter we discuss trends in agricultural land use in Central America between 1961 and 2001, and how they point in the coming decades to changes in regional production patterns, changes in agricultural systems, and regional forest cover. First, we introduce some concepts of sustainable agricultural development and its significance for the transformation of agricultural land use, and consequently the sustained wellbeing of coupled human and natural systems. We then discuss limits to deforestation in Central America as a result of trade-offs between agricultural production and natural resource conservation, in the light of efforts to achieve sustainable rural development, and review some recent trends among the peninsular Central American nations (Guatemala, Honduras, El Salvador, Nicaragua, Costa Rica, and Panama). In particular, we explore trends in agricultural intensification, with capital and land intensive practices in food production, as an increasing response to land scarcity, and thus constituting an important factor in efforts to minimize agricultural extensification, the increase in food production through the expansion of farmland usually at the expense of forest conversion. Finally, we examine regional and national food production and forest cover trends over the last several decades in Central America. Forest cover change is based on FAO estimates of forest and woodlands while changes in agricultural production are examined jointly with its key inputs: land, labour, and capital for the period 1961 to 2001.

How to achieve a balance between socioeconomic development and the quality and quantity of environmental resources for present and future generations? This is the sustainable development conundrum. Whether current notions of sustainable development offer viable alternatives to antagonistic positions of doctrinaire development advocates and strict environmental conservationists cannot be foretold. But the intentions are clear as presented by Brundtland Report's (1987) definition as: 'development which meets the needs of the present without compromising the ability of future generations to

F. Brouwer and B.A. McCarl (eds.), Agriculture and Climate Beyond 2015, 91-107.

meet their own needs.' Following this definition, sustainable agricultural development is the maintenance of future production and consumption needs, which implies a sustainable interaction between humans and the environment. An adequate food production to meet food demand over time implies potential trade-offs relative to the sustenance of rural livelihoods and forest conservation. Balancing continued improvements in agricultural output on decreasingly available arable lands while limiting agricultural expansion to forest ecosystems is critical in a world of over 6 billion and growing. In recent decades agricultural intensification has meant that yield increases have handily outpaced increases in agricultural land expansion. Indeed in much of the developed world agricultural land has declined, a forest transition that has yet to take purchase throughout the developing world.

A forest transition occurs when net deforestation gives way to net reforestation. The orthodox transition theory posits that forests tend to shrink initially and expand again later at higher levels of economic development (Mather et al., 1999). Such a transition results in the concentration of agricultural production in smaller areas of better land and the agricultural abandonment of larger areas of poor land. As this pattern develops, relatively larger areas of poor quality land become available for reforestation through natural regeneration or planting (Mather, Needle 1999). Forest-transition theory thus suggests that economic development eventually leads to forest recovery, but much is unknown about the existence, the characteristics, and the mechanisms of forest transitions that might be occurring under current socioeconomic conditions. Further, incipient stages of the transition are characterized by geographical heterogeneity. For example, Klooster's study in highland Mexico finds forest degradation to be caused by woodcutting despite the presence of agricultural abandonment and forest regeneration (Klooster, 2003). Regional variation in forest transitions has increasingly been framed within the uneven evolution of institutions that coordinate rural peoples' land use. For example, in a highland Mexican community, Klooster and Masera (2000) benefits from forestry increased dramatically after community control management improved. Thus it is argued that community forest management offers concrete local benefits while at the same time helps to conserve forests and to sequester carbon. Indeed, the Clean Development Mechanism (CDM) of the Kyoto Protocol was established to leverage additional resources to promote such an approach.

The outcome of food production versus forest conservation trade-offs has important human and environment implications. With most of the best farmland already in production, much of the world's forest elimination occurs on oxidized, nutrient-leached soils, unsuitable for agricultural development (Moran, 1983). Farmers in such regions are among the poorest of all rural inhabitants (Leonard et al., 1989), and suffer a litany of problems, including poor access to roads, potable water, schools, and health care (Murphy et al., 1997).

Short-term financial gains from tropical forest conversion mortgage scientific advances in medicine, and food production as biodiversity is compromised (Smith and Schultes, 1990; Wilson, 1992). This is particularly the case in tropical environments where approximately 90% of species extinctions occur (Myers, 1993). Deforestation also causes soil erosion and watershed sedimentation

(Southgate and Whitaker, 1992), nutrient leaching (Lal, 1996), and perturbations in nutrient cycling (Fearnside and Barbosa, 1998).

Land conversion from forests to agriculture and pasture has been associated with climate changes at the global scale (Fearnside, 1996). While developed countries have contributed to much of the planet's recent warming trend by burning fossil fuels and via industrial compounds, Adger and Brown (1994) estimate that tropical deforestation is responsible for between 25% and 30% of the purported climate warming in the world; and forests are responsible for about 90% of the carbon stored in global vegetation (Dale, 1997). Furthermore, climate change is believed to affect world food supply and productivity (Brown, 1994). This situation has led to reforestation efforts in developing countries as a way to reduce carbon emissions.[1] Reforestation can help to break down excess atmospheric carbon dioxide and contribute to the recycling of moisture and the reduction in reflectivity of the earth's surface (Myers, 1989).

Forest conversion is also linked to climate changes at the local scale (Shukla et al., 1990; O'Brien, 1995; Tinker et al., 1996). Deforestation can alter patterns of reflectance of the earth's surface and consequently induce local warming or cooling (Dale, 1997). Furthermore, aggregate local-level forest clearing contributes to global warming through the emission of carbon dioxide and other greenhouse gases to the atmosphere (Klooster and Masera, 2000). In Latin America, Laurance and Williamson (2001) suggest that deforestation in the Amazon has reduced regional rainfall and increased the vulnerability of forests to fire.

Nowhere are interactions among competing demands between humans and forest systems more dynamic than in Central America (Figure 6.1). Central America has cleared a greater percentage of its forests, most all of it for food production, than any major world region in recent decades. Agricultural land expansion and food production outpaced rapid population growth during this period. Most forest clearing for agricultural expansion, however, has occurred on lands marginal for production while often rich in natural biodiversity and ecosystem functioning. Conversely, virtually all growth in food production has occurred on capital-intensive plantations developed mainly for export dollars. To the extent growth in the latter exceeds that of the former, food production increases are achieved with relatively minimal destruction of forest resources. Nonetheless growth in large-scale food production has accompanied other problematic impacts on rural human and natural landscapes. Capital intensive production has displaced thousands of rural farmers - most of them out-migrating to urban areas, but also to marginal lands rich in biodiversity and forest resources - and also involves other ecological alterations, such as chemical runoff into riverine, lake, and ocean ecosystems, and soil degradation. Sustainable agricultural practices in this dynamic region will be necessary to balance the demand for food and requirements of environmental conservation and reducing gas emissions to the atmosphere. We now briefly review the state of some of those efforts.

---

[1] However, following the Marrakesh round of the Kyoto negotiations it was decided that carbon credits could not be issued for avoided deforestation.

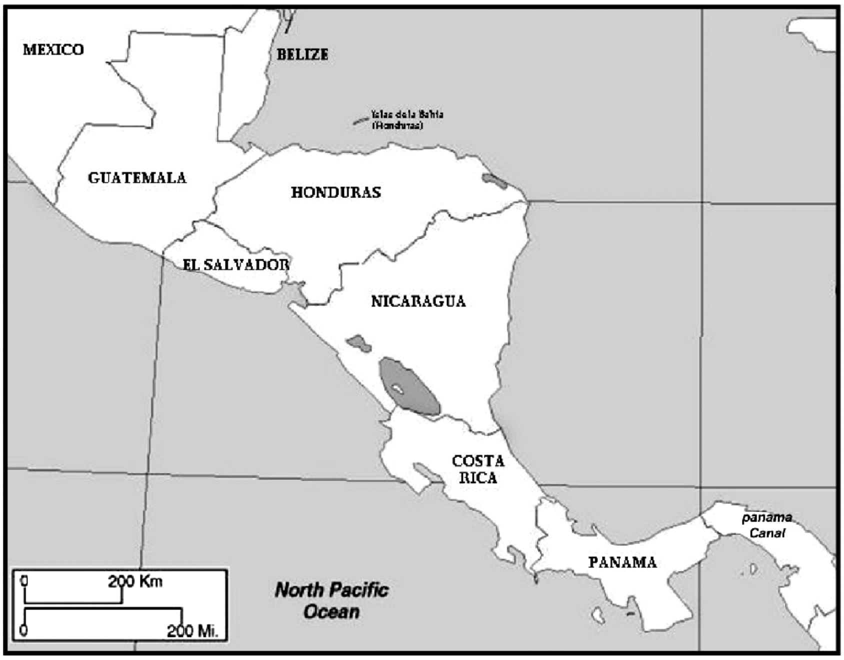


Figure 6.1 Map of Central America

RURAL SUSTAINABLE DEVELOPMENT EFFORTS

The promotion of sustainability as an instrument to reconcile economic development with the conservation of natural resources was first advanced in earnest at the Earth Summit in Rio de Janeiro in 1992. The main document emerging from the historic meeting, Agenda 21, underscores the intimate relationship between poverty and environmental degradation in developing countries, along with the unsustainable pattern of consumption in developed countries (United Nations 1992). A major conclusion of the *Agenda* authors was the need to maintain and improve the capacity of the most productive agricultural land to support an expanding population, while at the same time to implement measures towards conservation and rehabilitation of natural resources (land, water, forests) on less productive lands. Many scholars argue that a primary means to achieving this outcome is through the promotion of sustainable intensification techniques (Tisdell, 1988; Tisdell, 1999; Lee and Barrett, 2000). However, as explained in the following section, agricultural intensification, increasing output per unit of land, is far from a panacea with diminishing returns to inputs and potentially deleterious impacts for humans and the environment.

To date policy prescriptions have insufficiently reconciled the tension between the imperative for economic development and the desire for environmental conservation in rural regions of developing countries. Many of the poorest Central Americans are situated in rural populations concentrated on marginal, less productive lands. Given the lack of access to capital, land security, credit and alternative income sources, poor farmers are more likely to adopt short-term land use strategies to maximize income. Often this has meant overexploitation of available resources, including land degradation and the depletion of soil fertility, and subsequent agricultural expansion to other marginal lands, especially lowland tropical lands, with further land degradation ensuing in a vicious cycle as farmers attempt to compensate for declining yields (Barbier, 2000).

A host of authors have called recently for policies integrating the three pillars of human, environmental, and food sustainability in agricultural systems. Advocates of this 'eco-agriculture' approach aim to address these three issues concomitantly and, consequently, to create systems that produce food and safeguard wild lands and essential ecosystem services. To quote the authors of a recent book on the topic: 'enhancing rural livelihoods through more productive and profitable farming systems is a core strategy for both agricultural development and conservation of biodiversity' (Mc Neely and Scherr, 2002). We now examine some trends in trade-offs between deforestation and agricultural development in Central America.

SUSTAINABLE AGRICULTURE IN CENTRAL AMERICA

Agricultural trade-offs to mitigate deforestation

Throughout the developing world, the scarcity of remaining land resources means that capital and land intensive agriculture represents an increasing share of the overall means to food production. Growth in food production slowed worldwide starting in the 1960s (World Bank, 1995). Half of potentially arable unused land remains locked (*de jure* if not *de facto*) in protected lands, and another three-fourths has soil or topographic limitations. Further, over 10% of land currently in production is substantially degraded (World Bank, 1995). This is particularly the case in Central America where forest cover decreased at an average rate of 1.2% per year from 1961 to 2001 (Figure 6.2). With just over half the original 1961 forest cover remaining, future increases in agricultural production in Central America will likely take the form of more intensive agriculture rather than agricultural expansion as in, for example, the Amazonian nations.

Even if food production is sustainable over time, maintaining production to keep pace with growing demand has implications for the environment and rural livelihoods. Land allocated to pasture and permanent crops (perennials) in Central America has increased about 40% (13 percentage points) from 1961 to 2001 (Figure 6.3) with a simultaneous increase in production of 170% (Figure 6.4).[2] Most of the extensification noted in Figure 6.3 is due to the expansion of pasture rather than arable and cropped land; therefore, the increase in agricultural production can most likely be attributed to intensification over time. However, while the purpose of most forest clearing is for agricultural expansion, the flip

---

[2] Net production is computed by FAO as (Production – Feed – Seed).

side of the coin is habitat destruction. In Central America, forest conversion increasingly occurs on dwindling remnants of biodiversity-rich tropical forests, often in and adjacent to protected areas (Brandon and Wells, 1992; Rudel and Roper, 1996). As much as 90% of species extinctions (over 20,000 annually, according to Myers, 1993) have occurred in tropical forests, though these regions make up a fraction of the world's land cover. These processes impoverish Central America's considerable gene pool, a potential gold mine for scientific advancements and food production (Smith and Schultes, 1990; Myers, 1996).

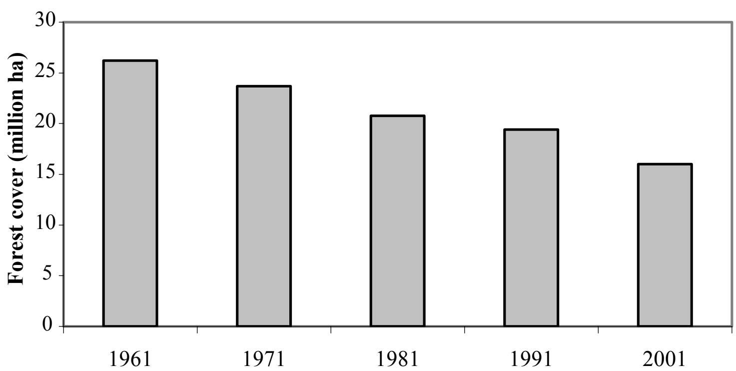


Figure 6.2 Total forest cover (million ha) in Central America over time

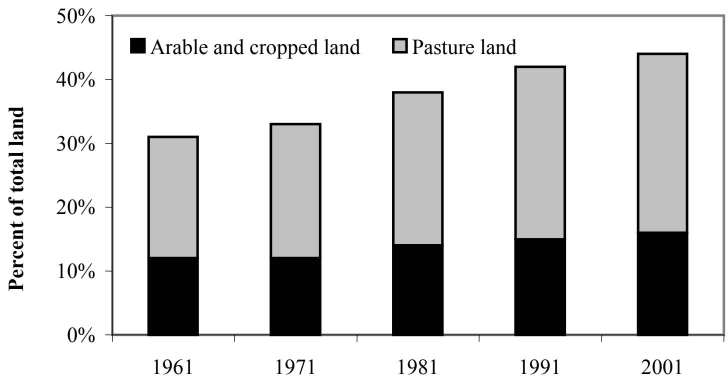


Figure 6.3 Agricultural extensification by year in Central America

Agricultural intensification also poses severe problems for environmental sustainability and the maintenance of agricultural inputs. Examples include waterlogged soils and alterations in water table levels in areas of intensive use of irrigation; salinization; water and soil contamination with excessive and inappropriate use of chemical inputs; and loss of genetic diversity in areas of monoculture, with higher vulnerability to pests and the weather (Ruttan, 1994). Further, increasing agricultural intensification in developing countries has threatened the quality of surface and groundwater due to the runoff of plant nutrients and use of pesticides, with increases in the former posing an increasing threat to the health of rural workers (Crissman et al., 2000).

Land degradation and health problems are not the only impacts on rural residents originating from agricultural and environmental change. Figure 6.5 shows the gradual decreasing trend of people in Central America living in rural areas, with the largest drop occurring between 1991 and 2001. Despite rapid urbanization in recent decades, nearly half of the population still resides in rural areas, and virtually all of them work in agriculture. This is particularly important since the majority of Central America's poorest inhabit rural environments where natural population growth remains considerably higher than in urban locales. Despite notable progress in some rural areas, particularly in Costa Rica, the majority of rural Central Americans eke a living from pauperesque plots or are landless. In both cases, the sale of one's own labour is often the main strategy for earning capital (Leonard et al., 1989). Rural people are disadvantaged in their access to roads, water, public works, schools, health care, and other government investments (Murphy et al., 1997; Pichón, 1997). Yet when development reaches the countryside, food production systems tend to change from labour to capital intensive, pushing small farm families off the land, often to cities where their agricultural skills offer meagre comparative advantage in urban labour pools. Inexorably, this process marches on - perhaps necessarily so if food production is to continue to keep pace with demand. Nevertheless, a host of socio-economic and political-ecological forces enable and constrain local land use decisions. We will now discuss some of these determinants.

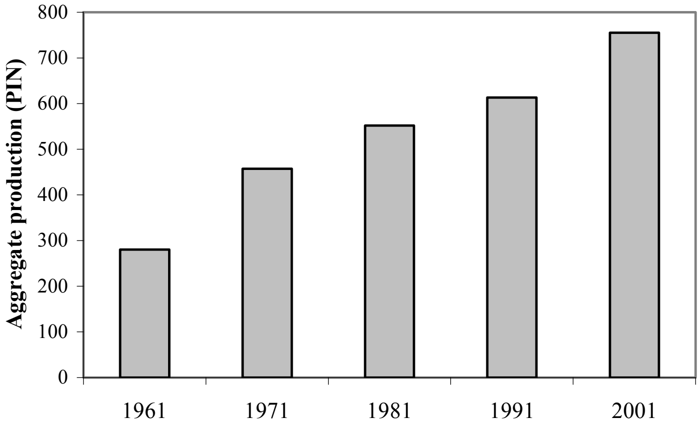


Figure 6.4 Agricultural production by year in Central America[3]

[3] The FAO indices of agricultural production measure 'the relative level of the aggregate volume of agricultural production for each year in comparison with the base period 1999-2001. They are based on the sum of price-weighted quantities of different agricultural commodities produced after deductions of quantities used as seed and feed weighted in a

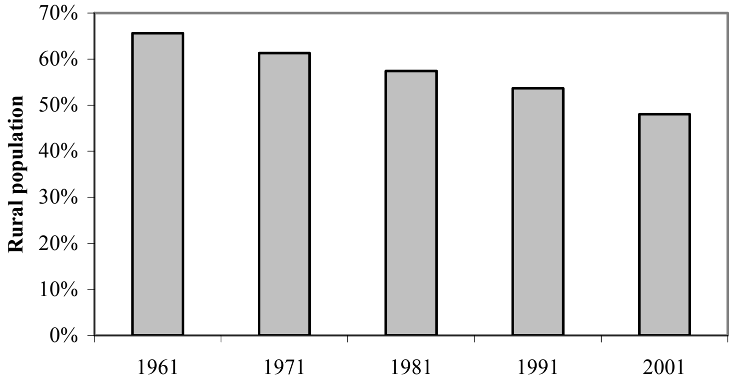


Figure 6.5 Rural population (%) in Central America

Determinants of agricultural production and forest cover change

Given the heterogeneity of coupled human-agricultural systems across the world, it is critical to understand the meaning of rural agricultural and livelihood sustainability in terms of local and regional contexts (Bowler et al., 2001). The most traditional agricultural system in Central America is the maize-beans tandem, which together with coffee, intensive small-scale irrigated vegetable production and seasonal migration of wage labour to lowland and coffee estates, are the main sources of farm income (Food and Agriculture Organization of the United Nations (FAO), 2001). As in other developing regions, sustainable agricultural development in Central America is challenged by a myriad of factors including rural poverty, population dynamics, and institutional factors, such as absence of credit markets, land insecurity and inappropriate land management (Bilsborrow and Carr, 2000).

While some studies have found a 'Boserupian' pattern in Central America, i.e., a positive relationship between population density and farm yields (Carr, 2002), the question remains as to whether technological advancements will continue to overcome challenges to agricultural sustainability such as soil overuse, inadequate land management, and natural resource degradation (FAO, 2001). The region has experienced rapidly falling (but still high in rural areas) fertility and rural-urban migration in recent decades. An understudied demographic challenge to agricultural sustainability in Central America is population momentum. In addition to the high population density of the region, the young age-composition promises that future demand for land and natural resources will challenge current agricultural systems. The population density in

---

similar manner. The resulting aggregate represents, therefore, disposable production for any use except as seed and feed' (www.fao.org/waicent/faostat/agricult/indices-e.htm).

the region in 2002 was 57 people per km^2 (compared to the Latin America and Caribbean average, 26 per km^2), while 34% of the population was below 15 years old (United Nations Population Division (UNPD), 2003). Thus, even with drastic fertility declines in the next years, the current high proportion of population in younger age groups will assure high population growth in the coming decades. Population pressure - along with land concentration as measured by a high Gini coefficient of land distribution - has been a primordial reason for the usually small landholdings in Central America - less than 2 ha on average (FAO, 2001), a land size insufficient with current economic development patterns to alleviate poverty and assure food security. Consequently, small farmers are unlikely to adopt environmentally benign agricultural practices if they do not translate into income gains or improved food security (Mc Neely and Scherr, 2002).

Decreasing farm income and deterioration of wages, due to a combination of trade liberalization and the protection of national production, has also induced the overexploitation of existing resources and environmental degradation (Dragun, 1999; FAO, 2001). Agricultural sustainability in a population-dense world is predicated on scientific and technological developments, which require investment in, for example, credit markets and governmental technical assistance. However, for small farmers, imperfect markets, the paucity of credits for agricultural investments, and the middle or long-term returns required by more sustainable agricultural practices are usually incompatible with the short term demands of food security and other household needs. Similarly, the adoption of conservation measures such as agroforestry systems, usually involves large-scale production, with large amounts of land, labour and capital resources (Current et al., 1995).

Small farmers are the primary agents expanding the agricultural frontier in tropical lowland areas, a recurrent phenomenon throughout the Central America nations (Jones, 1990). Expansion of agriculture threatens common natural resources in protected areas, as is the case, for example, in Guatemala's Petén (Carr, 2001) and throughout the national park system of Costa Rica (Sánchez-Azofeifa et al., 2003). Barbier (1997) suggests that deforestation in tropical lands was responsible for 22% of soil erosion in Central America over the period 1945-1990. Lutz et al. (1998) suggest that 56% of total land in Central America has experienced moderate degradation (with substantial reduction in productivity), and 41% has experienced strong degradation (agricultural use becoming impossible). Such patterns have not arisen only as responses to the physical environmental, but also to changes in policies promoting the occupation of fragile lands and the adoption of extensive land practices such as cattle (Loker, 1993; Turner II and Benjamin, 1994). However, agricultural extensification and land degradation are not a *fait accompli*. Some encouraging patterns have been observed in Central America in terms of safeguarding habitat integrity, species diversity, agricultural supply and rural livelihoods (Mc Neely and Scherr, 2002).

While noting the importance of local variation, the focus here is to delineate regional-level trade-offs between forest conversion for agricultural extensification and agricultural intensification through human, land, and capital inputs. We will now explore some regional variation in agricultural change in Central America. The following section of the chapter addresses the methodology used in this examination, followed by a presentation of results in agricultural production trends and changes in the means to sustaining agricultural production. We will then interpret the findings to speculate on the sustainability of these recent patterns for continued food production as forest resources dwindle.

REGIONAL VARIATION OF AGRICULTURAL CHANGE

Methods

Data come from the Food and Agriculture Organization's Agricultural Yearbooks, as well as FAO online statistical resources (www.fao.org). We examine key indices of agricultural production between 1961 and 2001 for six Central American countries, and seek to interpret trends in food production sustainability. Indices examined include total forest cover in hectares (ha), percentage of land in agriculture, rural population, and fertilizer use. In exploring the means to production we examine changes in rural population, agricultural extensification (in the form of arable, permanently cropped land, and pasture), and intensification through the use of fertilizers. Lastly, based on forest cover change patterns, we speculate on the extent to which increases may occur through continued agricultural extensification. These are but a subset of a broader series of variables that ultimately must be researched to achieve a more complete analysis of sustainability trade-offs for agricultural, human, and environmental systems. Although a more in-depth data analysis is beyond the scope of this chapter, we consider potential variables and forms of analysis in the conclusion.

Agricultural extensification, intensification, and production in Central America: 1961-2001

As shown in Figure 6.2, total forest cover in Central America declined approximately 40% between 1961 and 2001. Several countries lost nearly half their forest cover, including Nicaragua, Guatemala, and El Salvador during this period. Table 6.1 shows the loss of forest cover by country in total ha. Nicaragua and Guatemala, with the majority of their land cover in forest in the 1960s, experienced the highest level of total forest cover loss of 3.4 million ha and 2.7 million ha respectively. Obviously such trends are unsustainable; when projecting recent trends merely several decades into the future the Central American nations would become devoid of all forest cover.

Pasture land and arable and permanently cropped land expanded steadily in Central America between 1961 and 2001, with total land in agriculture for the region increasing from 31% in 1961 to 44% in 2001 (Figure 6.3 and Table 6.2). Honduras was the only country to experience an overall decrease in pastureland and arable and permanently cropped land during this period. We are dubious of the reliability of these data based on case studies from Honduras describing substantial agricultural expansion (Stonich, 1996; Godoy et al., 1998; Humphries, 1998; Jansen, 1998), though there appears to be recent reforestation in some regions (Southworth et al., 2002). Costa Rica and Guatemala underwent the most agricultural extensification between 1961 and 2001, while El Salvador, Nicaragua, and Panama all experienced roughly 37% agricultural expansion. Increases in agricultural land in Costa Rica, Guatemala, and Panama were primarily due to expansion of pasture, while increases in El Salvador, which had the highest proportion of land devoted to agricultural use consistently over the entire period, were primarily attributed to expansion in arable and cropped land. Nicaragua experienced an initial increase in pasture land from 1961-1981 followed by a subsequent increase in arable and cropped land with pasture plateauing from 1981-2001.

Table 6.1 Forest cover by year and country (1,000 ha)

Country	1961	1971	1981	1991	2001
Costa Rica	3,240	2,490	1,730	1,570	1,790
El Salvador	208	178	134	105	107
Guatemala	5,370	5,070	4,470	5,212	2,717
Honduras	6,000	6,000	6,000	6,000	5,335
Nicaragua	6,650	5,510	4,370	3,270	3,232
Panama	4,740	4,440	4,070	3,260	2,836
Total	26,208	23,688	20,774	19,417	16,017

Table 6.3 shows the relative level of the aggregate volume of agricultural production for each year in comparison with the base period 1989-91. Agricultural production nearly tripled from 1961 to 2001, a trend inversely related to forest cover, as one might expect, in the absence of agricultural outputs responding exclusively to intensification. However, much of this growth occurred during the 1960s and 1970s. Between the years of 1961 and 1981, total production nearly doubled; however, the rate of total production slowed to an increase of 36% between 1981 and 2001. In contrast, forest cover decreased 21% between 1961 and 1981 and 23% between 1981 and 2001.

Table 6.2 Share of land in agriculture by year and country (%)

Country	1961	1971	1981	1991	2001
Costa Rica	27	37	51	56	56
El Salvador	60	61	64	71	82
Guatemala	24	26	29	40	42
Honduras	27	27	29	30	26
Nicaragua	42	46	51	52	58
Panama	22	23	23	29	30
Average	31	33	38	42	44

Table 6.3 FAO aggregate agricultural production by year and country[a]

Country	1961	1971	1981	1991	2001
Costa Rica	29	54	70	106	142
El Salvador	63	85	101	105	104
Guatemala	38	58	85	101	132
Honduras	43	72	93	102	127
Nicaragua	62	115	116	101	144
Panama	45	73	87	98	106
Total	280	457	552	613	755
Average	47	76	92	102	126

[a] Net PIN base 1989-1991. The Net Production Index Number (PIN) is computed by dividing the aggregate for a given year by the average aggregate for the base period, following a Laspeyres formula.

While the rate of forest decline remained similar between 1961 and 2001, the pace of increase in agricultural production drastically decreased after 1981. Costa Rica led the region with a nearly five-fold agricultural production increase, accompanied by the highest increase in land converted to agriculture over the time period. Output in the remaining nations more than doubled, with the exception of El Salvador, whose total agricultural production increased 65%.

Due to a substantial increase in rural labour productivity per capita, agricultural production increased during the time period while rural labour pools shrank. Rural population as a percentage of total population in Central America decreased by 27% between 1961 and 2001. Honduras, Costa Rica, and El Salvador experienced the largest and most rapid decreases in percent rural population, each with its 2001 percent rural representing approximately 60% of what it was forty years earlier. Guatemala showed the lowest rate of decrease in rural population relative to total population, with an overall decrease of 10% over the entire period. The countries in 2001 with the highest percentage of rural population were the later-developing and less population-dense Guatemala and Honduras, and the lowest two were the earlier industrialized El Salvador and Costa Rica. However, the decrease in rural population in El Salvador occurred mostly between 1991 and 2001, while Costa Rica has experienced a steadily declining rural population over the past 40 years.

The rate of increase in the consumption of fertilizers per ha far outpaced the rate of increase in agricultural production in the region. Table 6.5 provides a breakdown of fertilizer use by country, indicating that the total consumption of fertilizers per ha in 2001 was more than six times the region’s 1961 level. Costa Rica, Honduras, and Guatemala had the highest fertilizer per ha consumption in 2001, respectively. The country that experienced the highest percentage increase of fertilizer use per ha was Honduras, whose 2001 level had increased by twenty-five times its 1961 level. Honduras also shows the smallest decrease in forest cover between 1961 and 2001 (11%), showing that agricultural production (which increased almost 300% between 1961 and 2001) occurred without a substantial reduction in forest cover when compared to other Central American countries, most likely attributable to it being the largest user of fertilizer in the region. Costa Rica, whose fertilizer use per ha increased more than five times, had the third smallest decrease in forest cover (45%) between 1961 and 2001, after Honduras (11%) and Panama (40%). The other Central American countries (El Salvador, Guatemala, Nicaragua, and Panama) combined level of fertilizer use per ha of arable and permanently cropped land in 2001 was more than four times their combined 1961 level.

Table 6.4 Share of rural population by year and country (%)

Country	1961	1971	1981	1991	2001
Costa Rica	65.7	60.5	52.2	45.8	40.5
El Salvador	61.2	60.3	55.4	50.0	38.5
Guatemala	67.2	64.2	62.5	61.8	60.1
Honduras	77.1	70.4	64.6	57.1	46.3
Nicaragua	60.1	52.4	49.4	46.7	43.5
Panama	58.2	52.0	49.2	46.0	43.5
Total	65.6	61.4	57.4	53.7	48.0

Table 6.5 Fertilizer use on land cropped by year and country (kg/ha)

Country	1961	1971	1981	1991	2001
Costa Rica	39	115	142	226	244
El Salvador	32	121	122	94	80
Guatemala	10	16	51	80	96
Honduras	4	18	16	19	106
Nicaragua	3	22	45	23	10
Panama	9	43	54	39	42
Regional use	12	40	56	61	77
Average	16	56	72	80	96

DISCUSSION AND CONCLUSION

This chapter introduced the topic of limits to deforestation from an analysis of trade-offs between agricultural sustainability and deforestation in Central America, with a discussion of current trends and an examination of changes in a handful of key variables during the previous four decades. Following an exploration of the importance of sustainable agriculture in Central America, we analyzed changes in production for the region over the previous four decades at the expense of forests relative to intensification inputs. We will now briefly review the major findings before discussing the potential of future food production dynamics to increase production while preventing further substantial forest conversion in the region.

Agricultural production doubled in Central America from 1961 to 2001. As we expected, the greater proportion of this increase came from agricultural intensification, rather than from the expansion of agricultural land or labour investments. Extensification was greatest in the countries of most abundant remaining forestland, Guatemala and Costa Rica. However, intensification in the form of fertilizer usage increased dramatically in all nations and was highest in the nations of greatest rural development and most earnest export agriculture, Costa Rica and El Salvador. These countries also experienced the most rapid urbanization and had the smallest proportion of rural dwellers in 2001, suggesting that agricultural output per labourer, due to capital investments in mechanization and chemical inputs, increased disproportionately to agricultural output in these countries. Lastly, the more developed countries such as Costa Rica and El Salvador manifested a combination of earlier urbanization and increased agricultural intensification compared with less developed countries, such as Guatemala and Honduras.

Although production has increased, there are several patterns that raise doubts about the sustainability of recent trends. Intensification in the form of fertilizer use grew several times to assist in a mere doubling of food production. Such diminishing returns augur poorly for the sustainability of current systems. Although inputs have compensated for a declining rural labour pool, as rural families continue to migrate to cities, socio-economic levels should rise, along with demand for meat. This will tax rural production systems further as livestock production is a much less efficient land use than crop production. This trend is sobering given the rapidly diminishing forestland in the region, and thus, the ever-decreasing potential to increase production through agricultural extensification. Land extensification in the next decades is expected to contribute to some important environmental problems in the region, such as the loss of biodiversity, soil degradation (as land extensification occurs into fragile areas), and regional climate change.

Thus, future scenarios point to growing conflicts between regional production to meet the demands of a growing population and international markets, and mitigation initiatives regarding conservation of forests and other natural resources (soil, water and the regional biodiversity). Increasing global and local climate change is also likely to affect food supply and productivity, with important implications on the sustainability of agricultural systems. In this sense, policies will be needed to focus on sustainable development strategies that integrate human, environment, and food sustainability in agricultural systems.

Future research will need to further probe trade-offs between the means to production and the implications not only for food production, but also for the sustainability of natural environments and rural livelihoods. Further, more detailed measures of the means to production need to be examined. For example, our measure of agricultural intensification examines fertilizers, but not the use of pesticides, herbicides, mechanization, and irrigation - and their impacts on the environment. Such considerations would add to the depth of analysis on agricultural intensification and its environmental impacts. Lastly, trade-offs between labour, land, and capital intensification on the one hand and extensification and reduction in forest cover on the other hand need to be examined explicitly in terms of percent changes in one factor relative to changes in another. Only then can estimates of relative efficiency of returns to inputs be examined in the context of agricultural sustainability and its impacts on people and the environment.

REFERENCES

Adger, W.N. and K. Brown (1994) *Land Use and the Causes of Global Warming*. New York, John Wiley and Sons.

Barbier, E. (1997) The economic determinants of land degradation in developing countries. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, Vol. 352 (1356), pp. 891-899.

Barbier, E.B. (2000) Links between economic liberalization and rural resource degradation in the developing regions. *Agricultural Economics*, Vol. 23 (3), pp. 299-310.

Bilsborrow, R.E. and D.L. Carr (2000) Population, agricultural land use and the environment in developing countries. In: D.R. Lee and C.B. Barrett (Eds), *Tradeoffs or Synergies? Agricultural Intensification, Economic Development and the Environment*. Wallingford, CABI Publishing Company, pp. 35-56.

Bowler, I.R., C.R. Bryan and C. Cocklin (2001). *Sustainability of Rural Systems: Geographical Perspectives*. Dordrecht, Netherlands, Kluwer Academic Publishers.

Brandon, K. and M. Wells (1992) Planning for people and parks. *World Development*, Vol. 20 (4), pp. 557-570.

Brown, L. (1994) Facing food insecurity, A Worldwatch Institute Report on Progress Toward a Sustainable Society. In: L. Brown (ed.), *The State of the World 1994*. New York, NY, W.W. Norton & Co. Chapter 10.

Carr, D.L. (2001) Cambios en el uso del suelo de colonos agrícolas en el Parque Nacional Sierra de Lacandón, Petén, Guatemala. In: L.R. Bixby and A. Pebley (Eds), *Población del Istmo Centroamericano al Fin del Milenio*. Santa Monica, CA, Rand Corporation, pp. 361-382.

Carr, D.L. (2002) The role of population change in land use and land cover change in rural Latin America: Uncovering local processes concealed by macro-level data. In: M.H.Y. Himiyama and T. Ichinose (Eds), *Land Use Changes in Comparative Perspective*. Enfield, NH and Plymouth, UK, Science Publishers, pp. 133-147.

Crissman, C.C., J.M. Antle and J.J. Stoorvogel (2000) Tradeoffs in agriculture, the environment and human health: decision support for policy and technology managers. In: D.R. Lee and C.B. Barrett (Eds), *Tradeoffs or Synergies? Agricultural Intensification, Economic Development, and the Environment*. Ithaca, New York, CABI, pp. 135-150.

Current, D., E. Lutz and S. Scherr (1995) *Costs, Benefits, and Farmer Adoption of Agroforestry. Project Experience in Central America and the Caribbean*. Washington, D.C., World Bank.

Dale, Virginia H. (1997) The relationship between land-use change and climate change. *Ecological Applications*, Vol. 7 (3), pp. 753-769.

Dragun, A.K. (1999) Trade liberalisation, agriculture and sustainability. In: A.K. Dragum and C. Tisdell (Eds), *Sustianable Agriculture and the Environment: Globalisation and the Impact of Trade Liberalisation*. Cheltenham, UK, Edward Elgar, pp. 7-21.

Fearnside, P.M. (1996) Amazonian deforestation and global warming: carbon stocks in vegetation replacing Brazil's Amazon forest. *Forest Ecology and Management*, Vol. 80, pp. 21-34.

Fearnside, P.M. and R.I. Barbosa (1998) Soil carbon changes from conversion of forest to pasture in Brazilian Amazonia. *Forest Ecology and Management*, Vol. 108 (1-2), pp. 147-166.

Food and Agricultural Organization of the United Nations (FAO) (2001). *Farming Systems and Poverty: Improving Farmers' Livelihoods in a Changing World*. Rome and Washington D.C., FAO and World Bank.

Godoy, R., S. Groff and K.O' Neill (1998) The role of education in neotropical deforestation: household evidence from Amerindians in Honduras. *Human Ecology*, Vol. 26 (4), pp. 649-675.

Humphries, S. (1998) Milk cows, migrants, and land markets: unraveling the complexities of forest-to-pasture conversion in Northern Honduras. *Economic Development and Cultural Change*, Vol. 47 (1), pp. 95-124.

Jansen, K. (1998) *Political Ecology, Mountain Agriculture, and Knowledge in Honduras*. Amsterdam, Thela Publishers.

Jones, J.R. (1990) *Colonization and Environment: Land Settlement Projects in Central America*. Tokyo, United Nations University Press.

Klooster, Daniel and Omar Masera (2000) Community forest management in Mexico: carbon mitigation and biodiversity conservation through rural development. *Global Environmental Change*, Vol. 10, pp. 259-272.

Klooster, D. (2003) Forest transitions in Mexico: Institutions and forests in a globalized countryside. *Professional Geographer*, Vol. 55 (2), pp. 227-237.

Lal, R. (1996) Deforestation and land-use effects on soil degradation and rehabilitation in Western Nigeria. *Land Degradation and Development*, Vol. 7 (2), pp. 87-98.

Laurance, W.F. and G.B. Williamson (2001), Positive feedbacks among forest fragmentation, drought, and climate change in the Amazon. *Conservation Biology*, Vol. 15 (6), p. 1529.

Lee, D.R. and C.B. Barrett (2000) *Tradeoffs or Synergies? Agricultural Intensification, Economic Development and the Environment*. Wallingford, UK, CABI International.

Leonard, H. J., M. Yudelman, J.D. Stryker, J. Browder, A.J. De Boer, T. Campbell and A. Jolly (1989) *Environment and the Poor: Development Strategies for a Common Agenda*. New Brunswick, Transaction Books.

Loker, W.M. (1993) The human ecology of cattle raising in the Peruvian Amazon: The view from the farm. *Human Organization*, Vol. 52 (1), pp. 14-24.

Lutz, E., S. Pagiola and C. Reiche (1998) The costs and benefits of soil conservation in Central America and the Caribbean. In: E. Lutz (ed.), *Agriculture and the Environment: Perspectives on Sustainable Rural Development*. Washington, D.C., The World Bank, pp. 273-295.

Mather, A.S., C.L. Needle, J. Fairbairn (1999) Environmental Kuznets curves and forest trends. *Geography*, Vol. 84 (1), pp. 55-65.

Mc Neely, J. and S. Scherr (2002) *Ecoagriculture: Strategies to Feed the World and Save Wild Biodiversity*. Washington, D.C., Island Press.

Moran, E. (1983) Government-Directed Settlement in the 1970s: An Assessment of Transamazon Highway Colonization. In: E. Moran (ed.), *The Dilemma of Amazonian Development*. Boulder, Colorado, Westview Press, pp. 297-317.

Murphy, L., R.E. Bilsborrow and F.J. Pichón (1997) Poverty and prosperity among migrant settlers in the Amazon rainforest frontier of Ecuador. *Journal of Development Studies*, Vol. 34 (2), pp. 35-66.

Myers, N. (1989) Loss of biological diversity and its impact on agriculture and food production. In: D. Pimentel and C. Hall (Eds), *Food and Natural Resources*. San Diego: Academic Press, pp. 50-69.

Myers, N. (1996) The world's forests: Problems and potentials. *Environmental Conservation*, Vol. 23 (2), pp. 156-168.

Myers, N. (1993) Tropical forests: The main deforestation fronts. *Environmental Conservation*, Vol. 20 (1), pp. 9-16.

O' Brien, K. (1995) Deforestation and Climate Change in the Selva Lacandona of Chiapas, Mexico. Ph.D. Dissertation. Department of Geography. College Park, Penn. State University.

Pichón, F.J. (1997) Settler households and land-use patterns in the Amazon frontier: farm-level evidence from Ecuador. *World Development*, Vol. 25 (1), pp. 67-91.

Rudel, T. and J. Roper (1996) Regional patterns and historical trends in tropical deforestation, 1976-1990. *Ambio*, Vol. 25 (3), pp. 160-166.

Ruttan, V.H. (ed.) (1994) *Agriculture, Environment and Health: Sustainable Development in the 21th Century*. Minneapolis, University of Minnesota Press.

Sánchez-Azofeifa, A., C. Busch, G.C. Daily and A.S.P. Pfaff (2003), Integrity and isolation of Costa Rica's national parks and biological reserves: Examining the dynamics of land-cover change. *Biological Conservation*, Vol. 109 (1), pp. 123-135.

Shukla, J. C., C. Nobre and P. Sellers (1990) Amazon deforestation and climate change. *Science*, Vol. 247, pp. 1322-1325.

Smith, N. and R.E. Schultes (1990) Deforestation and shrinking crop gene-pools in Amazonia. *Environmental Conservation*, Vol. 17 (3), pp. 227-234.

Southworth, J., H. Nagendra and C. Tucker (2002) Fragmentation of a landscape: Incorporating landscape metrics into satellite analyses of land-cover change. *Landscape Research*, Vol. 27 (3), pp. 253-269.

Southgate, D. and M. Whitaker (1992) Promoting resource degradation in Latin America: tropical deforestation, soil erosion, and coastal ecosystem disturbance in Ecuador. *Economic Development and Cultural Change*, Vol. 35 (4), pp. 786-807.

Stonich, S. (1996) The political ecology of deforestation in Honduras. In: L. Sponsel, T. Headland and R. Bailey (Eds), *Tropical Deforestation: The Human Dimension*. New York, Columbia University Press, pp. 187-215.

Tinker, P. B., J. Ingram and S. Struwe (1996) Effects of slash-and-burn agriculture and deforestation on climate change. *Agriculture, Ecosystems & Environment*, Vol. 58 (June), pp. 13-22.

Tisdell, C. (1988). Sustainable development: Differing perspectives of Ecologists and Economists, and relavance to LDCs. *World Development*, Vol. 16 (3), pp. 373-384.

Tisdell, C. (1999) Conditions for sustainable development: Weak and strong. Sustainable agriculture and the environment. In: A.K. Dragum and C. Tisdell (Eds), *Globalisation and the Impact of Trade Liberalisation*. Cheltenham, UK, Edward Elgar, pp. 23-36.

Turner II, B.L. and P.A. Benjamin (1994) Fragile lands: Identification and land use for agriculture. In: V.W. Ruttan (Ed.), *Agriculture, Environment and Health: Sustainable Development in the 21st Century*. Minneapolis, University of Minnesota Press, pp. 104-145.

United Nations (1992) *Agenda 21*. New York, United Nations.

United Nations Population Division (UNPD) (2003) *World Population 2002*. New York, United Nations Population Division.

Wilson, E.O. (1992) *The Diversity of Life*. New York, W.W. Norton & Co.

World Bank (1995) World Bank World Data. New York, World Bank.

World Commission on Environment and Development (WCED) (1987) *Our Common Future. The Brundtland Report*. London, Oxford University Press.

Rising Food Demand, Climate Change and the Use of Land and Water

7

Hermann Lotze-Campen, Christoph Müller, Alberte Bondeau, Pascalle Smith and Wolfgang Lucht

AGRICULTURE AS A CRUCIAL LINK BETWEEN HUMAN SOCIETY AND THE BIOSPHERE

Some of the most important interactions between human society and the environment occur in the agricultural sector. Agricultural production is – more than most other economic activities – affected by socio-economic and environmental conditions. Human demand for food effectively drives production and land use patterns. With respect to climate, agriculture acts as a source and a sink of greenhouse gases at the same time. The complex linkages between food production, land use and climate change can only be understood in a long-term, interdisciplinary framework. However, there is still a lack of consistent modelling approaches which take spatial variations of environmental conditions into account and represent biophysical as well as socio-economic driving forces over several decades into the future.

From an economic perspective, the importance of agriculture varies according to the level of economic development. In poor countries, agricultural and food production contributes a major share to GDP and is an important source of employment and household income. Many economists claim that there is no way out of poverty, except through agricultural and rural development (McCalla, 1999). In the process of economic development, the role of agriculture is decreasing, and in rich industrialised countries the share of agriculture in GDP and overall labour force is now below 5%. These trends occur despite wide-ranging government interventions to achieve the contrary. Like most economic sectors, agriculture is also strongly affected by macroeconomic conditions, lifestyles changes and consumption patterns.

From an environmental point of view, agriculture is of key importance in rich and poor countries, regardless of the level of economic development. On a global scale, agricultural production accounts for about 40% of total land use, and about 70% of all freshwater withdrawals. It also affects important nutrient cycles, contributes significantly to climate change through emissions of methane and nitrous oxide, and it is considered one of the most important causes for

F. Brouwer and B.A. McCarl (eds.), Agriculture and Climate Beyond 2015, 109-129.

biodiversity loss (Kendall and Pimentel, 1994). At the same time, agricultural productivity may be strongly affected by global environmental change.

If we want to understand the interactions between human society and the biosphere in general, an in-depth understanding of the links between food consumption, agricultural production, land use and climate change is indispensable. The major challenge to this understanding is the fact that socio-economic and environmental driving forces and impacts occur at different spatial, temporal and thematic scales. It is, for instance, not meaningful to talk about environmental impacts without looking at reasonably small regional units. However, economic analysis and the related data are often confined to nation states as the typical unit of analysis.

For the purpose of an integrated environmental-economic analysis of the food system across different scales we are presenting a coupled modelling framework. The biosphere part of the system is represented by the well established Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ), a spatially explicit, grid-based process model which runs on a global scale. The socio-economic part is represented by a resource allocation model which we call a 'Management model of Agricultural Production and its Impact on the Environment' (MAgPIE). This model is under development and we present preliminary modelling results here.

For the analysis in this chapter, these two models run sequentially and exchange information on key economic and environmental conditions and driving forces. Changes in economic and environmental conditions can be modelled separately or in combination. Outputs of the modelling framework include standard economic variables as well as environmentally relevant information.

While the scope of our modelling work is global in principle, for the purpose of testing the coupled system and demonstrating the viability of our concept we have zoomed into a small region as a first example. We chose Germany as the sample region. It has to be stressed, though, that the resolution of our global models may be too coarse to provide convincing results for a region the size of Germany. However, we are able to show that the concept works and can be extended to the global scale with reasonable effort.

AGRICULTURAL CHALLENGES

Whether food production can keep pace with the demand for improved diets for a rapidly growing world population is a question that has been debated vigorously since it was raised by Malthus two centuries ago. Although much of mankind has experienced improvements in diets over the past century, expert views about prospects for the coming decades differ as sharply as ever (Bongaarts, 1996).

There is a rather optimistic group consisting primarily of economists and modellers in the neoclassical tradition. They note the relatively low crop yields, inefficiencies throughout the food production and consumption chain, and the ample reserves of potential arable land in many developing countries. They further hold the view that sounder government policies, wider application of green revolution technology, reduced inefficiencies, upgraded rural infrastructure, and greater investments in human resources and research will make much larger harvests possible and no insurmountable environmental constraints are foreseen (Alexandratos, 1999; Alexandratos, 1995; Pinstrup-Andersen and Pandya-Lorch, 1998; Rosegrant and Ringler, 1997).

The rather pessimistic group primarily belongs to the ecology and ecological economics communities focussing on the carrying capacity of the Earth. They point to the many signs of environmental stress and the increasing difficulties encountered in expanding agricultural land, water supply, crop yields, and in controlling pests. In their view a large expansion of agricultural output is not feasible, and they even doubt whether current levels of crop production can be sustained in a number of countries. Global warming would impose further stress on agricultural systems, and thus the prospects for increased food production would become even less favourable than they are at present. A major expansion of food supply would require a highly organized global effort by both the developed and the developing countries that has no historic precedent (Brown and Kane, 1994; Kendall and Pimentel, 1994).

In the debate about global food security over the next century there is a clear focus on supply-side effects and developments, i.e. technological change in agricultural production, limits to natural resource availability and resource quality, most of all agricultural land and water for irrigation. Surprisingly, the importance of changes in demand growth and demand structure have been studied to a lesser extent. In many scenarios, the current trend towards higher meat consumption at higher income levels is simply extrapolated over a wide range of countries on a global scale in the course of economic development. However, there may be significant scope for altering the relationship between income and food demand. For example, changes in dietary structures may evolve due to increasing knowledge and concerns about health impacts of alternative diets (Bender 1994). In addition to improved production efficiency and waste reduction, demand changes towards healthier diets could also significantly affect the outcome of long-term global food scenarios (Table 7.1).

Most scenarios and analyses on the development of the global food system cover the period up to 2025 at most (Alexandratos, 1999; Alexandratos, 1995; Pinstrup-Andersen and Pandya-Lorch, 1998; Rosegrant and Ringler, 1997). From a social science point of view the time span of one generation is already very long and it may be questionable whether model simulations and scenario analyses beyond two to three decades are possible and have any meaning (Smil, 1994). A few such analyses beyond the year 2050 have been conducted mainly with respect to the impact of climate change on agricultural production, as significant changes in the global climate system are not to be expected before the middle of the 21st century (Parry et al., 1999; Sands and Leimbach, 2003). Like long-term environmental changes, profound alterations in cultural habits and dietary preferences may also come about only within several decades, so there may be scope for longer-term analyses from this perspective as well.

Table 7.1 Conservative estimates of efficiency gains in the global food system achievable by the year 2050

Changes compared to 1990 practices		Gains equivalent to global 1990 food energy consumption (%)
Improved field efficiencies	Better agronomic practices (raise average yields by 20%)	22
	Higher fertilizer uptake (raise nutrient use efficiency by 30%)	7
	Reduced irrigation waste (raise water use efficiency by 30%)	7
Reduced waste	Post-harvest losses (lower by 20%)	6
	End-use waste (lower by 20%)	8
Healthier diet	(Limit fat intakes to 30% of total energy)	10
Total gain		60

Source: Smil (1994).

Food demand and dietary choices

World population growth is likely to come to an end in the foreseeable future. According to Lutz et al. (2001), there is around an 85% chance that the world's population will stop growing before the end of the 21st century. Furthermore, there is a 60% probability that the world's population will not exceed 10 billion people before the year 2100, with a median projection for the year 2050 of 8.8 billion. In any case this means that by 2050 about 50% more people have to be fed than currently.

Human diets are largely determined by economic factors, particularly prices and incomes. As income rises, people tend to consume more calories in total, and the share of animal calories increases, especially the consumption of animal fats. In Africa, people derive two-thirds of their calories from starchy staple foods and only 6% from animal products. In Europe, people derive 33% of their calories from animal products and less than one third from starchy staples. The average global diet falls somewhere in between these two extremes (Table 7.2) (Bender and Smith, 1997).

As most developing countries in the future are likely to follow the trends in rich countries, global meat consumption can be expected to rise strongly over the next decades, due to a combination of population growth, growth in per-capita income and a high income elasticity of meat demand. Annual growth rates of aggregate meat consumption until 2030 are estimated between 1.4 and 3.0%. This would imply an increase in average global meat consumption per capita from 32.6 kg/year to 44-54 kg/year, depending on growth assumptions (Keyzer et al., 2001).

Table 7.2 Major sources of food energy in industrialised and developing countries (1994, % share)

Product group	Industrialised countries	Developing countries
Cereals	31	56
Meat and dairy products	28	12
Sweeteners and vegetable oils	23	17
Roots and tubers	4	5
Others	14	10

Source: Adapted from Bender and Smith (1997).

Agricultural supply and resource use

In view of the described rapid developments on the demand side, it is heavily debated whether global food supply will keep up with this pace or whether farming activities will run into serious conflict with the concurrent goal of preserving local environmental conditions. In the past, agricultural production could rely on virtually costless water supplies as well as available land for expansion. Meanwhile, most of the potentially available arable land is already under cultivation and future production increases will have to be achieved mainly through more intensive production technologies on the currently used area of land. However, improper management and irrigation techniques have already caused serious land degradation on a large scale. In the future, agriculture will have to compete for water and land with other economic activities, like urban development, industrial use, forestry, and nature conservation (Kendall and Pimentel, 1994).

With respect to future yield increases, one can take an optimistic view and assume that past trends in agricultural productivity growth will continue for some time. Some model calculations show that even at conservatively reduced growth rates, global food supply will outpace demand up to 2020 and real prices for agricultural commodities are likely to continue to fall (Dyson, 1999; Rosegrant and Ringler, 1997). However, the assumption of exponential growth paths instead of logistic curves has been questioned. This distinction will become even more important in the very long run (Harris, 1996; Harris and Kennedy, 1999). The potential of biotechnology and genetic engineering for accelerating agricultural productivity growth is still very unclear and subject to strong public debate. Some initial trials show positive effects, but environmental consequences have to be further investigated and widespread social acceptance remains questionable (Qaim and Zilberman, 2003).

Land use

The amount of land necessary for the production of various food items differs widely, especially for animal products. Different animals have different feed requirements and feed conversion rates (Table 7.3) (Bender, 1997).

This directly contributes to the area of land required for certain food products (Table 7.4) (Gerbens-Leenes and Nonhebel, 2002). However, the required quality of land differs for various livestock production types. For example, ruminants like cows and goats are able to convert grass from permanent pasture land into valuable food for human consumption, but cattle can also be fattened on a feed mix with a large share of cereals. Pigs can be raised primarily on grains, but also on human food residuals. Hence, the amount and quality of land required for livestock production depends very much on the specific production systems.

Table 7.3 Conversion rates of grain to animal products (feed input per unit of output)

Animal product	Kg of feed/kg of output	Kcal of feed/kcal of output
Beef	7.0	9.8
Pork	6.5	7.1
Poultry	2.7	5.7
Milk	1.0	4.9

Note: These conversions are very approximate, as the caloric density of both feeds and animal products can vary greatly. Furthermore, data units are often not specified or precisely comparable.
Source: Bender (1997).

The total amount of land available for agriculture not only depends on biophysical conditions, but also on the demand for land for other economic and environmental purposes. Infrastructure development and urbanisation may reduce agricultural areas around the major population centres. In the course of a major energy transition there might arise a significant demand for bio-fuel production not only from fast growing forests, but also from agricultural crops. Moreover, a certain share of land may have to be set aside for nature conservation and biodiversity management, in order to maintain nature's basic life supporting functions (Goklany, 1998; Sands and Leimbach, 2003).

More intensive production systems may lead to land degradation, if they are applied year after year on the same area. The main types of land degradation are soil erosion from wind and water, chemical degradation (e.g. nutrient loss, salinisation, pollution), and physical degradation (e.g. compaction, water-logging). Land degradation is a very important issue in some geographic regions, but it remains unclear whether it may become a serious threat to global food supply (Döös, 2002; Rosegrant et al., 1997). While in some parts of the industrialised world problems of fertilizer overuse, like nitrate leaching and eutrophication, are of considerable concern, in many developing regions, like Sub-Saharan Africa, inadequate replenishment of removed nutrients reduce soil fertility and increase erosion. Hence, in order to assure sufficient nutrient supply for more intensive production on a global scale, the demand for fertilizer will rise. Especially nitrogen requirements will increase significantly, according to some estimates to 50% above current consumption by 2050. What this means for sensitive environmental systems and the nitrogen cycle, which is as yet neither well observed nor understood, remains unclear (Gilland, 2002; Rosegrant and Ringler, 1997).

Table 7.4 Specific land requirements per food item per year in the Netherlands in 1990 (m^2/kg)

Food item		Specific land requirement
Fats	Vegetable oil	20.7
	Low fat spread	10.3
Meat	Beef	20.9
	Pork	8.9
	Chicken filet	7.3
Milk products and eggs	Whole milk	1.2
	Cheese	10.2
	Eggs	3.5
Cereals and other crops	Cereals	1.4
	Sugar	1.2
	Vegetables (average)	0.3

Source: Adopted from Gerbens-Leenes and Nonhebel (2002).

Water use

The resource base that may pose the most serious limitations to future global food supplies is water. Irrigated area accounts for nearly two-thirds of world rice and wheat production, so growth in irrigated output per unit of land and water is essential to feed growing populations. Since the development of traditional irrigation and water supplies is increasingly expensive and new sources like desalination are not expected to play a major role soon, water savings at every level are necessary. Crop output per unit of evaporative loss has to be increased and water pollution has to be reduced. However, the size of potential water savings in agricultural irrigation systems is unclear. While specific water uses can be made more efficient through better technology, especially in many poor countries, the potential overall savings in many river basins are probably much smaller, because much of the water currently lost from irrigation systems is re-used elsewhere. Increasing water demand from households and industry will further exacerbate the challenge (Rosegrant and Cai, 2003; Wallace, 2000).

The specific water requirements for various agricultural products differs widely, from less than 200 litres per kg output for potatoes, sugar beets or vegetables, to more than 1000 litres per kg output for wheat and rice (Hoekstra and Hung, 2002). A typical diet with meat consumption at American levels requires about 5,400 litres of water for crop evapotranspiration, while a comparable vegetarian diet requires only about half the amount. In comparison, the daily amount of water required for drinking and sanitary purposes is almost negligible at less than 60 litres. The future global challenge with respect to agriculture and water implies that over the next 25 years food production has to be increased by about 40% while reducing the renewable water resources used in agriculture by 10-20% (Jaeger, 2001; Rijsberman, 2001).

Climate change

An additional influence on agricultural production in the long run, i.e. in the second half of the 21st century, is likely to occur through global climate change. A rise in atmospheric CO_2-levels and a corresponding rise in global temperatures will not only affect plant growth and yields, but also alter the regional patterns of precipitation and water availability as well as land erosion and fertility. Sensitivity studies of world agriculture to potential climate changes have indicated that global warming may have only a small overall impact on world food production because reduced production and yields in some areas are offset by increases in others. However, regional impacts vary quite significantly, with tropical regions especially suffering from droughts. Moreover, the combined effects of various changes in the long run are still highly uncertain (IPCC, 2001).

AN INTEGRATED ENVIRONMENTAL-ECONOMIC MODELLING FRAMEWORK

The impacts of agricultural production on natural conditions are strongly dependent on specific local conditions. Changes in water or nutrient cycles are related to soil conditions, terrain type and local climate conditions. Hence it is necessary to link economic conditions of agricultural production to the place-specific biophysical conditions, in order to better understand their interactions. The key challenge with respect to modelling is to link place-specific models of agricultural production and land use with models representing important elements of the biosphere and hydrology.

A comprehensive analysis of the world food system can draw upon a substantial volume of existing research in the area of integrated assessment and modelling. Issues of climate change and agricultural land use have been covered in the IMAGE[1] project and the ICLIPS[2] project (Toth et al., 2003), where greenhouse gas emissions of different land use patterns as well as the potential of bio-fuel production on agricultural land as an alternative energy source have been analysed (Sands and Leimbach, 2003). The US Department of Agriculture maintains its FARM[3] model, a computable general equilibrium (CGE) model with a focus on the interaction between climate change, economic growth, agricultural production and environmental resource use. The GTAP[4] consortium has developed a CGE modelling framework as well as a database for global economic analysis, and is also extending its focus towards agricultural resource use, especially land use issues. The International Institute for Applied Systems Analysis (IIASA) maintains its Basic Linked System (BLS) which has been applied to various questions on global environmental change (Fischer et al., 1988). It has also been linked with the agro-ecological zones (AEZ) model to

[1] Integrated Model to Assess the Global Environment. See also: http://sedac.ciesin.org/mva/image-2.0/image-2.0-toc.html.
[2] Integrated Assessment of Climate Protection Strategies.
[3] Future Agricultural Resources Model: www.cru.uea.ac.uk/link/hadcm2/abstracts/darwin_paper.html
[4] Global Trade Analysis Project: www.gtap.agecon.purdue.edu.

assess future changes in global land use and land cover (Fischer, 2001). The International Food Policy Research Institute (IFPRI) has a long tradition of partial equilibrium agricultural trade modelling with its IMPACT[5] model (Rosegrant and Ringler, 1997). Recently the IMPACT model has been coupled with the global hydrological model WaterGAP[6] in order to come up with more reliable global projections for water demand and supply (Cai and Rosegrant, 2002).

Our starting point to improve the understanding of society-biosphere interactions is the extension of one of the most advanced and comprehensive models of the global biosphere - the Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ).[7] We suggest a way to integrate human activities into LPJ and come up with a coupled climate-biosphere-economy modelling framework, including the global water cycle. This is an important improvement on existing research, as LPJ endogenously models the linkages between climate and soil conditions, water availability and plant growth in a dynamic way. This yields an advanced representation of global biogeochemical conditions, which can be used to define plausible biophysical constraints to agricultural production, or to human activities in general for that matter.

The Lund-Potsdam-Jena model (LPJ)

LPJ is a coupled non-equilibrium biogeography-biogeochemistry model which combines process-based representations of terrestrial vegetation dynamics and land-atmosphere carbon and water exchanges in a modular framework (Sitch et al., 2003). LPJ explicitly considers key ecosystem processes such as vegetation growth, mortality, carbon allocation, and resource competition, though their representation is of intermediate complexity to allow for global applications. To account for the variety of structure and functioning among plants, 10 plant functional types (PFTs) are distinguished. Leaf phenology of summergreen and of raingreen PFTs is determined daily, depending on temperature and water stress thresholds. Gross primary production is computed based on a coupled photosynthesis-water balance scheme; net primary production is given by subtracting autotrophic respiration. After additional subtraction of a reproduction cost, the remaining carbon is allocated to three pools for producing new tissue. Carbon from dead leaves and roots enters litter; decomposition of litter and soil organic matter is driven by soil temperature and water content. A PFT-specific mortality rate is determined at the end of each year as a result of heat stress, low growth efficiency, a negative carbon balance, light competition, or violation of bioclimatic limits. The presence and fractional coverage of PFTs is thus determined annually according to individual bioclimatic, physiological, morphological, and fire-resistance features (Sitch et al., 2003). The structure and distribution of the PFTs is decisive for the simulated site water balance, since evapotranspiration, soil water content, and runoff generation are modulated by

[5] International Model for Policy Analysis of Commodities and Trade.
[6] Water – Global Analysis and Prognosis: http://www.usf.unikassel.de/usf/mitarbeit/homepages/doell/research3.htm
[7] For a full documentation see: www.pik-potsdam.de/lpj/

PFT-specific attributes such as interception storage capacity, seasonal phenology, rooting depth, and photosynthetic activity.

The fundamental entity simulated in LPJ is the average individual PFT. This concept provides a simple way for process acting at the level of the plant individual to be scaled up to the 'population' over a grid cell. The grid cell is treated as a mosaic divided into fractional coverages of PFTs and bare ground. It is assumed that the physical environment of the plants is well mixed, i.e., the PFTs do not occupy discrete blocks, but compete locally for resources. The global version of LPJ has a spatial resolution of 0.5°, which is equivalent to a pixel size of about 50 x 50 km at the equator. This implies a total number of about 60,000 grid cells covering the whole terrestrial earth surface.

Overall, LPJ simulates the global terrestrial carbon pool sizes and fluxes, and captures the biogeographical distribution of Earth's major biomes. Recent applications of the model include assessments of the carbon balance of the terrestrial biosphere, the representation of fire regimes, and the simulation of transient vegetation responses to climate warming.[8]

A typical simulation with LPJ starts from 'bare ground' and 'spins up' for 1,000 model years until approximate equilibrium is reached with respect to carbon pools and vegetation cover. The model can then be driven with a transient climate (i.e. future climate scenarios provided by MPI Hamburg or the Hadley Centre). The standard LPJ simulation is run with the transient CRU data for 1900-1998.

In addition to the PFTs representing natural vegetation, recently 13 crop functional types (CFTs) have been implemented in LPJ in order to simulate potential agricultural production. These CFTs represent 8 classes of agricultural crops, e.g. temperate cereals (wheat), tropical cereals (millet), rice, maize, pulses (lentil), oil crops (sunflower, soybean, groundnut, rapeseed), roots and tubers (sugar beet, maniok), and fodder crops (C3 and C4 grass). As agricultural crops cover about 40% of the global land area, it has been shown that global carbon pools and water runoff are significantly affected when crops are taken into account in a global vegetation model like LPJ (Bondeau et al., 2003).

Input data required by LPJ are monthly fields of mean temperature, precipitation and cloud cover, which are taken from the Climate Research Unit (CRU) monthly climate data on a 0.5° x 0.5° global grid (CRU05, 1901-1998).[9] A data set of historical global atmospheric CO_2 concentrations extending from 1901-1995 was obtained from Carbon Cycle Model Linkage Project (CCMLP).[10] Soil texture data are from the FAO soil data set. Standard LPJ outputs include changes in net primary production and different fractions of biomass, changes in carbon pools (e.g. vegetation carbon, soil carbon), and changes in water balances (e.g. runoff). Under given climate conditions, soil type and water supply, the CFTs generate crop yields in terms of above-ground biomass as well as harvested organs (like grains, roots etc.). The CFTs are currently specified as to represent observable yields at the end of the 20th century.

---

[8] See LPJ website at http://www.pik-potsdam.de/lpj/lpj_publicvt1.html for a full list of publications.
[9] Climate Research Unit (CRU), University of East Anglia, Norwich, UK; www.cru.uea.ac.uk.
[10] CCMLP data source: http://eos-webster.sr.unh.edu/data_guides/ccmlp_dg.jsp.

MAgPIE - a management model of agricultural production and its impact on the environment

MAgPIE is set up as a linear-programming optimisation model with a focus on agricultural production, land and water use. The goal function is to produce a required amount of food energy, defined in GigaJoule (GJ), at minimal costs. Food demand is defined for an exogenously given population in three energy categories: crop energy, meat energy, and milk energy (at the moment we abstract from other vital food ingredients like proteins, etc.). Energy can be produced by choosing from 8 cropping activities (food grains, feed grains, oil crops, sugar crops, roots/tubers/pulses, vegetables/fruits/nuts, rice, fodder crops) and 3 livestock activities (ruminant meat like beef, veal, sheep and goat meat; non-ruminant meat like pork and poultry meat; milk).

Input factors of production are labour, chemicals, and other capital (measured in US$), land and water (measured in physical units, ha and m^3, respectively). Labour, chemicals and capital are in unlimited supply at a given price. Land and water are available in fixed amounts and are implemented as physical constraints to production. Available land is divided in crop land and pasture.

Given a certain yield per hectare for each cropping activity, the corresponding energy delivery is calculated with standard energy content parameters. Livestock energy is produced either with feed grains (non-ruminant meat) or with a mixture of pasture, green fodder and feed grain (ruminant meat, milk), in addition to labour, chemicals and capital. Currently we are looking only at one region without external trade. That means, the regional demand for intermediate inputs like feed grain and green fodder has to be met by regional production. In the model, the region is forced to be self-sufficient in food production.

Water supply is currently entirely from precipitation inflows. There are no managed water stocks like groundwater reservoirs, lakes or water storages. Water demand from production activities is calculated using fixed coefficients per unit of crop or livestock output. Water balances are calculated in the hydrological subsystem of LPJ.

In order to keep the cropping mix within plausible bounds we introduce rotational constraints. In our sample region Germany, for instance, it seems plausible to limit grain production to a maximum of 66% of total crop area, as on average every third year a different crop will be planted for reasons of crop management. For the same reason, sugar beets have been limited to 25% and oil crops to 33% of total crop area.

Even though in this chapter we are looking at Germany as an example, we use only data sources that are also available on a global scale. Crop yields are taken from the CFTs in LPJ and are checked for consistency with average regional yields according to FAO statistics. Average cost structures for production activities are calculated on the basis of FAO production and land use statistics and national social accounting matrices (SAMs) from GTAP.[11]

[11] At the time of writing this chapter, SAMs are available in the GTAP database for 78 regions with up to 57 economic sectors. See: http://www.gtap.agecon.purdue.edu/databases/v5/default.asp.

Output generated by MAgPIE includes crop and livestock energy produced, shares of different crops in total use of arable land, purchases of variable inputs, and shadow prices for inputs in limited supply and other constraints, like rotational limits. The generation of shadow prices (or ‘opportunity costs’) for land and water is probably the most useful feature of this model. It facilitates the assignment of internal use values to factors of production for which no proper markets and, hence, no observable prices exist. This can be particularly useful for the systematic valuation of ecosystem services, like water supply, as this model provides a rigorous economic framework for the use of these services.

Of course, this model is a strong over-simplification of real agricultural production. It is, for instance, not at all clear whether or not actual producers always act as strict cost minimisers or profit maximisers. Hence, the optimised mix of production and resource use generated by the model almost certainly differs from empirical observations. Moreover, the current version is a static model with a lot of exogenous inputs. However, this type of model can be easily scaled down to a single farm and scaled up to the world as a whole, thus providing the opportunity for nested modelling structures. It can also in principle be coupled to a food demand model or an economy-wide model, in order to make markets and prices for outputs and inputs endogenous. Here we will build upon recent developments in the area of model coupling and meta-optimisation at PIK (Jaeger et al., 2002).

Spatial scaling, model coupling and information flow

Several challenges have to be overcome in coupling a biosphere model like LPJ with an economic model like MAgPIE. First, thematic scales have to be matched. CFTs in LPJ, which are defined according to plant-physiological properties, have to be matched with groups of crops which provide a similar type of output for human consumption. Oil crops, for instance, comprise a wide variety of plant species (e.g. rapeseed, groundnuts, sunflowers, oil palms etc.), but they all deliver similar types of oil, which are almost perfectly substitutable in the processing of agricultural products. Currently our 8 cropping activities in MAgPIE match sufficiently well with the CFTs defined in LPJ.

Second, temporal scales have to be made consistent. Standard LPJ runs into the future covering a period up to the year 2100. Most economic forecasting exercises do not go beyond a time frame of 10-20 years. As they run into the longer-term future, they usually get more aggregated and lack structural detail. One of the reasons is that changes in technology and input use are very hard to predict in the long run. At the moment, we abstract from technical change and restrict ourselves to stylised scenarios in a comparative static manner. That means, we take ‘time slices’ out of certain LPJ runs, and couple them with static MAgPIE scenarios.

Third, and most importantly for the illustrative purpose here, we have to bridge the gap between the national (or even larger) scale in MAgPIE and the 0.5°-grid scale in LPJ. This is the most challenging aspect in coupling these two models. On the one hand, LPJ provides information on climate, soil, biomass and crop yields, carbon and water balances for about 60,000 grid cells on a global scale. On the other hand, information on food demand, agricultural cost structures, input use, crop shares and many crucial economic indicators are usually only available from official statistics for whole nation states. While it is obviously impossible to model economic activity on a 0.5°-grid, it does not make much sense either to model environmental impacts on the national level.

In order to bridge this gap, we developed a procedure to group the grid cells in LPJ into a small number of 'productivity zones', according to the normalised level of crop yields in each grid cell. These zones do not have to form compact geographic regions. However, once the zones are established, they are taken as homogeneous and in MAgPIE all cells within a certain zone are treated in the same way. The zones can differ with respect to climate conditions (temperature, precipitation), crop yields, share of crop land in total area, and their total size (i.e. number of grid cells belonging to the zone).

For the case of Germany we have 185 grid cells grouped into 6 different zones. Effectively this means, that MAgPIE can choose among 8 cropping activities and 3 livestock activities in 6 different zones, yielding in total 66 (i.e. 8 x 6 + 3 x 6) different production activities in the given region. With this procedure we are able to generate considerable differences in regional cropping patterns without being too demanding with respect to required data, especially on the economic side of our modelling framework.

We are also able to distinguish between constraints to be fulfilled in each zone and constraints to be fulfilled at the regional level. This introduces aspects of trade between zones. For instance, feed grain produced in any zone is pooled across all zones and can be used in the whole region, as long as the overall balance is maintained. In contrast, green fodder realistically has to be used locally (usually even on the same farm) and, hence, we impose a separate constraint for each zone. Land and water are also constrained in each zone, as they cannot be easily moved around. For the moment we abstract from the possibility of water transport through rivers, canals and pipes.

Having separate constraints for different zones implies that MAgPIE generates different shadow prices for each zone. Moreover, we get different patterns of specialisation and land use shares for each zone. The sequence of our joint modelling exercises runs as follows:

- Run LPJ for all crops separately with one CFT at a time, in order to determine potential crop yields for all crops in each grid cell at a certain point in time.
- Group the grid cells into productivity zones, according to normalised crop yields. Here, we should note that depending on climate and soil conditions, some crops are more productive than others - and vice versa - in different zones.
- Deliver information on zones (number of grid cells, average fraction of arable land, average precipitation) and crop yields (ton/ha, average for each crop in each zone) from LPJ to MAgPIE.
- Optimise production pattern and resource use for the whole region in MAgPIE.

- Deliver land use shares for all crops in all zones from MAgPIE to LPJ.
- Calculate impacts of different land use patterns on carbon and water balances in LPJ.

SCENARIOS AND SELECTED MODEL RESULTS

With the described modelling framework we want to simulate agricultural land use changes, driven by stylised economic and environmental forces. These driving forces can be analysed separately or in combination, and we can compare the magnitude of their economic and environmental effects. As a reference scenario we chose the situation in Germany in the year 2000, i.e. climate conditions, yields, the fraction of arable land and pasture in total area, and cost structures in agricultural production are taken for this point in time. Then we look at 4 different scenarios which are either driven by climate change through LPJ or by stylised socio-economic changes through MAgPIE. In a fifth scenario we combine all separate scenarios into one.

Scenarios

Five scenarios are defined:

- Climate conditions as predicted for the year 2020 (stylised representation of a typical environmental driving force).
- Increase in total food energy demand by 10% (stylised representation of an increase in food exports driven by increased global food demand).
- Decrease in meat energy demand by 10% (stylised representation of a change in lifestyles towards more vegetarian diets).
- Decrease in available crop land by 10% (stylised representation of increased demand for land for non-food purposes, e.g. bio-fuel production).
- Joint scenario - all 4 previous scenarios combined.

For our sample region Germany we have restricted our set of relevant cropping activities in MAgPIE to 5 crop types (food grains, feed grains, oil crops (i.e. rapeseed), sugar crops (i.e. sugar beets), and green fodder (i.e. silage maize)). According to FAO statistics these crop types currently account for about 87% of total crop land in Germany.

In Step (1) of our analysis we run LPJ for a selection of 185 grid cells covering Germany, with all CFTs separately in order to define potential yields for each grid cell. We do this twice, once with the average climate for the years 1991-2000 and once with a climate scenario for the average in years 2011-2020, taken from the ECHAM4 model.[12] Figure 7.1 shows yield distributions for the CFT 'temperate cereals' (i.e. wheat) in 2000. The map reveals significant variation in yields across the region. However, yields seem to depend too strongly

[12] ECHAM = European Centre for Medium-Range Weather Forecasts model, Hamburg version. For more information on ECHAM4 and other climate model scenarios see: http://ipcc-ddc.cru.uea.ac.uk/dkrz/dkrz_index.html.

on precipitation and less on soil conditions. This is partly to be explained by the rather crude soil classification in the global FAO soil data set used in LPJ.

Figure 7.1 Regional distribution of cereal yields in Germany in 2000 (tonnes dry matter/ha; own calculations with LPJ)

In Step (2) we use normalised yields of all CFTs in order to define 6 productivity zones. These can be roughly characterised by high, medium and low cereal yields in combination with high and low silage maize yields. Due to different climate conditions and yields, the spatial distribution of zones varies considerably between both years. Table 7.5 shows average yields for the 5 cropping activities in different zones as calculated in LPJ. A comparison with official FAO statistics on crop yields for Germany shows that LPJ currently overestimates yields in cereals and oil crops, while sugar beet yields are underestimated.

Table 7.5 Characteristics of productivity zones under different climate conditions

Zone	Share of regional crop land (%)	Precipitation (mm/year)	Yield (ton/ha)			
			Cereals	Sugar beet	Rapeseed	Silage maize
Climate 2000						
1	9	953	9.7	43.0	6.1	34.1
2	7	1016	9.9	32.0	5.7	23.0
3	19	755	8.7	42.1	5.5	32.7
4	39	691	8.6	35.4	5.4	25.6
5	4	653	7.8	39.3	5.0	31.9
6	22	593	7.8	36.0	4.9	26.3
Climate 2020						
1	3	967	10.8	49.7	6.7	36.1
2	2	1305	12.1	34.4	6.4	5.8
3	24	737	8.9	46.2	5.6	34.2
4	18	632	8.3	41.6	5.2	29.0
5	1	627	7.7	42.8	4.8	31.9
6	52	552	7.0	35.6	4.4	26.1

Source: Own calculations (LPJ), ECHAM4 climate scenario.

In Step (3) of our analysis these characteristics of zones and yields are imposed on the production activities in MAgPIE, and in Step (4) agricultural production and resource use are optimised for Germany.

Total food energy demand for Germany is calculated by multiplying a population of 82 million by an average daily food availability of 3,411 kcal or 14,272 MJ (according to the FAO food balance sheets). Note that this is not strictly food consumption, but rather food availability for consumption. More precise data on effective food intake are not available. The shares of total food energy consumption are 69% for plant-based energy, 17% for meat-based energy, and 14% for milk-based energy.

With the current specification of MAgPIE, in the reference situation total food demand in Germany can be met, in fact the self-sufficiency ratio is about 110%. Under these conditions the optimal solution for the model leaves about 10% of the crop land and 9% of the pasture unused. The resulting average land use shares for the whole region in all scenarios are shown in Table 7.6. To illustrate the variation in land use patterns among the zones, Table 7.7 shows the shares for all zones in scenario (b).

As a further important economic output of our modelling exercise we show calculated shadow prices for the combined Scenario (e) in Table 7.8. The results show considerable variation between zones, as e.g. crop land and pasture are

Table 7.6 Average land use shares for Germany under various scenarios (%)

Description	(reference)	(a)	(b)	(c)	(d)	(e)
	Year 2000	Climate 2020	Demand increase	Reduced meat	Reduced crop land	Combined scenario
Bread grain	16	11	11	21	11	13
Feed grain	50	53	55	45	55	52
Rapeseed	14	15	19	9	22	18
Sugar beet	0	0	3	0	1	0
Silage maize	10	11	12	10	11	12
Unused crop land	10	9	0	15	0	5
Unused pasture	9	1	4	9	10	1

Source: Own calculations (MAgPIE).

Table 7.7 Land use shares (%) in all zones in Scenario (b) (demand increase by 10%)

Description	Zone					
	1	2	3	4	5	6
Bread grain	66	66	3	0	0	0
Feed grain	0	0	63	66	66	66
Rapeseed	14	9	16	22	0	26
Sugar beet	0	0	8	0	24	0
Silage maize	20	25	10	12	10	8
Unused crop land	0	0	0	0	0	0
Unused pasture	0	55	0	0	0	0

Source: Own calculations (MAgPIE).

Table 7.8 Zone-specific shadow prices in Combined Scenario (e)

Constraint	Zone					
	1	2	3	4	5	6
Green fodder balance	-14	-127	-12	-14	-11	-13
Crop land	-612	-1,288	-319	-213	-106	0
Pasture	-2,800	0	-2,848	-2,819	-2,875	-2,841
Rotation cereals	-291	0	-319	-310	-301	-272
Water	0	0	0	0	0	0

Source: Own calculations (MAgPIE).

scarce in some zones, but not in all. Water is not a binding constraint in any zone, i.e. the shadow price is always zero. The rotational constraint on cereals is binding in all zones, except zone 2, which is, however, rather small in this scenario.

In Step (5) of the analysis the land use patterns for each zone are implemented in LPJ and in Step (6) the impacts on net primary production (NPP), carbon and water balances are calculated. Figure 7.2 shows the difference in NPP in scenario (e) compared to the reference situation in 2000. In this case the differences are mainly due to changes in climate conditions.

CONCLUDING REMARKS

With the preceding analysis we have shown how a grid-based dynamic global vegetation model and a non-spatial economic optimisation model can be coupled. The preliminary results are promising and show the viability of the concept. We were able to model combined impacts of changes in food demand and climate conditions on agricultural production and land use. Land use changes were disaggregated on a spatial grid and the related biophysical changes in net primary production, carbon and water balances were calculated. While in the reference scenario there is still a surplus of crop land in Germany, this is completely used up when demand for meat increases by 10%. In this scenario also more high-energy crops like sugar beet and rapeseed are produced. Pasture land only becomes scarce under changing climate conditions. The regional land use patterns are more strongly affected by climate change than by socio-economic driving forces. This is not surprising, as so far we have not considered any kind of yield growth through technical change, which would most likely have a strong impact over the period of two decades covered in our scenarios. Biophysical parameters in LPJ are not much affected by changing agricultural land use, since they much depend on non-agricultural land cover like forest, which we have not altered.

Several caveats apply to our analysis and it is too early to rely on the presented results. The 0.5°-resolution of the current version of LPJ is appropriate on the global scale, but too coarse for the analysis of specific smaller regions. Crop yields and crop growth functions in LPJ have to be further evaluated. The specification of production activities in MAgPIE is preliminary, especially the linkages between livestock and crop production, and water requirements by crops. The linear-programming technique is powerful, flexible, and computationally very efficient. However, LP models tend to be sensitive to minor changes in certain parameters and may not be robust in the case of large structural breaks. Our current approach to define productivity zones has to be reconsidered to be applicable for global-scale analyses. Immediate further research steps include the definition of two or more economic regions and to allow for trade in products among them. Activities of land conversion (e.g. deforestation or bio-fuel production on crop land) are also indispensable for modelling agricultural production on a global scale. A dynamic version of MAgPIE would be required to model perennial crops or forest management, and also to implement management of stocks of natural resources, like water. A dynamic optimisation model would also be more appropriate to be linked to the time-step mode of LPJ. The most challenging task will probably be the implementation of technological change, which is crucial for scenario analysis in the very long-run. Many aspects of water

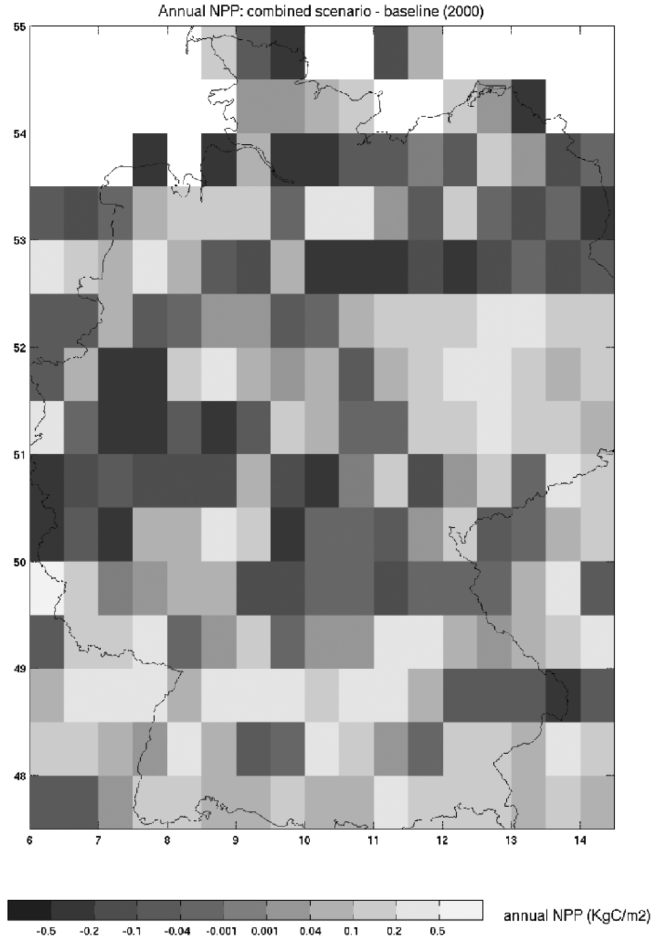


Figure 7.2 Regional changes in Net Primary Production (NPP), Scenario (e) compared to reference (kg C/m^2; own calculations with LPJ)

and nutrient cycles, especially nitrogen cycles, are only poorly monitored and not yet well understood, but they are strongly influenced by agricultural production technologies. A theoretical challenge would be to further enhance the knowledge about how technological changes are triggered by environmental conditions for production.

REFERENCES

Alexandratos, N. (1999) World food and agriculture: Outlook for the medium and longer term. *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 96 (11), pp. 5908-5914.

Alexandratos, N. (ed.) (1995) *World Agriculture: Towards 2010, an FAO Study*. Wiley and Sons, Chichester, UK.

Bender, W. and M. Smith (1997) Population, food, and nutrition. *Population Bulletin*, Vol. 51 (4), pp. 2-47.

Bender, W.H. (1994) An end-use analysis of global food-requirements. *Food Policy*, Vol. 19 (4), pp. 381-395.

Bender, W.H. (1997) How much food will we need in the 21st century?. *Environment*, Vol. 39 (2), pp. 7-28.

Bondeau, A., P. Smith, S. Schaphoff, S. Zaehle, B. Smith, S. Sitch, D. Gerten, B. Schröder, W. Lucht and W. Cramer (2003) *Accounting for agriculture in modelling the global terrestrial carbon cycle*. Poster presented at the European Geophysical Society (EGS) Meeting, Nice, April 6-11. http://www.pik-potsdam.de/lpj/egs2003_bondeau.pdf.

Bongaarts, J. (1996) Population pressure and the food supply system in the developing world. *Population and Development Review*, Vol. 22 (3), pp. 483-503.

Brown, L.R. and H. Kane (1994) *Full House: Reassessing the Earth's population carrying capacity*. Norton, New York.

Cai, X. and M.W. Rosegrant (2002) Global water demand and supply projections. Part 1: a modelling approach. *Water International*, Vol. 27 (2), pp. 159-169.

Döös, B.R. (2002) Population growth and loss of arable land. *Global Environmental Change-Human and Policy Dimensions*, Vol. 12 (4), pp. 303-311.

Dyson, T. (1999) World food trends and prospects to 2025. *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 96 (11), pp. 5929-5936.

Fischer, G. (2001) Integrating biophysical and socioeconomic factors in modeling impacts of global environmental change. In: T. Matsuno and H. Kida (Eds) *Present and Future of Modeling Global Environmental Change: toward integrated modeling*. Terrapub, Tokyo, pp. 271-292.

Fischer, G., K. Frohberg, M.A. Keyzer and K.S. Parikh (1988) *Linked National Models: a tool for international policy analysis*. Kluwer Academic Publishers, Dordrecht.

Gerbens-Leenes, P.W. and S. Nonhebel (2002) Consumption patterns and their effects on land required for food. *Ecological Economics*, Vol. 42 (1-2), pp. 185-199.

Gilland, B. (2002) World population and food supply - Can food production keep pace with population growth in the next half-century?. *Food Policy*, Vol. 27 (1), pp. 47-63.

Goklany, I.M. (1998) Saving habitat and conserving biodiversity on a crowded planet. *Bioscience*, Vol. 48 (11), pp. 941-953.

Harris, J.M. (1996) World agricultural futures: Regional sustainability and ecological limits. *Ecological Economics*, Vol. 17 (2), pp. 95-115.

Harris, J.M. and S. Kennedy (1999) Carrying capacity in agriculture: global and regional issues. *Ecological Economics*, Vol. 29 (3), pp. 443-461.

Hoekstra, A. and P.Q. Hung (2002) *Virtual Water Trade - A quantification of virtual water flows between nations in relation to international crop trade.* Research Report Series No. 11. IHE, Delft.

Intergovernmental Panel on Climate Change (IPCC) (2001) *Third Assessment Report - Climate Change 2001*. Geneva.

Jaeger, C.C. (2001) The challenge of global water management. In: E. Ehlers and T. Krafft (Eds) *Understanding the Earth System. Compartments, Processes and Interactions*. Springer, Heidelberg, pp. 125-135.

Jaeger, C.C., M. Leimbach, C. Carraro, K. Hasselmann, J.C. Hourcade, A. Keeler and R. Klein (2002) *Integrated assessment modeling: modules for cooperation.* FEEM Working Paper 53-2002.

Keyzer, M.A., M.D. Merbis and I.F.P.W. Pavel (2001) *Can we feed the animals? Origins and Implications of rising meat demand.* Working Paper WP-01-05, Centre for World Food Studies, Amsterdam.

Kendall, H.W. and D. Pimentel (1994) Constraints on the expansion of the global food supply. *Ambio*, Vol. 23 (3), pp. 198-205.

Lutz, W., W. Sanderson and S. Scherbov (2001) The end of population growth. *Nature*, Vol. 412, pp. 543-545.

McCalla, A.F. (1999) Prospects for food security in the 21st Century: with special emphasis on Africa. *Agricultural Economics*, Vol. 20 (2), pp. 95-103.

Parry, M., C. Rosenzweig, A. Iglesias, G. Fischer and M. Livermore (1999) Climate change and world food security: a new assessment. *Global Environmental Change*, Vol. 9 pp. 51-67.

Pinstrup-Andersen, P. and R. Pandya-Lorch (1998) Food security and sustainable use of natural resources: A 2020 Vision. *Ecological Economics*, Vol. 26 (1), pp. 1-10.

Qaim, M. and D. Zilberman (2003) Yield effects of genetically modified crops in developing countries. *Science*, Vol. 299, pp. 900-902.

Rijsberman, F.R. and D. Molden (2001) Balancing water uses: water for food and water for nature. Thematic background paper to the International Conference on Freshwater, Bonn.

Rosegrant, M.W. and X. Cai (2003) Global water demand and supply projections. Part 2: results and prospects to 2025. *Water International*, Vol. 27 (2), pp. 170-182.

Rosegrant, M.W. and C. Ringler (1997) World food markets into the 21st century: environmental and resource constraints and policies. *Australian Journal of Agricultural and Resource Economics*, Vol. 41 (3), pp. 401-428.

Rosegrant, M.W., C. Ringler and R.V. Gerpacio (1997) Water and land resources and global food supply. In: G.H. Peter and J. Von Braun (Eds) *Food security, diversification and resource management: refocusing the role of agriculture?* Ashgate, Aldershot, pp. 167-185.

Sands, R.D. and M. Leimbach (2003) Modeling agriculture and land use in an integrated assessment framework. *Climatic Change*, Vol. 56 (1), pp. 185-210.

Sitch, S., B. Smith, I.C. Prentice, A. Arneth, A. Bondeau, W. Cramer, J. Kaplan, S. Levis, W. Lucht, M. Sykes, K. Thonicke and S. Venevski (2003) Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ Dynamic Vegetation Model. *Global Change Biology*, Vol. 9, pp. 161-185.

Smil, V. (1994) How many people can the Earth feed. *Population and Development Review*, Vol. 20 (2), pp. 255-292.

Toth, F.L., T. Bruckner, H.M. Fussel, M. Leimbach and G. Petschel-Held (2003) Integrated assessment of long-term climate policies: part 1 - Model presentation. *Climatic Change*, Vol. 56 (1), pp. 37-56.

Wallace, J.S. (2000) Increasing agricultural water use efficiency to meet future food production. *Agriculture Ecosystems & Environment*, Vol. 82 (1-3), pp. 105-119.

Population and Economic Growth as Drivers of Future Land Use in India

8

Neeraj Sharma[1]

INTRODUCTION

With the world moving into a new millennium, the focus, concerns and confabulations across the globe centre on the direction of various components of well being in the next few decades. This includes development, production, as well as the environment we live in. This is so because we have just one 'World' and by the most conservative estimates the countdown to finality may already have been set in motion by man or to put mildly by the 'dynamic forces of Nature'.

This chapter presents a perspective on the challenges facing India in terms of population and economic growth and future land use patterns. It argues that, for a developing country like India, the future land use patterns are likely to be decided by the growth in population and economy over the next few generations. Climate change, agriculture and land use are so much interdependent that, in our context, a change in one of them would have effects on the other two parameters. These changes are likely to result in a transition to the next level of development. In this chapter, we shall discuss the present status of India's population, projections for selected years up to 2050. Then we shall discuss the current state of food availability and projections of demand and supply of food grains up to 2050. And finally, an attempt has been made to see whether the food supply would be able to keep pace with increasing population and economic growth. In the last sections the implications of change in climate, future land use patterns and agriculture is examined.

The background

In today's global scenario India accounts for nearly one sixth of the world's six billion people and only about 2% of the world's area. Over the last five and a half decades, since India gained independence, its population has increased at a very rapid pace – growing nearly two and a half times since 1947. India's investment

[1] The views expressed in the chapter are the author's alone. Usual disclaimers apply.

F. Brouwer and B.A. McCarl (eds.), Agriculture and Climate Beyond 2015, 131-146.

in agricultural research and development coupled with contributions from international scientific collaborations especially in agriculture in the early sixties and also trade, to a limited extent, has helped it feed the burgeoning population. On a macro scale, India is self sufficient in food grain production However, such self sufficiency may not necessarily continue into the future. A growing population and economy exert pressures on production inputs - the most critical of them being land. New agricultural technologies and increased rural incomes are likely to change food demand and rural living patterns in the coming decades. Food demand will be determined by population distribution in different income groups. This in turn, would affect land use patterns and demand for agricultural resources. There has already been a shift in cropping and consumption patterns since the mid-sixties. The chapter, as stated earlier, examines trends in food demand, cropping patterns, and trade in terms of resulting land use, food production, and environmental attributes. The analysis is done for India, which will support nearly one sixth of world population by 2050.

POPULATION GROWTH

India was the first country in the world to adopt a programme to reduce birth rates aimed at stabilizing population 'consistent with the requirement of the national economy.' Ironically the programme could not achieve the desired results in the early decades of its implementation. Replacement level fertility is estimated to be achieved by 2026. Yet, because of population momentum, the population will continue to grow for some more time. Mukhopadhyaya (2000) observed that during 1901-1921, the population of India increased from 238 to 251 millions, in subsequent three decades the annual exponential growth rates were above 1%. After 1951 the population exhibited an average annual growth rate of around 2%. The second half of the twentieth century witnessed India's population increasing from 361 million in 1951 to 964 million in 1998.

While global population has increased threefold during this century, from 2 billion to 6 billion, the population of India has increased nearly five fold. India's current annual average 15.5 million people population increase is large enough to neutralize efforts to conserve the resource endowment and environment (Government of India, 2001) and most of the increase in food grain production has been absorbed by population growth. The growth rate of population has slowed down from 2.1% per annum in 1980s to 1.7% in the 1990s.

As India could not reduce its population growth to desired levels, the National Health Policy, 1983, set more specific goals. It stated the long-term goal of Net Reproduction Rate of unity (NRR = 1.0) by the year 2000 AD. This goal corresponds to a family size of 2.1, crude birth rate of 21, crude death rate of 9 and natural rate of population growth of 1.2% per annum. It would require a contraceptive prevalence rate of 60%.[2]

India's population was 361.6 million in 1950-51, which increased to 683.3 million in 1980-81 and to one billion in May 2000. The birth rate and death rate

[2] United Nations Fund for Population Activities, (www.unfpa.org.in/Publications/FOOD/populationpress.htm)

were 39.9 and 27.4 in 1950-51, which came down to 33.9 and 12.5 respectively in 1980-81 and to 26.4 and 8.8 respectively in 1998-99. The fall in death rate is explained by better availability and access to medical facilities coupled with increased availability of food grains. If current trends continue, India will overtake China by 2045 to become the most populous country in the world.

Population projections

India's population growth rate has continued to decline since 1971. It came down from a high of 2.25% per annum in the 1970s to 1.69% in the late 1990s. The growth rate is expected to decline further with projections it will approach 0.92% by 2020. Numerous attempts have been made to estimate population at different points in the future. The India Vision 2020 Document considered two alternate scenarios for achieving population stabilization. In their optimistic scenario, based on achieving the demographic goals of National Population Policy 2000, life expectancy is assumed to rise to 71 for males and 74 for females by 2020. Under their realistic scenario, life expectancy is assumed to reach 65 for males and 69 for females by 2020. Under either scenario India's population would exceed 1.3 billion by 2020.

The growth rate of population is expected to be positive (0.33%) even in 2051 (Kulkarni, 2000) compared to growth rates of nearly 2% during 1980s and 1990s. The projected size of the population in 2051 is 1,646 million, an increase of nearly 95% over that in 1991. This makes the doubling interval about 60 years. Lower fertility rates would mean that the rate of growth of population shall be lower.

Projections for different age groups (Table 8.1) show that the 15-64 year age group will have expanded by 46% by 2020. The dependency ratios of the population shall also change and shall be lower at 46% than 67% which prevailed in the year 2000. Dependency ratio is a measure of the portion of population which is dependent (either because they are too young or too old to work) on the working population. The dependency ratio is equal to the number of individuals aged below 15 or above 64 (economically dependent) divided by the number of individuals aged between 15 and 64 (economically productive), expressed as a percentage. The World Development Report (1984) projects population to reach 1,522 million by the year 2050. The population growth rate during 1991-2000 was calculated using the figures of 846.6 and 1,000 million respectively which came to 1.85[3]. It was then assumed that there shall be a reduction in this rate of growth by 0.3% in every decade. This gave a population size of 1168.2 million in the year 2010. The background paper for the Tenth Plan states that the population of the country is expected to grow from 1,027 million in 2001 to 1,409 million in 2026 and to 1,628 million by 2051 (Srinivasan and Shastri, 2002).

The difficulty is that depending on the requirements and objectives of their studies, different researchers have estimated population size for different years in future. For simplicity the target years taken in this study are 2020 and 2050. The population estimates in this chapter have been assessed more from the point of

[3] Natural rate of growth was calculated using the formula $a=be^{it}$ where i=growth rate and t=time period.

view of getting a reasonably good idea of its possible size rather than very accurate mathematical precision as long term projections for such a variable will be influenced by numerous factors difficult to assess and measure. Factors like education, per capita GDP etc. are themselves dependent on other variables.

Table 8.1 Distribution of population by age category for 2000 and 2020 (million inhabitants)

Age category	2000	2020
<15	45	76
15-64	604	882
>65	361	373
Total	1,010	1,331

Source: Bhat (2001).

Srinivasan and Shastri (2002) projected that the population of India would be around 1.4 billion in 2025. He goes on to state that the population size is expected to reach this mark whether India attains the goals of the National Population Policy for 2010 or not, by 2051, India's population would almost be equal to that of China's. But India's population would still be growing at a rate of 1% per annum, even though the level of fertility required for long-run population stabilization would have been achieved by then (Bhatt, 2001). The trends of population growth in India has been broadly in tune with the classical theory of demographic transition into four phases and India is supposed to have entered now in the fifth phase, of rapidly declining fertility. The point of concern is that this growing population shall exert pressure on the economy of the country as well as the environment. It is with this view that the productivity of agriculture is discussed in the following section.

Table 8.2 Projection of India's population up to the year 2050 (million)

Year	Average annual growth rate (%)	Author's projection
2010	1.55	1,168
2020	1.25	1,324
2030	0.95	1,457
2040	0.65	1,555
2050	0.35	1,611

PRODUCTIVITY OF AGRICULTURE

During the last 30 years, India's food grain production nearly doubled from 102 million tons in the triennium ending 1973 to nearly 200 million tons by 1999 (Table 8.3). Virtually all of the increase in the production resulted from yield gains rather than expansion of cultivated area. Availability of food grains per capita increased from 452 gm/person/day to over 476 gm/person/day, even as the country's population almost doubled, swelling from 548 million to nearly 1000 million (Singh, 2002b).

Table 8.3 Production of food grain between 1950 and 2002

Year	Area (million ha)	Production (million tons)	Yield (kg/ha)	% area under irrigation
1950-51	97.32	50.82	522	18.1
1960-61	115.58	82.02	710	19.1
1970-71	124.32	108.42	872	24.1
1980-81	126.67	129.59	1,023	29.7
1990-91	127.84	176.39	1,380	35.1
1998-99	125.17	203.61	1,627	42.4
1999-00	123.10	209.80	1,704	43.9
2000-01	121.50	196.81	1,626	NA
2001-02	121.91	212.03	1,739	NA
2002-03	113.13	182.87	1,614	NA

NA = not available.
Source: Government of India (2003).

The area under food grains has hovered around 125 million ha since 1970-71. This indicates that the limit to increasing production through area expansion may have been reached as far as the cultivable land is concerned.

During the period 2002-05 GDP of the country was expected to grow at a rate of about 6.5% and the population at the rate of 1.7% per annum. The demand for food grains would grow at a rate of 2.5-3%. Under such a case the observed rate of growth of agriculture production would be just enough to feed the growing population. However, to make the country hunger free the food grain production will have to be accelerated at a compound rate of 4% per annum.

Taking the above evidence into account various scenarios estimations were made (Paroda and Kumar 2000) for the year 2020. These are presented in Table 8.4. In addition, taking the set of population projections in Table 8.4, an attempt was made to work out the food grains requirements for various decades until the year 2050. This has been worked out using the assumption that with 201.56 million tons of food grains India is able to feed its population of one billion and that this ratio of production to population would feed the population at any point in the future and that consumption will not fall below this level. The present daily caloric intake in has been taken at 2,500. With increase in incomes as a result of development, this intake has been assumed to increase to 3,500 in 2050 - an increase of 40% (over the base level daily consumption of 2,500 calories) in next fifty years. This would generate additional demand for food grains as a result of better nutritional intake. The present share of animal products in daily calorie intake is about 7%. It has been assumed that over the next fifty years the share of animal products in daily calorie intake would increase to 15%. The results are presented in Table 8.5.

Table 8.4 Projected demand for agricultural commodities in 2020

Item	Average 1997-99			Demand in 2020 (million tons)	
	Area (million ha)	Production (million tons)	Yield (kg/ha)	Low growth (3.5% per capita growth of GDP)	High growth (5.5% per capita growth of GDP)
Food grains	120.8	199	1,595	255.9	252.8
Edible oil	28.6	6.4	269	10.8	11.4
Potatoes	1.2	21.6	17,188	27.8	30.6
Vegetables	5.3	74.5	14,204	135.6	168
Fruits	3.2	43	13,437	77	93.6
Sugarcane/ gur	3.7	26.9	7,006	32.6	33.7
Milk	-	71.2	-	115.8	137.3
Meat	-	5	-	8.8	11.4
Eggs	-	2,873	-	7,750	10,000
Fish	-	5.3	-	10.1	12.8

Based on Paroda and Kumar (2000).

Table 8.5 Population and food grain requirements during the period 2010–2050

Year	Population (million)	Food grain requirements (million tons)
2010	1,168	268
2020	1,324	344
2030	1,457	425
2040	1,555	506
2050	1,611	582

Bhalla et al. (1999) took the official figures for population projection for 2020 as base and considering different determinants of demand such as rate of urbanization, rise in per capita income, changes in consumption behaviour and expenditure elasticities estimated the demand for food grains. The projections are presented in Table 8.6.

Table 8.6 Estimation of food demand in India for the year 2020 (in million tons)

Year/Source	Food	Feed	Total	Average (kg/ capita/day)
1993 (actual)	147.12	3.71	150.83	0.47
For 2020				
GDP growth rate (%)				
2.0	231.51	25.75	257.26	0.53
3.7	246.08	50.11	296.19	0.61
6.0	267.21	107.52	374.73	0.77

Source: Bhalla et al. (1999).

The supply side

Given that the demand for cereals will be around 350 million tons, we now examine whether this demand is likely to be fulfilled. India has high population pressure on land and other resources to meet its food and development needs. The natural resource base of land, water and biodiversity is under severe pressure. Food demand challenges ahead are formidable considering the non-availability of favourable factors of past growth, fast declining factor productivity in major cropping systems and rapidly shrinking resource base.

Future increases in the production of cereals and non-cereal agricultural commodities will have to be achieved mainly through increases in productivity, as the possibilities of expansion of area and livestock population are minimal. Average yields of most crops in India are still rather low (Singh, 2002a). To meet the projected demand in 2020, the Indian Agricultural Research Institute estimates that yields must attain per hectare levels of 2.7 tons for rice, 3.1 tons for wheat, 2.1 tons for maize, 1.3 tons for coarse cereals, 2.4 tons for cereal, 1.3 tons for pulses, 22.3 tons for potato, 25.7 for vegetables, and 24.1 tons for fruits. The production of livestock and poultry products must be improved by 61% for milk, 76% for meat, 91% for fish, and 169% for eggs relative to 1997-9 yields.

Virtually no productive land remains uncultivated in India today, so there is little scope for increasing the area cultivated. The remaining land is relatively unproductive and bringing it under cultivation would entail high environmental costs, including deforestation and soil erosion. Future growth will therefore have to continue to depend on yield and this will require the spread of yield-enhancing technologies, improved natural resource management, and greater technical efficiency (Bhalla et al., 1999). Taking into account the constraints and likely progress being made in production, processing and storage technologies it is estimated that India would be able to meet its food requirements. However, in the estimates arrived at by Bhalla et al. (1999) there is a gap between the demand and supply of cereals in India in 2020. Their estimates are presented in Table 8.7. This effectively means that even in the case where the country's GDP grows by a modest rate of 3.7% per annum there shall be a shortage of food grains in India. This gap widens as the country's growth rate increases. An increasing population along with increasing incomes would exert pressure on the available resources.

Table 8.7 Projected demand and supply of food and feed grains in India for the year 2020 (million tons)

Scenario	Supply scenario	Total supply (net of seed and waste)	Projected demand with growth of per capita income (%)		
			2.0	3.7	6.0
	Total demand		257.3	296.2	374.7
1	1962/65 -1993 trend extrapolated	321.1	63.8	24.9	-53.6
2	Reasonable increase in fertilizer and irrigation use	232.2	-25.1	-64.0	-142.5
3	(2) +genetic and efficiency improvements	259.9	2.6	-36.3	-114.8
4	(3) + additional land degradation	242.1	-15.2	-54.1	-132.6

Source: Bhalla et al. (1999).

Table 8.8 Projections for rice and wheat production using yields from National Demonstrations

Crop	Area (1998-99) (million ha)	Yield based on current practice (kg/ha)	Total production (million tons)	Yield based on demonstration plots (kg/ha)	Total production (million tons)
Rice	44.6	1,928	86.0	3,182	141.9
Wheat	27.4	2,584	70.8	3,500	95.9
Total	72.0	-	156.8	-	237.8

It has been observed that yield potentials of crops have not been realized to the fullest extent possible. For example for rice and wheat, which account for nearly 75% of total food grains in the country, only about 58% and 68% respectively of the yields achieved in the national demonstration plots have been realized (Table 8.8). Only 46% and 82% area under rice and wheat is irrigated. The average yield of rice was 1,851 kg/ha while that on demonstration plots was 3,182 kg/ha. Similarly, for wheat, the average yield was 2,387 kg/ha while that on demonstration plots it was 3,500 kg/ha (Pandey and Sharma, 1996). Thus, if the average yield increased even to the level equal to that achieved on the demonstration plots, India would be able to increase the production of food grains from the existing land base by around 50%. Then, in the second run if the yields of food grains reach the levels attained on research stations, the problem of shortages and pressures on land may be under control.

There is a small surplus in supply to demand in the 'medium' per capita growth scenario with the extrapolated growth rates. This however is wiped out only if moderate progress is made in genetic and technical efficiency in crops production. It would be prudent to assume that such shortfalls would be made good by international trade. Much would depend on international prices of grains as well as the size of their demand. The situation calls for caution well in advance as some steps may still be taken to reduce or mitigate the problems.

TRANSITION IN LAND USE PATTERNS

As in the past, public investment in rural infrastructure, agricultural research and extension, and the education and health of rural people will continue to play a key role in determining the rate of agricultural growth. In fact, the marginal returns to several infrastructure investments are now higher in many rain fed areas, and they also have a potentially greater impact on reducing rural poverty. This suggests the possibility that investment in infrastructure in rain fed areas can offer India a win-win strategy for addressing productivity and poverty problems.

The biggest constraint faced in increasing future supply of cereals would be the magnitude and efficiency of land used for crop production. There are competing uses of finite resource of land within a country's boundaries. Changes in land use and land cover, together with land degradation have adverse impacts on forest resources and biodiversity. Increasing demand for forest resources is of particular concern. In the 'India Vision 2020' report, it is observed that the potential exists for dramatically reversing this pattern of degradation during the next two decades (Table 8.9). The report argues this can be done by a concerted and systematic effort to halt soil erosion, restore precious nutrients and organic material to crop lands, recharge groundwater tables, and re-establish depleted forest lands, together with a holistic approach to land management that combines technologies and policies to integrate ecological, socio-economic, and institutional principles.

It has been estimated by Gupta (2002) that, at present, 40% of the commercial demand for timber and less than 20% of the demand for fuel wood are being met by sustainable supply from the forests. Population growth will result in rising demand for both. Over-grazing and over-extraction of green fodder lead to forest degradation through decreased vegetative regeneration, soil compaction and erosion. The degradation of land and forest is also endangering India's rich biodiversity.

Table 8.9 Projected land use patters for the year 2020

Sector	1997	Business-as-usual	Best case scenario
Agriculture	45.9	45.8	45.3
Forest cover	23.0	23.9	26.6
Pastures	3.5	3.5	3.5
Settlements and industry	6.8	8.5	8.4
Unused land	20.7	18.3	16.2

Source: Gupta (2002).

Ecological consequences of population pressure

The UNCED (United Nations Conference on Environment and Development) from 1992 acknowledged that population growth, rising income levels, changing technologies, and increasing consumption pattern will collectively have adverse impacts on environment. Ensuring that there is no further deterioration depends on choices made by the population about family size, life styles, environmental protection and equity. Availability of appropriate technology and commitment towards ensuring sustainable development is increasing throughout the world. Consequently, it might be possible to initiate steps to see that the natural carrying capacity of the environment is not damaged beyond recovery and that ecological balance is to a large extent maintained. It is imperative that the environmental sustainability of all developmental projects is taken care of by appropriate inputs at the planning, implementation, monitoring and evaluation stages.

Poor land use practices and management are responsible for the rapid land degradation in India. Various strategies need to be developed by the Government including policy intervention, promoting research and stakeholder participation, and technological intervention to control land degradation. The strategies identified by the government are as follows:

- An assessment of the nature and extent of the existing degraded land needs to be carried out.
- The adoption of land use according to the land capability classes (USDA classification modified to suit Indian conditions) will ensure that land is put to appropriate use.
- A balanced use of organic nutrients, chemical fertilizers, bio-fertilizers, and other agrochemicals will ensure sustainability.

- A well-defined integrated land use policy should be developed. Rural fuel wood, grazing and fodder policies also need to be developed.
- A national land use commission should be instituted to lay down such formulate policies, implementation strategies and monitoring guidelines.

The Tenth Five Year Plan (period 2002-2007) adds additional strategies like improving cropping intensity, development of rural infrastructure, and increasing public investments in agriculture. Since considerable investment is planned to go into improving infrastructure especially for irrigation and technology development it will have a beneficial effect on the GHG emission from this sector by reducing energy consumption.

AGRICULTURE, LAND USE AND EMISSIONS OF GREENHOUSE GASES

With emissions of greenhouse gases (GHG) increasing, the only way out is to control and reduce such emissions from different sources. This chapter concentrates only on the aspects of agricultural land use resulting in emissions of greenhouse gases. It is only during the last few years that research in India has started focusing on the vulnerability and assessment of GHGs. Long term time series observations are not readily available and have to be estimated using different assessment methods.

India's share of total world carbon emissions is 4%. This is relatively low compared to the 13% share of China and the 23% share of the US. Patterns of land use in India fased considerable changes during the past fifty years. Most of these changes took place during the period from 1950 to 1971. The changes involve the cropping pattern, diversion of land to non-agricultural uses, changes in the ownership of land and the influence of land reform measures like consolidation of holdings. Large tracts of fertile land have been diverted to urban needs. Since 1970, the net sown area remained more or less stagnant at 125 million ha. More than half of the country's total geographical area is suffering from degradation. More importantly, the extent of degradation is not only increasing over time but also growing at an increasing rate. Land degradation takes place largely in the form of soil erosion from water. In India, with growing population, there is relentless pressure to convert forest lands for agriculture. Several factors increasing considerably, including cattle grazing, collection of fuel and fodder, industrial use of land, irrigation projects, housing and urban development. Up-to the late 1970s, forestland was a prime target for diversion for resettlement, agriculture and industrialization, and this trend was contained only by the Forest (Conservation) Act of 1980. Until 1980, India's forest cover was being lost at the rate of 144,000 ha a year. The average annual costs of this degradation have been estimated to be about 3.5% to 4.9% of the GDP (Table 8.10).

Harasawa et al. (2002) state that the productivity of agricultural land will be greatly influenced by future environmental changes. For example, climate-induced changes are expected to have profound impacts on potential crop yields and influence the distribution of cropping patterns in the Asia-Pacific area. GTAP (Global Trade Analysis Project) was used by Harasawa et al. (2002) to assess the impact of climate change on the economy through changes in crop productivity within each region examining changes in producer prices, agricultural production and social welfare. Comparing the changes in social welfare per capita, India was the country likely to suffer the most damage as the model reflected a significant decline in the productivity of wheat in India and the comparatively large share of agricultural products purchased using private funds.

Table 8.10 Annual costs of environmental degradation in India 1994-1997 (% of GDP)

Resource	Cost range
Air	0.4
Forests	1.1 – 1.6
Soil	0.3 – 0.8
Water	1.7 – 2.1
Total	3.5 – 4.9

Source: Parikh and Parikh (2001).

Impact of climate change on Indian agriculture

The main direct effects on agriculture in India in next 25-30 years will be through changes in factors such as temperature, precipitation, length of growing season, and timing of extreme or critical threshold events relative to crop development, as well as through changes in atmospheric CO_2 concentration (which may have a beneficial effect on the growth of many crop types). According to Shukla et al. (2003) the indirect effects will include potentially detrimental changes in diseases, pests and weeds, the effects of which have not yet been quantified in most available studies. In the tropics where some crops are near their maximum temperature tolerance and where dry land, non-irrigated agriculture predominates, yields are likely to decrease.

The present scenario of GHGs in India

In the GHG emission estimations in the Asia Least-cost Greenhouse Gas Abatement Strategy (ALGAS) project undertaken by the Asian Development Bank, the CH_4 emissions from the agricultural sector were 12,654 Ggs while N_2O, NO_x and CO was 243; 109 and 3038 Ggs respectively. Total emissions were estimated at 1,001,352 Ggs of CO2 Equivalent. Of these estimated emissions from the agricultural sector were 341,064 Ggs. The total CO_2-equivalent emissions from India were estimated to be 1,001,352 Gg, which were about 3% of the total global CO_2-equivalent emissions. Based on this, the per capita CO_2-equivalent emissions for 1990 were estimated to be 1.194 tonnes (325 kg C). The per capita emissions for Japan and USA were 2,400 and 5,400 kg C in 1990. The projections made in the ALGAS Report (ADB, 1998) for 2020 indicated that per capita emissions for India in 2020 would be in the range of 460-485 kg C, a mere one tenth of 1990 per capita emissions in the USA.

Table 8.11 India's greenhouse gas inventory in agriculture in 1990 (in Gg)

	CH_4	N_2O	NO_x	CO	CO_2 equivalent
Enteric fermentation	7,563	-	-	-	158,823
Manure management	905	-	-	-	19,005
Rice cultivation	4,070	-	-	-	85,470
Agricultural soils	-	240	-	-	74,400
Prescribed burning of savannas	-	-	-	-	-
Field burning of agricultural residues	116	3	109	3,038	3,366
Total	12,654	243	109	3,038	341,064

Source: Asian Development Bank (1998).

Projections of green house gas emissions from agricultural sector for the year 2020 have been done by the Tata Energy Research Institute (TERI) as well as the National Physical Laboratory (NPL) New-Delhi. Their findings are summarized in Table 8.12.

Table 8.12 Projections for methane emissions until 2020 (in Gg)

	1900	2000	2010	2020
Enteric fermentation	7,563	8,297	9,102	9,985
Manure management	905	977	1,036	1,099
Rice				
- NPL	4,070	4,560	4,830	5,120
- TERI	3,090	3,260	3,630	4,050
Total	12,538	13,834	14,968	16,204

Source: Asian Development Bank (1998).

The Planning Commission in India has devoted attention to mitigation of GHGs in the coming decades. Figures for projected air emissions, not exclusively of the agricultural sector are presented in Table 8.13.

Table 8.13 Projected air emissions for the year 2020 (million tons)

	1997	2020 (business-as-usual)	2020 (best case scenario)
Sulphur dioxide	1.38	3.57	2.47
Particulate	13.93	8.92	2.83
Nitrogen oxides	1.91	3.84	2.37
Hydrocarbons	0.02	0.07	0.04
Carbon monoxide	11.33	22.32	13.27

Present data for the GHGs emissions from the agricultural sector are still not very precise as the base data for livestock population as well as land use need a long time to collect. However, in the recent years the National Remote Sensing Agency has been conducting extensive surveys to help ascertain land cover and land use besides many other parameters. Satellite image based land use planning would provide more accurate results if long term satellite based land use statistics is readily available.

CONCLUSIONS AND EPILOGUE

A growing population, increasing rural incomes and change in the structure as well as the magnitude of food demand will exert pressure on land and would result in change in crop mix and green cover. The production pressure on land base is evident from soil erosion degradation and even water logging and salinisation.

The conclusions emerge from the analysis:

- India’s population has increased rapidly in spite of an operational population control programme since last fifty years.
- This growing population would need additional food as a result of growth in numbers, increase in per capita income and changing consumption patterns.
- Requirement of additional food as well as a resultant change in the cropping pattern would affect the future land use patterns as well as emissions in greenhouse gases from agricultural sector.
- India would be able to meet its food demand.
- All the effects of a transition in agriculture may not be beneficial.
- Population and economic growth shall be the drivers of future land use patterns in India.

The dilemmas faced are very well summed up in the opening lines of Eileen Wilson’s report ‘Is agriculture part of the problem or part of the solution?’ where the opening lines are ‘Every year, nearly 17 million hectares of tropical rain forests are destroyed, thousands of irreplaceable plant varieties are lost, and millions of hectares of land turn into deserts. Will increased agricultural production, with its associated use of fertilizers, pesticides, irrigation, and farm machinery only exacerbate these severe global environmental problems? In short, does the goal of meeting the world's future food needs conflict with the goal of protecting the environment? According to researchers, one of the major causes of the environmental stress in the developing world is poverty, and one of the major causes of poverty is environmental stress.'

REFERENCES

Agarwal, C., G.M. Green, J.M. Grove, T.P. Evans and C.M. Schweik (2001) *A Review and Assessment of Land Use Change Models. Dynamics of Space, Time, and Human Choice*. Center for the Study of Institutions, Population, and Environmental Change, Indiana University and USDA Forest Service.

Asian Development Bank (1998) *Asia Least-cost Greenhouse Gas Abatement Strategy (ALGAS)*. India, Asian Development Bank, Manila Philippines.

Bhalla, G.S., P. Hazell and J. Kerr (1999) *Prospects for India's cereal supply and demand to 2020; food, agriculture and the environment*. Discussion Paper 29, International Food Policy Research Institute, Washington.

Bhat, P.N. Mari (2001) Indian Demographic Scenario 2025, Population Research Centre, Institute of Economic Growth, Delhi.

Government of India (2001) *National population policy 2001*. Planning Commission, New Delhi.

Government of India (2003) India's initial national communication to the UNFCCC, www.natcomindia.org/initial_natcom.pdf, accessed 16 Nov 2003.

Gupta, S.P. (2002) *Report of the Committee on India Vision 2020*. Planning Commission, Government of India, New Delhi.

Harasawa, H., Y. Matsuoka, K. Takahashi, Y. Hijioka, Y. Shimada, Y. Munesue and M. Lal (2002) Potential Impacts of Global Climate Change, www.nies.go.jp/social/aim/india0210/presentation/AIM_papers/03_Impact_Global.pdf, accessed 16 Nov 2003.

Kulkarni, P.M. (2000) *Prospective changes in the size and structure of India's [population-implications of PFI projections up to 2051*. Department of Population Studies, Bharathiar University, Coimbatore.

Mukhopadhyay, S.K. (2000) *Population growth and agricultural development in India*. Institute for Studies in Population, Agriculture and Rural Change (INSPARC), University of Kalyani, Kalyani.

Pandey,V.K. and K.C. Sharma (1996) Crop diversification and self-sufficiency in food grains, *Indian Journal of Agricultural Eco*nomics, Vol. 51 (4), pp. 644-651.

Parikh, J. and K. Parikh (2001) Accounting for environmental degradation: A case study of India. SDF-India Project Report. UNU/IAS, Tokyo.

Paroda, R.S. and P. Kumar (2000) Food production and demand in South Asia, *Agricultural Economics Research Review*, Vol. 13 (1), pp.1-24.

Shukla, P.R., R. Nair, M. Kapshe, A. Garg, S. Balasubramaniam, D. Menon and K.K. Sharma (2003) Development and climate - an assessment for India. Indian Institute of Management, Ahmedabad, May.

Singh, P. (2002a) *Agriculture policy: Vision 2020*. Background paper for Committee on Vision 2020 for India, Planning Commission, New Delhi.

Singh, P. (2002b) *Trends in fertility, mortality, nutrition and health indicators*. Background paper for Committee on Vision 2020 for India, Planning Commission, New Delhi.

Srinivasan, K. and V.D. Shastri (2002) A set of population projections of India and the larger states based on 2001 census results, Background Paper Committee on Vision 2020 for India, Planning Commission, New Delhi.

Bottom-up Methodologies for Assessing Technical and Economic Bioenergy Production Potential

9

Edward M.W. Smeets, Jinke van Dam, André P.C. Faaij and Iris M. Lewandowski

INTRODUCTION

Biomass has the potential to provide a renewable (green or largely CO_2 or climate neutral) energy source, locally available in large parts of the world. Biomass is also a very versatile energy source, because it can be used directly for heat and power or converted into liquid fuels.

Various studies have been undertaken during the 1990's to analyse the potential future contribution of bioenergy to the global energy supply. Most existing studies apply a top-down approach and use models (e.g. models on energy demand or net primary productivity) to calculate bioenergy potentials. The state-of-the-art in the global bioenergy production assessments consist of studies that use integrated models (such as the Global Land Use and Energy Model (GLUE) (Fujino et al., 1999), the Integrated Model to Assess the Global Environment (IMAGE) (Leemans et al., 1996; Hoogwijk et al., 2004), IIASA's Basic Linked System Model of the world food system (BLS) (Fisher and Schrattenholzer, 2001) and studies that estimate ranges in the contribution of biomass in the future global energy supply by reviewing previous assessments (e.g. Hoogwijk et al., 2002; Berndes et al., 2003).

There are many scenarios that project a further increase in the demand and use of modern biomass (e.g. Lashof and Tirpak, 1990; WEC, 1994; Shell, 1995; IPCC, 2000). Estimates of the contribution of bioenergy in 2050 to the global energy supply range between 0 to 1,135 EJ/yr[1] (Hoogwijk et al., 2002). For comparison the global primary energy consumption in 2002 was 428 EJ (IEA, 2004) and is projected to grow to 586 to 1,047 EJ in 2050 (WEC, 1994). The largest potential for bioenergy (up to 988 EJ/yr) comes from specialised bioenergy crops such as eucalyptus, willow, poplar, rapeseed, sugar cane or miscanthus (e.g. Lashof and Tirpak, 1990; Hall et al., 1993; Sorensen, 1999; Fisher and Schrattenholzer, 2001). Other biomass sources are forest harvests and

[1] All data on potentials used in this chapter refer to the primary energy content of biomass, without further specifying the further application for electricity or heat generation or for the production of liquid fuels.

F. Brouwer and B.A. McCarl (eds.), Agriculture and Climate Beyond 2015, 147-170.

residue flows from the agricultural and forestry sector such as straw, hulls, oilcakes, sawdust, woodchips and (organic) urban wastes.

If the mitigation of CO_2 emissions through bioenergy production is going to take place, global land use patterns may change drastically. These changes are usually not included in existing outlook studies on agriculture and forestry. The most extreme scenarios project that in the year 2050 2.6 Gha land are used for bioenergy crops, compared to a total area arable land and permanent crops of 1.5 Gha and an area permanent pastures of 3.5 Gha in 2001 (the total global land area is 13 Gha) (FAO, 2003a). Thus, bioenergy offers new opportunities for the agricultural sector. It also holds out the potential for developing regions to benefit. Developing country exports and export market expansion are limited by saturated markets and low prices (e.g. as found for coffee) and protectionism by industrialised countries (e.g. as found for sugar). Various outlook studies indicate that food prices will remain stable or decrease during coming decades (e.g. (IFPRI, 2001a), which limits the potential of the agricultural sector in developing countries. Bioenergy crop production may provide a new and/or more stable source of income. After all, the potential market for (bio) energy is enormous and the developing regions have a competitive advantage compared to the industrialised regions. Furthermore, the trade of bioenergy (biotrade) is presently a free and unregulated market.

The wide range in estimates of bioenergy potential provides little concrete information about regional possibilities and to what extent the (technical) potential can practically be developed. More detailed studies are required on the underlying factors that determine the potential for bioenergy production. Berndes et al. (2003) argue that the major reason for the large range of estimates on bioenergy crop potential is that the two most crucial factors, land availability and yields, are very uncertain. This uncertainty, in turn, is the result of uncertainties about the underlying factors that determine land use patterns, such as population growth, income growth (and resulting food demand and demand for biomaterials), agricultural and energy policies etc.

For a further development of bioenergy production projects, more detailed and regionally oriented assessments are required that provide insight into these uncertainties. In this chapter, some of the most recent developments in this field are summarised. Subsequently, some of the methodologies being employed and results of ongoing research are shown. For the calculation of bioenergy potentials, we can make a difference in various types of potential:

- Theoretical potential: the theoretically upper limit of global primary biomass production, which is limited by physical and biological barriers (the genetic potential of the crop) and the global surface.
- Technical potential: the theoretical potential that can be produced given a certain level of technology. E.g. the yield of a crop depends on the level of agricultural technology (the use of fertilisers, hybrid species, pesticides).
- Economical potential: the technical maximum that can be realised at profitable levels, usually depicted by a cost-supply curve of secondary biomass energy.

- Implementation potential: the fraction of the economic potential that can be implemented within a certain timeframe, taking into account institutional and social constraints and incentives.

In this chapter we present a methodology for and preliminary results of a bottom-up analysis of global technical bioenergy production potential (aggregated in regions) in 2050.[2] Included in this study are:

- The best available knowledge obtained from extensive study of existing databases, scenarios and studies.
- The impact of gaps and weak spots in the knowledge base. Existing studies frequently ignore or only partially identify weak spots in the knowledge base, data from existing studies and the interaction between existing studies.
- The impact of important underlying factors that determine bioenergy production potential.
- The impact of sustainability criteria such as avoidance of deforestation and competition for land between bioenergy production and food production and protection of biodiversity and nature conservation.

Note that the impact of climate change on yields is not specifically included in this study, since this impact is relatively small compared to the projected potentially technologically induced increases in crop yields. According to the Intergovernmental Panel on Climate Change (IPCC), generally positive changes in yields at mid- and high latitudes, are overshadowed by reductions in yields at low latitudes (IPCC, 2001).

The selected approach aims to identify promising regions for bioenergy production and the conditions under which production in these regions is feasible. If we zoom in from the global level (regional aggregated) to the national and sub-national level, socio-economic circumstances become relevant. From this point of view, we will also discuss methodologies for the assessment of the economic potential for bioenergy in this chapter. This methodology is developed in Van Dam et al. (2003) and follows a bottom-up approach at a national and sub-national level. The methodology is applied for the Central and Eastern European Countries (CEEC). The aim of this analysis is to find out whether the bioenergy potential in the CEEC is large enough to supply bio-fuels to the European market.

In the discussion, we will address the results and advantages and disadvantages of the methodologies discussed and the overall impact on the results.

A BOTTOM-UP METHODOLOGY TO ASSESS BIO-ENERGY POTENTIALS

The methodology used to make bottom-up estimates of the technical production potential for bioenergy includes various databases, the most important are:

---

[2] This research is part of the FairBiotrade project which is funded by the Dutch electricity company Essent N.V. and NOVEM (Netherlands Organisation for Energy and the Environment).

- population;
- per capita food consumption;
- per capita use of biomaterials;
- land use patterns;
- food crop yields;
- natural forest growth;
- animal feeding patterns;
- bioenergy crop yields; and
- feed conversion efficiency in animal production.

Historic changes will be derived from existing databases and studies. Future trends are analysed by means of scenario analysis, which allows examination of the impact that various parameters have. The various parameters are grouped and correlations are included in a spreadsheet tool summarised in Figure 9.1.

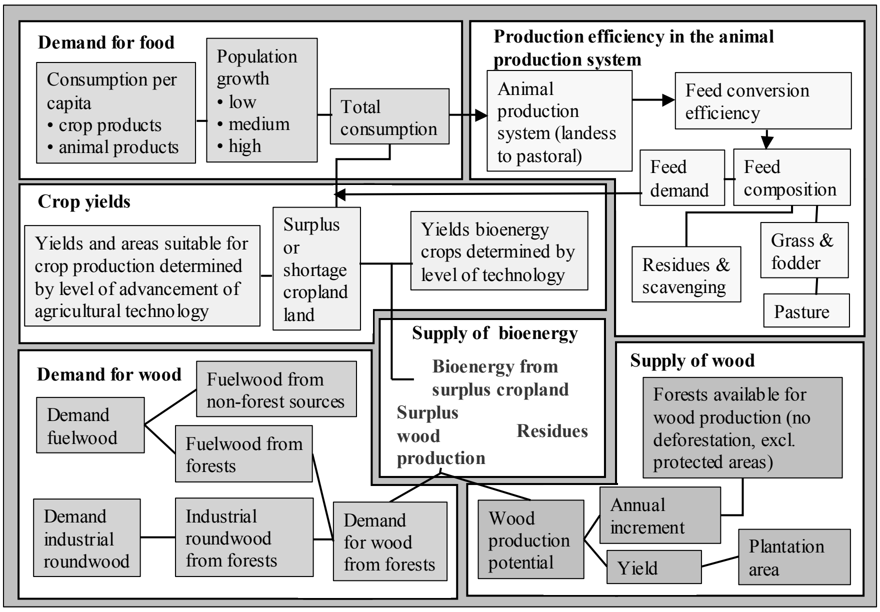


Figure 9.1 Overview of the key elements in the assessment of the bioenergy potential from specialised bioenergy crops

The model portrayed in Figure 9.1 can be divided into five sections relative to important determinants of bioenergy potential:

- Demand for food. The demand for food is modelled as a function of population growth and income growth.

- Crop yields and land use. The available resources, the level of advancement of agricultural technology and the spatial distribution (optimisation) of production determine the area cropland required for the production of food crops and feed crops. Forest areas are excluded from this analysis.
- Feed use efficiency in the animal production system. The production efficiency is determined by the type of animal in question, the production system (pastoral/grazing vs. industrialised stall-fed/landless production) and the feed composition.
- Demand for biomaterials. The demand for wood is the sum of the demand for industrial roundwood and fuelwood.
- Supply of wood. The supply of wood is determined by the forest and plantation area and the growth rate.

In addition the potential for bioenergy can be aggregated into three categories:

- Bioenergy from surplus agricultural land. This potential is determined by the yield of bioenergy crops and the surplus areas of cropland (food production is given priority above bioenergy production).
- Bioenergy from agricultural and wood processing industry residues. The supply of residues is based on the production and processing volumes multiplied by conversion efficiencies.
- Bioenergy from surplus forest growth. The supply of bioenergy from natural forest growth is limited to the surplus forest growth (the use of industrial roundwood or wood used as traditional fuel is given priority above the use as a source for bioenergy).

For each of these factors scenarios are included that capture the uncertainty related to land use patterns and food production. The results are aggregated into 11 world regions, but results can also be generated on a national or sub-national level when sufficient data are available. This methodology is also used as a basis for the assessment of the sub-national economic potential for bioenergy. The technical potential is translated into economic potential by estimating the production costs based on the level of (advancement of) technology applied to produce the bioenergy. Figure 9.2 shows an overview of the procedure used to calculate the production costs of bioenergy.

This methodology requires detailed data on the costs of various production factors such as pesticides, fertilizers, labour, fuels, land, and insurance. Sufficient data have to be available to implement this approach in a region. Preliminary results indicate that there can be a large variation in production costs on a sub-national level for energy crop production, which emphasises the need for accurate and detailed data.

Population growth

Population growth is an important cause of increased demand for food. In this study, population growth and changes in the capita consumption are analysed separately. Generally, population projections have been found to be fairly accurate for 5 to 10 years (Heilig, 1996), but long-term population projections are less reliable. The population projections of the United Nations Population Division (UNPD) reflect this uncertainty by encompassing six different scenarios based on mortality, fertility and migration rates. These projections are available at a national level and contain projections for rural and urban segments. The medium population growth scenario is the most likely scenarios and regional cases of it are shown in Figure 9.3.

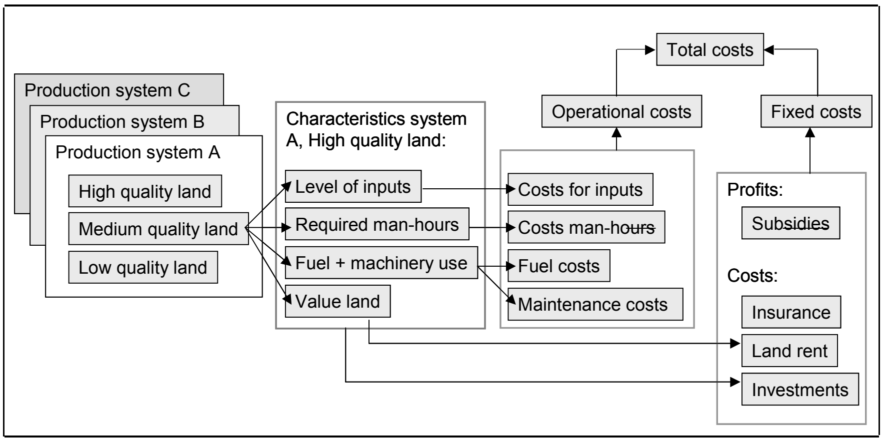


Figure 9.2 Data requirement for cost analysis for production system A (in this example) on medium quality land

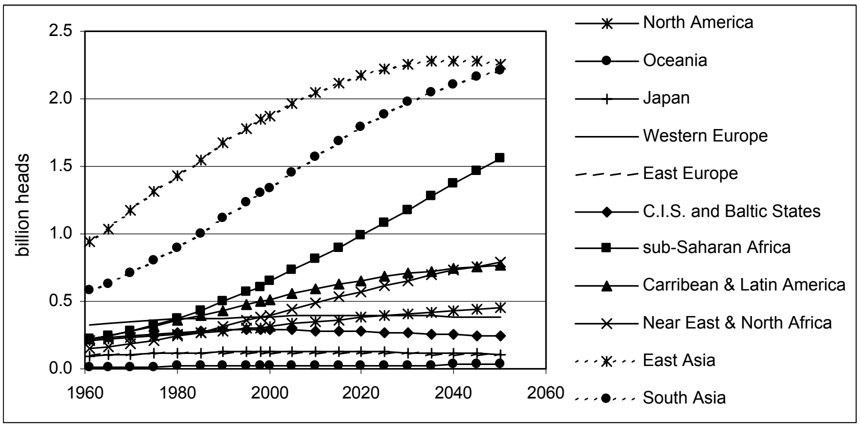


Figure 9.3 Population growth, 1960-2050 (1,000 heads)
Source: UNPD (2003).

The speed of growth generally decreases in the future compared to recent decades, but the absolute number of people continues to grow rising from 6.0

billion in 2000 to 8.9 billion in 2050 under the medium scenario. In the low and high scenarios the population increases to 7.3 and 10.5 billion people in 2050, respectively. According to the UNPD projections the difference between the high and low population scenarios are largest in developing countries, reflecting the present high fertility rates and future uncertainty concerning their decrease. The strongest population growth is projected for the developing regions, e.g. sub-Saharan Africa +138%, South Asia +65%, Caribbean & Latin America +48% and East Asia +21%. The population in Oceania and North America is also projected to increase significantly (+30% and +42% respectively). Regions with a decreasing population are Western Europe, Japan, Eastern Europe, C.I.S. and the Baltic States (-2%, -13%, -17%, -17% respectively).

Uncertainty related to population projections has increased during recent years, with population projections developed in the last decade being frequently downscaled. E.g. the medium projection of the global population is 1.1 billion lower than projected in 1990, mainly stemming from projected levels of HIV infections.

Food consumption

The main driver behind increasing or changing per capita food consumption is an increase in income (expressed in purchasing power). The methodology for estimating future consumption patterns is based on supply-demand equilibrium, considering the impact of the various underlying variables (e.g. agricultural policies and payments, Gross Domestic Product (GDP), population growth, technological development, cultural preferences etc.), their evolution over time and the correlations between these factors. Such an exercise is problematic, due to methodological problems related to the calculation and use of elasticities that describe correlation between for example GDP and consumption or food supply and prices and other parameters. In addition, data on the capacity of the natural resource base of the food production system to support an increasing food production level are often uncertain and insufficient and a detailed understanding of many of the underlying biological and physiological processes is not available. As a result, a considerable amount of expert judgement is involved in estimating future consumption patterns, particularly in the long term.

This uncertainty results in a considerable range of outcomes. They range from forecasts of a global food crisis to more mainstream (and optimistic) projections such as those of the Food and Agriculture Organisation (FAO) of the United Nations. The consensus is that consumption is likely to increase, although at a slower pace than in the past and that under-nourishment is likely to decrease.

FAO projections are used in this study, since these have the longest time horizon (to 2030) and may be regarded as the most widely used and reliable source of projections. The FAO projections are based on a combination of supply demand modelling based on a model developed by the International Food Policy Research Institute (IFPRI) in combination with iterative rounds of adjustments involving expert judgment of FAO consultants. The FAO projections are trend extrapolated to 2050 based on data from the IFPRI, the National Institute of

Public Health and the Environment (RIVM)[3] and our own assumptions. Figure 9.4 and Figure 9.5 show the projected increase in consumption in various regions.

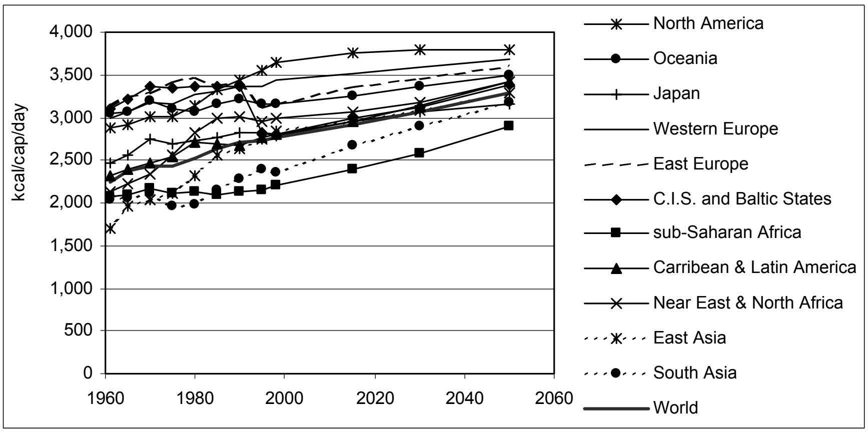


Figure 9.4 Historic and projected per capita total food intake, 1961-2050 (kcal/capita/day)
Source: IFPRI (2001a); IMAGE-team (2001); FAO (2003a, b); own calculations.

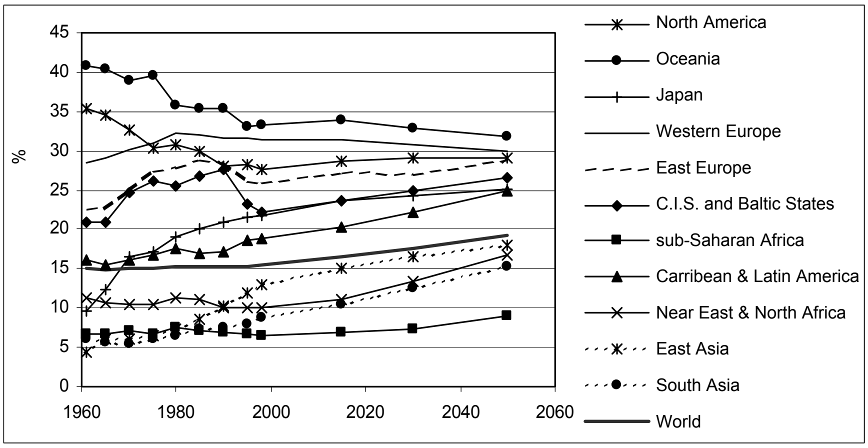


Figure 9.5 Consumption of animal products 1961-2050 (% of total daily caloric intake)
Source: IFPRI (2001a); IMAGE-team (2001); FAO (2003a, b); own calculations.

Figures 9.4 and 9.5 indicate that daily kcal intake in the industrialised regions is approaching an equilibrium level. The consumption share accounted for by animal products has decreased during recent decades and this decrease is

[3] RIVM data are derived from the Integrated Model to Assess the Global Environment (IMAGE). The IMAGE model is a dynamic integrated assessment modeling framework for global change.

projected to continue. In the transition economies, the collapse of communism and following economic restructuring caused a strong decrease in GDP, agricultural payments and consumption. It will take several years to decades before consumption and production have reached the level of the communistic era. In developing countries, food consumption is projected to increase, particularly in the economic booming region of East Asia, although consumption levels remain below saturation levels in 2050 in all developing regions. The regions with the highest shares of under nourishment are presently sub-Saharan Africa and South Asia. In the latter, relatively high economic growth is projected to reduce poverty and under nourishment, while in sub-Saharan Africa, strong population growth and poor economic performance limits the increase in consumption, particularly the consumption of animal products. Consequently, the relative incidence of under nourishment in the developing countries is likely to decline from 17% in 1997/99 to 6% in 2030, with 776 and 443 million malnourished, the bulk being in sub-Saharan Africa and South Asia. We acknowledge that food production should be prevented above bioenergy crop production, but in reality food shortages are often the result of armed conflicts, rather than a lack of suitable cropland.

The FAO and IFPRI projections could be the best available, but forecast errors for food consumption and production at the regional level in the range of +/-10 to 40% are common, with errors as large as 90% occurring in the past (IFPRI, 2001b). Globally aggregated data show much smaller projection errors. Since consumption levels in the developing regions are below saturation levels, consumption in those regions is very responsive to further increases in income or decreases in food prices compared to the scenario underlying the projections included in this study. A small change in GDP or prices may significantly increase consumption in these regions. Consumption in regions with consumption levels near the saturation level is likely less sensitive to changes in prices and GDP. This means that the projected increase in consumption is more uncertain for countries with low levels of consumption.

Wood consumption and production

During the 1990s several outlook studies and reviews investigating fuelwood and industrial roundwood consumption have been published. Despite public attention for concerns about deforestation, particularly with respect to rainforests, the data on such activities is relatively weak. Particularly data on illegal cutting and the use and production of fuelwood are largely based on estimates that may provide too little information for the production of reliable forecasts (EFI, 1996). In addition, the methodological problems encountered are similar to those of encountered when projecting future food consumption and land use patterns.

Because of a high degree of uncertainty related to wood consumption and production, only a few projections go beyond 2010. Most that do, only give data on total consumption of roundwood with a regional subdivision limited to industrialised and developing countries. The projections are difficult to compare due to a lack of information on key assumptions and methodologies applied. Also not all studies are intended to produce equivalent results, but also to mimic the effects of various factors (EFI, 1996). The range of projections for the demand for industrial roundwood, fuelwood, plantation production and natural forest growth are translated into a set of demand and supply scenarios (Table 9.1). Since no supply-demand matching is included, the combination of low consumption and high supply results in the highest potential for bioenergy, but also ignores many interactive issues.

Table 9.1 Demand and supply scenarios for wood in 1998 and 2050 (million m^3)

	1998	2050 low	2050 medium	2050 high
Demand				
Industrial roundwood	1,672	1,900	2,500	3,100
Fuelwood	1,807	1,700	2,200	2,600
Supply				
Industrial plantations	330	609	863	1,488
Non-industrial plantations	85	173	245	479
Total natural forest growth	9,402	9,402	9,402	9,402

Source: various.

The consumption of industrial roundwood is projected to increase from ca. 1.7 billion m^3 to 1.9 to 3.0 billion m^3 in 2050, although in the most extreme scenario found in the literature the consumption is projected to increase to some 7 billion m^3 in 2050.

Despite many uncertainties and conflicting trends there seems to be general agreement that the demand for fuelwood is not going to change rapidly (EFI, 1996; FAO, 2003b). Increasing income and urbanisation encourage a switch from fuelwood to more modern commercial fuels (gas, oil) while rapid population growth in many developing regions and increasing (but still low) income levels on behalf of the majority of the mainly rural, fuelwood consumers counteract this effect. Data from existing studies indicate a consumption of fuelwood between 1.7 in 2050 and 2.5 billion m^3 in 2020, compared to the present ca. 1.8 billion m^3. The upper range is based on a constant per capita consumption and results in a consumption of 2.6 billion m^3 in 2050.

Fuelwood and industrial roundwood stem from very different sources and production systems, ranging from well-managed plantations to full deforestation of virgin forests or gathering of twigs for use as fuelwood. In this study we distinguish plantations and natural forests.

The contribution of plantations to the global supply is significant and increasing. According to a study on future wood production from plantations, the production from plantations may increase to 0.8 to 2.0 billion m^3 in 2050. The theoretical production from natural forests is estimated based on forest area data and data on gross annual increment (GAI). Note that the data on GAI are considered very uncertain. We also assume 10% of the forest area is set-aside for biodiversity protection and nature conservation. In turn, annual forest growth is constant at 9.4 billion m^3, assuming no deforestation. The total surplus forest growth is estimated at 72 EJ/yr, maximum. However, most of the production is classified as unavailable[4] or consists of non-commercial species, for which there is presently no market due to poor quality or characteristics of the species. In addition, roughly half of the global forest area is old-growth undisturbed forest. For reasons of nature protection, these areas may be excluded from supply. More detailed analysis show that if all three limiting factors are included, the wood demand in 2050 cannot be met and the potential for bioenergy is zero.

In reality, any gap between demand and supply is closed, since there is a general agreement that 'the technological global wood production capacity is sufficiently large to fulfil the largest projected increases in demand' (EFI, 1996); in line with the supply and demand situation shown in Table 9.1. Further, standing stocks may serve as a buffer to reduce the effect of regional or temporary market fluctuations. The volume in standing stocks is more than 120 times the current total wood consumption.

It is not known to which extent the three scenarios include the effects of technological improvements. Recent studies indicate that both through increasing conversion efficiencies and the development of new wood products which make more efficient use of resources (e.g. medium density fibre board), the growth of demand for industrial roundwood will slow down (FAO, 2003b). Energy efficiency improvements (e.g. improved stoves or the use of modern bioenergy carriers such as liquid fuels) on the other hand have (in theory) the potential to more than offset increasing demand up to 2030.

Agricultural land use and agricultural management

In this analysis, the production of bioenergy from specialised crops is limited to surplus land or land not suitable for agriculture. The mainstream studies on agricultural land use project an increase in yields and an increase in the area under crop production in the developing regions during the coming decades, partially at the expense of forests. Globally, the arable land area is projected to increase 13% until 2030 (FAO, 2003b). Cropland area in the transition and industrialised regions is expected to increase marginally, if not remain stable or decrease, though the FAO states that a potential decline could be partially offset by emerging trends towards de-intensification and the increasing demand for ecologically produced crops (without or with minimum use of fertilizers and chemicals). Pastures are not included in the FAO calculations, although globally pastureland area is likely to decrease due to increasing mixed farming, improved pastures and stall-fed systems, and demand for animal products in the developing countries.

---

[4] Unavailable areas are defined as:

- Physically inaccessible areas due to factors such as steepness of terrain.
- Areas far from industrial sites due to transportation distances or lack of infrastructure.
- Areas too low in commercial volume, degraded forest or some other legitimate reason specific to each country.

The FAO projections of agricultural land use are based on the same methodology as used in determining the consumption projections. Again the projected land use changes are uncertain. Many studies indicate that there are large 'exploitable yield gaps', both with respect to crop yields and the efficiency of production of animal products. Yield advances are thus a key determinant of future bioenergy production, since the efficiency of food production determines the area of surplus cropland and pastureland available for bioenergy production. The closing of these yield- and efficiency gaps is a matter of agricultural management,[5] which is the prime target of agricultural, economic policies. A newly emerging market for bioenergy production and related policies could further speed up the adoption of more efficient agricultural production systems.

The impact of yield increases is analysed by translating the total demand for food into a demand for cropland. A more sophisticated management system results in higher yields per hectare, larger areas suitable for crop production, higher production per animal, lower demand for feed and an overall lower demand for agricultural land.

For the production of crops six management levels are defined that vary with respect to the level of advancement of agricultural technology (including the level of agricultural inputs) and the use of natural rainfall and/or irrigation:

- Low, rain-fed: using no fertilizers, pesticides or improved seeds, equivalent to subsistence farming.
- Intermediate, rain-fed: average of high and low.
- High, rain-fed: full use of all required inputs and management practices as in advanced commercial farming.
- Very high, rain-fed: see below.
- Very high, rain-fed and/or irrigated: use of high level of technology on very suitable and suitable soils, intermediate level of technology on moderately suitable areas and low level on moderately and marginally suitable areas. The rationale for this methodology is that it is unlikely to make economic sense to cultivate moderately and marginally suitable areas under the high technology level, or to cultivate marginally suitable areas under the intermediate technology level.
- Super high, rain-fed and/or irrigated: the high and very high level of agricultural technology exclude the impact of the development of technology beyond the best available technologies presently used in the industrialised regions. We consider it likely that agricultural technologies will continue to become more efficient and productive, although at a much slower pace than previously. Based on various sources, we assume that the total bioenergy potential may be 25% higher than in a very high level of technology without further specifying the origin of this increase. This is referred to as the super high level of technology.

[5] The term management usually refers to the use of fertilizers, pesticides, mechanised tools, improved breeds, double cropping, and the application of irrigation. In this chapter the term also includes the level of agricultural technology and the optimalisation of land use patterns to minimize land use or optimize profits.

The impact of the application of these management systems is analysed separately for crop production and the production of animal products as described in the following section.

Cropland and agricultural management

The impact of management systems on crop yields is analysed using data from a crop yield model from the International Institute of Applied Systems Analysis (IIASA) (IIASA/FAO, 2002). The crop yield model uses georeferenced data on climate, soil quality etc. and may be regarded as the state-of-the-art in crop growth modelling considering the global coverage and number of crops included. In total, data for 19 different crops are included. Since the data from the crop growth model are based on georeferenced datasets (employing Geographic Information Systems), this type of data can be made available per region, sub-region, and country or per grid cell.

The data are specified for yield and area by country and follow a classification of suitability for crop growth. The classification is based on the maximum constraint free yield (MCFY): very suitable (VS, 80-100% of MCFY), suitable (S, 60-80% of MCFY), moderately suitable (MS, 40-60% of MCFY), marginally suitable (mS, 20-40% of MCFY) and not suitable (NS, < 20% of the MCFY).[6] No yield levels are included for areas classified as NS. A dataset that indicates the total extent of cropland not under forest cover is also provided. In addition, a set of simple allocation rules was used to determine use of suitable cropland (VS, S, MS or mS) for other purposes than crop production. Data were derived from the FAOSTAT database (FAO, 2003a) and the IIASA data (IIASA/FAO, 2002). The total global land area is 13 Gha, divided into other land (3.6 Gha), permanent pasture (3.5 Gha), built-up land (0.2 Gha), forest (4.2 Gha, divided into plantations and natural forest), permanent crops (0.1 Gha), and arable land (1.4 Gha). In this study, deforestation is not allowed, so increases in e.g. the areas of built-up land occur at the expense of the area of agricultural land in the base year 1998.

These data were integrated into a spreadsheet tool wherein the projected demand for food and feed in 2050 is translated into yield-area combinations. A given demand for crops can be produced for different combinations of yield and area; a small area with very productive land can produce the same amount of crops as a large area of low productive land. The spreadsheet includes:

- Optimisation of production ‘geographically’. Geographic optimalisation includes the allocation of crops to areas with high yields first (leaving the least productive areas for bioenergy production) and a cropping intensity of 1 (defined as the ratio harvested land to arable land).[7]

[6] Because the classifications VS to mS are based on the percentage of maximum constraint free yield (MCFY), not the absolute level of yields, economic optimalization of production is included in this dataset. A VS yield in region 1 can be lower than a VS yield in region 2, but are equally important in the allocation procedure. Production in region 1 on VS areas is however attractive considering the relative high suitability compared with areas in that region.

[7] The FAOSTAT database does not include data on total harvested land. Data can be obtained by summing up the harvested areas reported for different crops. Data are available for total arable land in

- Application of a certain level of technology.
- Regional if not global self-sufficiency. The demand for food in a region is allocated within the region. When a region is not self-sufficient (meaning that the projected demand for food and feed in a region can not be produced within that region), the remaining demand is allocated to other regions that are self-sufficient and have surplus areas of cropland.

The area of cropland required to produce the regional demand is calculated and compared with the present agricultural land. When a region exhibits decreasing demand for agricultural land, the surplus land is available for crop production. The potential increases in yields are considerable, globally between 190% and 360%. The calculated (theoretical) potential yield increases for a number of regions for scenario 1 and scenario 4 are shown in Table 9.2 (scenarios are defined below). The 1998 yield levels are set at 1; average increases are weighed averages based on harvested areas.

Table 9.2 Average increase in crop yields (1998=1)

Region	Very high rainfed level of technology (scenario 1)	Super high rainfed/irrigated level of technology (scenario 4)
North America	1.6	3.2
Oceania	2.4	4.6
West Europe	0.9	1.9
C.I.S. and Baltic States	3.2	6.7
Sub-Saharan Africa	5.6	7.7
Caribbean & Latin America	2.8	4.5
South Asia	3.7	5.6
World	2.9	4.6

Source: IIASA/FAO (2002); FAO (2003a), own calculations.

Animal production and agricultural management

The management system applied for the production of animal products determines the future demand for various feed categories (pasture biomass, feed from crops, residues & scavenging biomass) based on Equation 9.1.

agricultural use (named 'arable land' and 'land in permanent crops' in the FAO statistics). It is not known to which extent these datasets are consistent, but the cropping intensity can be used as an indicator. Globally the area harvested is 93% of the area arable land, regional aggregated data are between 70 and 130%.

Feed = Demand x Prod x Fce x Fco (9.1)

where:

Demand = demand for animal products based on the consumption scenarios.

Prod = production system. Two extreme production systems are included: pastoral and landless. Combinations of the two are referred to as mixed production systems. The difference between these systems is the source of animal feed (cropland vs. pasture land) and the overallefficiency of production (feed conversion efficiency). Data are derived from the IMAGE projections (IMAGE-team, 2001).

Fce = feed conversion efficiency (total demand of biomass (dry weight = dw) per kg animal product); data are taken from the IMAGE model (IMAGE-team, 2001). The range in feed conversion efficiencies in the year 1995 is used to estimate feed conversion efficiencies in a low, intermediate and high level of technology production system. Table 9.3 gives an overview of feed conversion efficiencies for a selected number of animal products and regions.

Fco = feed composition. Data on feed composition (feed, pasture and fodder biomass, residues, scavenging) are specific for each region, type of animal product and production system. The demand for feed from crops is added up to the demand for food crops and is included in the spreadsheet tool used to calculate land use.

Table 9.3 Feed conversion efficiencies in 1995 and in a high level of technology in an animal production system in which all animal feed is derived from residues and feed crops (kg dw feed/kg product)

Region	Bovine meat	Pig meat	Poultry meat and eggs
North America	26	6.2	3.1
Oceania	36	6.2	3.1
West Europe	24	6.2	3.1
C.I.S. and Baltic States	21	7.4	3.9
Sub-Saharan Africa	99	6.6	4.1
Caribbean & Latin America	62	6.6	4.2
South Asia	72	6.6	4.1
World	45	6.7	3.6
High level of technology	15	6.2	3.1

Source: IMAGE-team (2001); FAO (2003b); own calculations.

The potential to increase feed conversion efficiencies in the developing countries is considerable (up to a factor 7), which is mainly the result of the low feed conversion efficiencies in pastoral production systems.

The calculations included in this study allow (in theory) a comparison of the demand for various feed sources with the supply of feed sources based on natural circumstances, prices etc. The demand for feed crops is included in the land allocation procedure. The demand for residues and scavenging biomass is compared to the future production of residues. The use of feed from pastures through grazing is unknown due to a lack of data on and models mimicking the productivity of pastures under various management schemes. Therefore, the relative change in demand for pasture biomass is used as a proxy for the areas of permanent pasture as explained below.

In case of an increase in the demand for grasses and fodder is projected compared to the base year, the increase in demand for grasses and fodder compared to the base year is added up to the demand for feed from crops. The reason for this approach is that an increasing demand for feed from grazing could lead to an expansion of the area permanent pasture by deforestation or higher grazing intensities, which in turn could lead to e.g. soil erosion and other problems related to overgrazing. In case of a decreasing area of pastureland, areas of permanent pasture become available for crop production. The data and methodology described above are also used in the assessment of the economic potential, though sub-national data on livestock production efficiencies and feed sources are generally not available.

Bioenergy yields

Data on bioenergy yields can be determined based on crop growth models or derived from field experiments. In this study, we use yield data for short rotation woody bioenergy crops, because there is extensive experience with woody bioenergy for fibre production for the pulp and paper industry. Also woody biomass can be converted in various types of fuel (e.g. eucalyptus, poplar or willow). We use data from the IMAGE model which are derived from crop modelling (IMAGE-team, 2001). Note that higher bioenergy yields in tropical regions are possible if herbaceous crops (e.g. *Miscanthus*) are used (Hall et al., 1993).

The calculation of bioenergy production potential is based on the areas of surplus land calculated in the previous section multiplied by the yields of bioenergy crops taking into account the quality of these surplus areas. Figure 9.6 shows the global (modelled) yield-area curve for the production of bioenergy based on a low and high level of technology.

The curves clearly show the impact of both the suitability of the land and the impact of the production system: the area suitable for bioenergy production is higher and yields are also higher in a production system based on a high level of advancement of agricultural technology compared to a low level of technology. The surface under the graph is the total global (technical) production potential for bioenergy. For a low and high level of advancement of agricultural technology this potential is estimated at 1,807 and 4,435 EJ/yr respectively (based on a higher heating value of 19 GJ/ton dw).

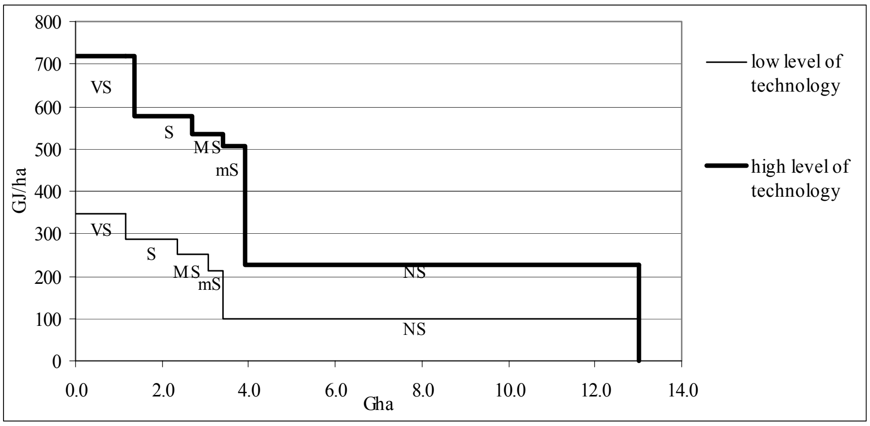


Figure 9.6 Simulated bioenergy yields (GJ/ha) based on a low and high level of advancement of agricultural technology (VS = Very Suitable Areas, S = Suitable Areas, MS = Moderately Suitable Areas, mS = Marginally Suitable Areas)
Source: IMAGE-team (2001); own calculations.

RESULTS OF THE GLOBAL BIOENERGY POTENTIAL ASSESSMENT

A large number of variables for which scenarios and ranges are given are included in calculations of the technical potential. Consequently, a large number of outcomes are possible. For the global assessment of bioenergy, the results are presented for four scenarios that vary with respect to the management level and the animal production system. These four scenarios are selected because in all four the global consumption of food in 2050 can be met without increasing the area of agricultural land and in order to keep the amount of results manageable and to limit the scenarios to plausible cases. E.g. the combination of a high level of technology for the production of food crops and a low level of technology used in the animal production system (low feed conversion efficiencies) is considered illogical. The production systems are shown in Table 9.4.

Table 9.4 Overview of systems included in this study

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Feed conversion efficiency	high	high	high	high
Animal production system	mixed	mixed	landless	landless
Level of technology for crop production	very high	very high	very high	super high
Water supply for agriculture	rain-fed	rain-fed/ irrigated	rain-fed/ irrigated	rain-fed/ irrigated

For the other variables the following scenarios are included: medium population growth, medium increases in per capita food consumption, high plantation establishment rate, high level of advancement of technology for the production of bioenergy crops and the application of irrigation. The total potential for bioenergy production (bioenergy from bioenergy crops, agricultural residues) is shown in Figure 9.7.

In all four systems significant areas of land are available for bioenergy production in 2050, ranging from 0.7 Gha, 1.2 Gha, 3.3 Gha and 3.6 Gha in system 1, 2, 3 and 4 respectively. The total production potential of bioenergy in the four scenarios is 364 EJ/yr; 607 EJ/yr; 1,270 EJ/yr and 1,545 EJ/yr. Biomass from harvest and processing residues accounts for 76 EJ/yr to 96 EJ/yr (in scenarios 1 and 2 and scenarios 3 and 4 respectively) and biomass from surplus forest growth contributes 72 EJ/yr.

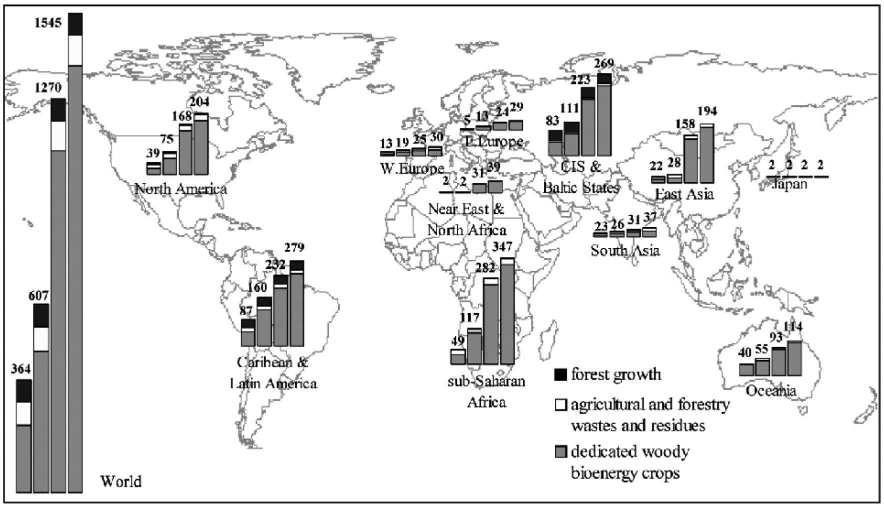


Figure 9.7 Total bioenergy production potential in 2050 in scenarios 1 to 4 (EJ/yr)

Most of the bioenergy production potentials come from areas of surplus permanent pastures, indicating the large areas permanent pasture presently used and the large potential efficiency gains. Comparison of scenario 2 and 3 also show a large impact of the animal production system on land use. A shift from pastoral and mixed production systems, which use feed from grazing, to a fully industrialised, stall-fed system, in which all animal feed comes from feed crops, results in large surplus of land areas. The impacts of animal production systems are also visible in the availability of harvesting and processing residues. The high(er) demand for feed crops in scenarios 3 and 4 creates high(er) production of processing and harvesting residues compared to scenarios 1 and 2. Irrigation is another important factor. The application of irrigation increases the bioenergy potential considerably, as a comparison of scenario 1 and scenario 2 shows. The surplus production potential of wood from natural forests is estimated at 72 EJ/yr (regional results not shown), although various limiting factors, such as the exclusion of undisturbed forest may reduce this potential to zero.

The regions with the highest bioenergy production potentials are in the developing regions of sub-Saharan Africa, the Caribbean & Latin America and East Asia. These three regions account for more than half of the global potential. In sub-Saharan Africa and the Caribbean & Latin America the potential originates from the large areas of land suitable for crop production and the present inefficient production systems. The land balance in East Asia is less favourable, but the growth in population and consumption is lower. The large potential for C.I.S. & Baltic State bioenergy production arises from a combination of drivers. Due to the collapse of communism and the economic restructuring afterwards, GDP and consumption have decreased, resulting in a decrease of yields and production. It will take several years to decades before consumption levels are back to levels common in the Soviet period. In addition, the population is projected to decrease to 2050. Consequently, the agricultural land area is relatively large compared to the projected demand for food, which makes the potential of these regions the greatest of all regions.

A prerequisite for bioenergy potential in all regions is that the present inefficient and low-intensive agricultural management systems are replaced in 2050 by best practice agricultural management systems and technologies. In addition, per capita food consumption projections for 2050 in these regions have not reached saturation levels and under nourishment may not be eradicated completely. Thus, the potential for bioenergy may be limited if food intake (income) increases more than projected in this study.

COSTS OF BIOENERGY

The general framework for the calculation of the sub-national (theoretical) supply of bioenergy is the same as used for the global bioenergy assessment. The definition of the production systems used in this chapter, allows the bottom up calculation of production costs. The variation in cost data due to different land suitability types and production systems in a country has an impact on the cost levels for biomass production. Figure 9.8 shows, as an example, that the price of agricultural land for different regions in the Czech Republic ranges from 0.50 to 13.50 $CZK_{(1999)}$ / m^2. For this reason, production costs for biomass are collected for different land suitability types and production systems.

Van Dam et al. (2003) subdivide the production costs in two different categories: Fixed costs (the costs are independent from production levels in the short run) and operational costs (the costs are dependent from production levels in the short run).

As Table 9.5 shows, several cost variables need to be collected to estimate the operational costs and fixed costs. For this study, this means that every Nuts-3 region[8] contains a dataset of cost variables for different production systems, subdivided to different land suitability classes, both for the present situation and for the future. For the collection of these cost data, we use a range of information sources.

In addition, price data and information about subsidies are collected as well. The combination of cost and price data for energy crops, food crops and forest products allows a comparison of different utilization options. It also gives insight into the degree of competition between different land utilizations and the influence of subsidies or taxes.

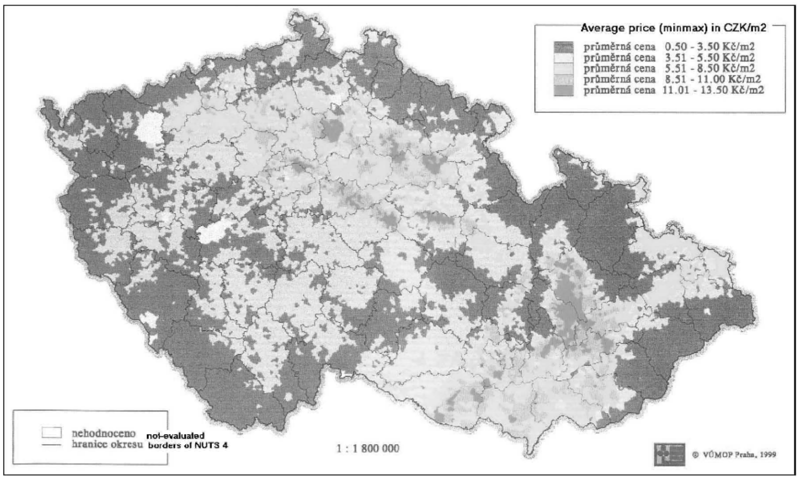


Figure 9.8 Average price of agricultural land in the Czech Republic (CZK/m^2) Source: VUMOP (1999).

To illustrate the results that can be expected, Figure 9.9 shows results from a case study in the Czech Republic (Lewandowski et al., 2005). The scenarios assume that crop production is equal to demand in 2030 and varies with yield level and land allocation. Cost levels vary over time according to expert judgment. The yields are calculated per agricultural production area[9] (Weger, 2003). The costs for poplar and willow are based on the required cultivation practices and its related costs.

The results in Figure 9.9 indicate that scenario 4 provides the largest supply of biomass and that agricultural residues represent the cheapest source of biomass. More expensive is the biomass from energy crops. Costs range for the production from poplar/willow are from 2.6 €/GJ, which is the most suitable area

[8] NUTS is an abbreviation for the Nomenclature of Territorial Units for Statistics. NUTS-3 regions are the statistical sub-sub-national regions of the European Union and the Accession Countries.

[9] The Czech Republic has five different agricultural production areas. The division of these production areas is based on the required stand conditions for agricultural (plant) production related to soil-ecological conditions in an area (Hooijdonk, 2003).

Table 9.5 Required operational and fixed cost data for cost-supply curves

Costs	Relation with management system and land suitability
Operational costs	
• Costs for fertiliser, pesticides, etc. • Wage • Fuel costs (related to required fuel) • Maintenance costs	• Level of inputs related to management system and land suitability • Required man-hours (efficiency system) • Fuel use (dependent on machinery, efficiency) • Related to management system
Fixed costs	
• Land costs • Investment costs • Insurance • Subsidies (not a cost factor)	• Related to land suitability • High input system requires more investment costs

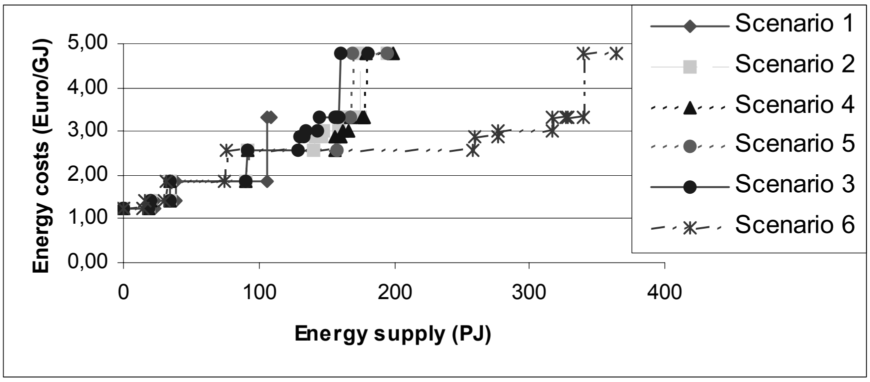


Figure 9.9 Cost-supply curve of energy supply from agricultural and forest residues and energy crop poplar/willow in the Czech Republic
Scenario 1: Actual Yield; Scenario 2: Optimal Yield; Scenario 3: optimal yield, but low feed conversion efficicnies; Scenario 4: Optimal Yield and Land Allocation within Nuts-3 regions; Scenario 5: Optimal Yield and Land Allocation Within the Country; Scenario 6: Actual Yield of the Netherlands (Lewandowski et al., 2005).

for biomass production, to 4.8 €/GJ. Based on the methodology of Van Dam et al. (2003), cost-supply curves are calculated for various CEEC countries.

The data requirements for this approach are high. When confronted with limited availability of cost data or high uncertainty a more theoretical, top-down approach based on the correlation between the production factors capital and labour can be used (Hoogwijk et al., 2004).

DISCUSSION AND CONCLUSIONS

The results in this chapter clearly show that the technical potential to increase crop yields and increase the efficiency of the animal production system is large enough to meet food demand in 2050 and reduce the area of agricultural land required for food production. Particularly, the potential efficiency gains in the animal production systems result in large surplus areas, up to 72% of the present agricultural land. The bioenergy production potential from these surplus areas are considerable, up to 1,471 EJ/yr. Other bioenergy potential assessments reveal that the potential for bioenergy varies globally between 40 and 1,100 EJ/yr with the bulk between 200 and 700 EJ/yr (Hoogwijk et al., 2002).[10]

The results of the global potential assessment show that all regions have a potential to produce bioenergy, but the conditions under which this can be achieved vary. The largest bioenergy potential comes from developing regions (notably sub-Saharan Africa and the Caribbean & Latin America), but these potentials require the improvement of production efficiency, the use of modern production technology and substantial increases in yields, up to an increase of 700%. The bioenergy production from the industrialised countries is less dependant on yield increases, due to decreasing population size and saturation of consumption. Industrialised regions are projected to exhibit decreasing agricultural land use as has been the case during the last decades (a trend frequently confirmed by outlook studies e.g. FAO (2003b)). The potential for bioenergy production in the transition economies may be regarded as the most robust potential. Due to the collapse of communism and economic restructuring afterwards, GDP and consumption have decreased, resulting in a decrease in production, agricultural land use and yields.

These results show that climate change mitigation policies aimed at the promotion of the sustainable production and use of bioenergy can have a major impact on global agricultural land use. Such a transition requires substantial increases in crop yields and efficiency and opens up new possibilities for income and jobs in the agricultural sector particularly in developing regions. To what extent this transition is going to be successful, depends partially on the costs of bioenergy production compared to fossil fuels and other renewable energy sources. This also includes costs of the transfer of technology to make the gains in yield and production efficiency possible. In reality, yield levels are the result of many complex interactions between numerous factors in the entire socio-economic system (e.g. prices of land and labour, available infrastructure, natural circumstances, trade negotiations, interest rates, education level of agricultural workforce). These complex interactions are poorly understood and are difficult to quantify (Döös and Shaw, 1999; IFPRI, 2001b), but strong involvement of the industrialised countries (the potential bioenergy importing regions) is likely to be essential for a successful implementation.

[10] The IMAGE model uses the scenarios (storylines) presented by the IPCC in their Special Report on Emission Scenarios (SRES) as basis for the bioenergy potential assessments. The global potential is 311 EJ/yr in the A2 scenario, 324 EJ/yr in the B2 scenario, 659 EJ/yr in the A1 scenario to 706 EJ/yr in the B1 scenario in 2050 (Hoogwijk et al., 2004).

Therefore, a next step in the field of bioenergy assessments is the estimation of the implementation potential. Due to the many uncertainties described above, further research is required to allow assessments of the (regional) implementation potential and to make more accurate bioenergy potential assessments. Key priorities for future research are:

- Data reliability and availability. There is a lack of data on the following issues: use and sources of fuelwood, feed composition, feed conversion efficiencies, production capacities of natural pastures and the impact of various management systems, the extent and severity of environmental degradation, the impact of various management systems, implications of sustainable forest management and the impact of wood harvests.
- The dynamics on the socio-economic system that determines land use patterns and yields. Particularly the impact of large energy crop production systems on the costs of land and other production costs are uncertain. Further, substitution possibilities between various production factors (substitution elasticities) are relatively unknown and need to be addressed in national and sub-national case studies.

REFERENCES

Berndes, G., M. Hoogwijk and R. van den Broek (2003) The contribution of biomass in the future global energy supply: a review of 17 studies. *Biomass and Bioenergy*, Vol. 25 (1), pp. 1-28.

Dam, J. van, A. Faaij and I. Lewandowski (2003) *Methodology and data requirement for regional biomass potential assessment in the Central and Eastern European Countries*. Utrecht University. Utrecht, the Netherlands.

Döös, B.R. and R. Shaw (1999) Can we predict the future food production? A sensitivity analysis. *Global Environmental Change*, Vol. 9 (4), pp. 261-283.

EFI (1996) *Long-term Trends and Prospects in World Supply and Demand for Food and Implications for Sustainable Forest Management.* Joensuu, European Forest Institute.

FAO (2003a) *FAO Stat Database - Agricultural Data*. http://apps.fao.org/page/collections, Food Agricultural Organisation. Rome, Italy.

FAO (2003b) *World Agriculture: Towards 2015/2030. An FAO perspective*. Food and Agriculture Organisation. Earthscan Publications Ltd, London, U.K.

Fisher, G. and L. Schrattenholzer (2001) Global bio-energy potentials through 2050. *Biomass and Bioenergy*, Vol. 20, pp. 151-159.

Fujino, J., K. Yamaji and H. Yamamoto (1999) Biomass-balance table for evaluating bioenergy resources. *Applied Energy*, Vol. 63 (2), pp. 75-89.

Hall, D. O., F. Rosillo-Calle, R.J. Williams and J. Woods (1993) Biomass for energy: supply prospects. In: T.B. Johansson, H. Kelly, A.K.N. Reddy and R.H. Williams (Eds) *Renewable Energy: Sources for Fuels and Electricity*. Washington D.C., Island Press, pp. 593-651.

Heilig, G.K. (1996) *World Population Prospects: Analyzing the 1996 UN Population Projections.* International Institute of Applied Systems Analysis. Laxenburg, Austria.

Hoogwijk, M., A. Faaij, B. De Vries and W. Turkenburg (2004) Potential of biomass energy under four land use scenarios. Exploration of regional and global cost supply curves. *Global Environmental Change* (submitted).

Hoogwijk, M., A. Faaij, R. Van den Broek, G. Berndes, D. Gielen and W. Turkenburg (2002) Exploration of the ranges of the global potential of biomass for energy. *Biomass and Bio-energy*, Vol. 25 (2), pp. 119-133.

Hooijdonk, A. (2003). *Case study biomass potential assessment in the Czech Republic.* Msc Thesis. Utrecht University. Utrecht, the Netherlands.

IEA (2004) *Key World Energy Statistics 2004*. International Energy Agency, Energy Statistics Division Paris, France.

IFPRI (2001a) *Global Food Projections to 2020. Emerging trends and alternative futures.* International Food Policy Research Institute. Washington, DC, U.S.A.

IFPRI (2001b) *Prospects for Global Food Security. A critical appraisal of past projections and predictions.* International Food Policy Research Institute. Washington, D.C., U.S.A.

IIASA/FAO (2002) Global *Agro-ecological Assessment for Agriculture in the 21st century: Methodology and Results*. International Institute of Applied Systems Analysis, Laxenburg, Austria; Food Agriculture Organisation, Rome, Italy.

IMAGE-team (2001) *The IMAGE 2.2 implementation of the SRES scenarios: A comprehensive analysis of emissions, climate change and impacts in the 21st century.* RIVM CD-ROM publication 481508018. National Institute for Public Health and the Environment. Bilthoven, The Netherlands.

IPCC (2000) *Special Report on Emissions Scenarios.* Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, U.K.

IPCC (2001) *Climate Change 2001: Impacts, Adaptation, and Vulnerability.* Cambridge, U.K., Cambridge University Press.

Lashof, D.A. and D.A. Tirpak (1990) *Policy Options for Stabilizing Global Climate*. United States Environmental Protection Agency. Hemisphere Publishing Corporation, New York, Washington, Philadelphia, U.S.A., London, U.K.

Leemans, R., A. van Amstel, E. Battjes, E. Kreileman and S. Toet (1996) The land cover and carbon cycle consequences of large-scale utilisations of biomass as an energy source. *Global Environmental Change*, Vol. 6 (4), pp. 335-357.

Lewandowski, I., J. Weger, A. v. Hooijdonk, K. Havlickova, J. Van Dam and A. Faaij (2005) *The Potential Biomass for Energy Production in the Czech Republic*. Biomass and Bioenergy submitted.

Shell (1995) *The Evolution of the Worlds Energy Systems 1860-2060.* Shell International. London, UK

Sorensen, B. (1999) *Long-term scenarios for global energy demand and supply: Four global greenhouse mitigation scenarios.* Energy & Environment Group, Roskilde University. Roskilde

UNPD (2003) *World Population Prospects - The 2002 revision - highlights.* United Nations Population Division. New York, U.S.A.

VUMOP (1999) Map of agricultural land prices in the Czech Republic. Research Insitute of Ameliorations and Soil Conservation (VUMOP), Prague, Czech Republic.

WEC (1994) *New Renewable Energy Sources. A guide to the future.* London, U.K., World Energy Council. Kogan Page Limited.

Weger, J. (2003) Personal communication with Jan Weger of the Department of Phytoenergy, the Silva Tarouca Research Insitute for Landscape and Ornamental Gardening, Pruhonice, Czech Republic.

Changes in Consumption Patterns: Options and Impacts of a Transition in Protein Foods

10

Harry Aiking, Xueqin Zhu, Ekko van Ierland, Frank Willemsen, Xinyou Yin and Jan Vos

INTRODUCTION

Food sustainability and the protein chain

Food is important to individuals and society, providing nutrients and generating income (Tansey and Worsley, 1995). The relationships between food production, environment and society are complex. In fact, the evolution of agriculture has both shaped and been shaped by world population growth (Evans, 1998). At any rate, a major proportion of global environmental pressure is generated by food-related human activities. Crops are produced, transported, processed and turned into food products in ever larger volumes, with ever-increasing impacts on the environment (Smil, 2001; Tilman et al., 2002). Lindblom (1990) notes that, although sustainability is a socially accepted goal, relative consensus exists concerning its 'ills' (such as food production related impacts), but hardly concerning its 'ideals'. In this respect, some large multinationals (WBCSD, 2004) claim they can protect sustainability better than anyone else. However, their definition of sustainability does not coincide with that of the average consumer or NGO, the difference being in attributes such as 'natural' and 'just', in particular (Kloppenburg et al., 2000). In order to reduce global environmental change, the production of food, energy and water have been identified as three main targets for stepwise transition, instead of gradual improvement (Vellinga and Herb, 1999). Moreover, these three main activities are not independent of one another, since food production appropriates a major share of freshwater and energy produced. Therefore, when striving for a major step towards sustainable production in the next few decades, it should be realised that agriculture, climate change and land-use change are inextricably intertwined.

Within the realm of food, meat has a unique status since consumers endow it with esoteric qualities (Beardsworth and Keil, 1997). Furthermore, its production is responsible for a disproportionate share of environmental pressure. When

F. Brouwer and B.A. McCarl (eds.), Agriculture and Climate Beyond 2015, 171-189.

striving for sustainable food production and consumption systems (Aiking and Vellinga, 2000; Green et al., 1999), therefore, the protein chain is a good place to start for more than one reason. Due to continued growth of the world population and the proportion of meat in the global diet, the pressure of food production and consumption on the environment is rising steadily. A large proportion of this environmental pressure derives from meat production (Bradford, 1999; Delgado et al., 1999), due to the inherently inefficient conversion step from plant protein to animal protein. Already, we are feeding 40-50% of the global grain harvest to livestock (Evans, 1998; Smil, 2000). A significant amount of deforestation, loss of biodiversity, and pollution by harmful inputs - such as pesticides, fertilisers and greenhouse gases - might be avoided if protein-rich crops were destined for direct human consumption, rather than *indirectly*, via cattle feed. In this respect, the multidisciplinary *PROFETAS* programme[1] (Aiking et al., 2000; Vellinga and Herb, 1999), endorsed by the International Human Dimensions Programme on Global Environmental Change (IHDP), aims to explore a (partial) transition from animal to plant protein as a means to decouple the increase in food demand from a concomitant increase in environmental pressure.

Establishing the boundary conditions

In order to develop more sustainable protein production *PROFETAS* did not have to start from scratch, since the results of a strategic programme on Sustainable Technology Development (STD) were available (Weaver et al., 2000). Though the latter had been a desk study exclusively, the STD programme had yielded clear conclusions on development of so-called Novel Protein Foods (NPFs). STD's rather convincing rationale had been that predicting actual products 10-40 years in advance is not feasible. So STD recommends that it is better to now develop the methodologies and the tools to facilitate problem solving in the future, as opposed to hardwired solutions for presently perceived future problems. The main conclusion of STD's NPF programme had been that trying to mimic whole meat chops (such as steaks or cutlets) with plant proteins is simply not feasible. Its main recommendation, therefore, was to develop novel plant protein products, which may serve as protein-containing meal ingredients.

Both the underlying toolbox philosophy and the ingredients focus were adopted, approximately focusing on the year 2020. Therefore, the programme should compare opportunities for the NPF sector with options for the intensive livestock sector. In addition, consumer preferences will be taken to be predominant in product development. Furthermore, environmental, industrial and social issues will be studied from the national and West-European perspectives in a global context, rather than vice versa. Although sustainability is a global issue, European researchers will experience difficulty enough trying to grasp what's on

[1]Under the *PROFETAS* (Protein Foods, Environment, Technology And Society) programme multidisciplinary researchers have been examining the dietary transition from meat towards NPFs (Novel Protein Foods) based on plant proteins. An interesting result is that combined sustainable production of both plant protein and biofuel is emerging as an important option, which may simultaneously mitigate agricultural resource depletion, agricultural pollution, and climate change.

the minds of European consumers (Verbeke, 1999), and could not possibly dream of modelling the non-European consumer with any degree of accuracy. Nevertheless, a trend setting Western diet change might have an impact world wide.

In summary, in 16 concerted projects *PROFETAS* (2005) studies the hypothesis that a substantial shift from animal to plant protein foods is environmentally more sustainable than present trends, technologically feasible, and socially desirable. The latter aspect includes environmental as well as economic considerations, thus leading to a clear transdisciplinary (environmental, economic, technological, ecological, political and chemical) design and evaluation of alternative protein production options and their impacts.

Consequences of a protein transition for European agriculture, climate change and future land-use patterns

As indicated above, changes in consumption patterns are required for environmental reasons (including climate change and resource depletion of agricultural land and freshwater). As a potential mitigation response, it is suggested above that even a partial transition from meat to NPFs would constitute an important step in that direction. Consequently, such a meat to NPFs transition might lead to huge changes in land-use during one generation (20 years). Drawing on selected *PROFETAS* results, it is the purpose of this chapter to underpin these assumptions. First, economic-environmental modelling will substantiate the necessity and impacts of a transition (why and how much?). Second, crop growth modelling will address the spatial component (where can we expect land-use changes in Europe?). Third, alternative crop options will be dealt with (which protein crops are realistic sustainable options?). Taken together, these three projects will provide us with a sneak preview of environmentally desirable changes in consumption patterns and the concomitant changes to be expected in land-use patterns beyond 2015. Through this approach the present chapter will contribute to the book's objective to delineate the major interactions between agriculture, climate change and changes in land-use patterns to be expected in the near future.

ENVIRONMENTAL AND ECONOMIC ASPECTS OF PROTEIN FOODS

Reference chains

Food production and consumption are supported by the natural resource base and the environment, using them both as a source of inputs and for the disposal or recycling of wastes. Food production and consumption systems include the whole chain of human-organised activities from agriculture through food processing and retailing to the food service sector and, of course in consumption by households, including the activity of shopping, cooking and waste disposal. Any economic system in pursuit of sustainability needs to consider this system as a whole with its interconnecting regional, national and international dimensions.

Protein food production and consumption results in environmental impacts in all phases of the production and consumption chain. Two reference production and consumption chains were devised in the *PROFETAS* programme. For the animal protein chain, the pork chain was selected as a common reference meat chain since it makes a major contribution to the production of animal-based protein products (European Commission, 2002). Also pork production is characterised by the absence of secondary products such as milk or eggs. In addition, pigs are among the most efficient animals in converting feedstuffs and agricultural wastes (by-products) into high-quality protein for human consumption. Finally, pork production is causing large environmental impacts both in developing and developed countries (Bolsius and Frouws, 1996). For the plant protein chain, it has been decided in the *PROFETAS* programme to focus on NPFs from green peas as the model raw material (Aiking et al., 2000; Smil, 2002).

Pork production in the European Union (EU) has strong environmental impacts and impacts on human health and animal welfare. First of all, the intensive production system results in a series of environmental problems due to manure surplus, which affects the quality of soil, water and air.

Second, large-scale imports of feed determine that the problems related to the European and in particular the Dutch pork production system are not only local but also global. For example, the increased production of raw materials for animal feed in Thailand, Brazil and Argentina has resulted in large-scale deforestation. Feed production is quite land and water intensive, which imposes a strong pressure on natural resources in the developing world.

Third, concentration of livestock might lead to increases in the incidence of animal diseases (e.g. swine fever or foot-and-mouth-disease) and in the incidence of food-borne human diseases. Intensive animal production systems, especially in areas close to population concentrations, result in increased risks of disease infection to livestock as well as to human beings. Finally, intensive livestock production may also lead to practices with a negative impact on animal welfare.

What can be done about these problems? First, from an environmental point of view, more pork production could be located in areas with arable products. This would reduce feed transport, and fewer problems would arise in terms of air, water and soil pollution. Agriculture is, however, often the economic locomotive of a region and an important source of direct and indirect employment. For example, a reduction by 5 million pigs in the Netherlands would in the short run mean a loss of 28,000 jobs (Bolsius and Frouws, 1996). Simply closing pork production incurs economic costs. So we need to make a trade-off between environmental improvement and its economics impacts.

In the following sections we deal with several environmental and economic aspects of protein production and consumption chains. The objective is to understand the main environmental pressures of the pork chain and the NPFs chain, and to obtain some insights into the effects of a shift from animal protein foods to plant protein foods on the environment and the economy.

Environmental assessment

For the environmental assessment, life cycle analysis (LCA) was carried out for both the pork chain and the NPFs chain. Environmental life cycle assessment is a method for assessing the environmental impacts of a material, product, process or service throughout its entire life cycle. It is an increasingly important tool for supporting choices at both the policy and industry levels (Guinee, 1995; Mattsson, 1999). LCA is intended for comparative use, i.e. the results of LCA studies have a comparative significance rather than providing absolute values on the environmental impact related to the product.

For the LCA we first provide a systematic description of both protein chains, which is useful for developing a consistent framework for a quantitative analysis of the chain. Then we develop a number of environmental pressure indicators for the assessment of environmental impacts. Finally, we compare the indicators for both chains.

The pork chain includes several stages. Along the pork chain, crops are grown for the supply of compound feed. Such crops are processed into feed, which is then fed to pigs. Pigs are slaughtered, and parts of the carcass are processed into meat products and transported to the retailers for distribution. Finally, the consumers will prepare and consume the meat products. Similarly, a production and consumption chain of Novel Protein Foods includes agricultural production of peas, NPFs processing (including protein extraction, texturisation and flavour addition), distribution and consumption. Compared with the pork chain, the NPFs chain has fewer stages.

Feed is the main input for pork production and peas are the main input for NPF production. Both use land, water, energy, fertilisers and pesticides. Energy, fertiliser and pesticide production leads to emissions of gases (e.g. CO_2, SO_2 and NO_x), minerals (e.g. N and P), and toxic substances (e.g. Cu, Zn). In addition, manure is also a main output, which leads in turn to emissions of minerals (e.g. N, P), and gaseous substances (e.g. NH_3, CH_4 and N_2O).

Considering the diversity of the emissions and their environmental impacts, we define emission indicators based on environmental themes. The emissions contributing to the same environmental impact can be aggregated into one indicator. The emissions of CH_4, CO_2 and N_2O lead to global warming and thus can be converted into CO_2 equivalents. Similarly, the emissions of NH_3, NO_x and SO_2 can be aggregated into an acidification indicator by using NH_3 equivalents. Nitrogen (N) and phosphate (P) emissions to soil and water systems cause eutrophication and can be included in the eutrophication indicator by using N equivalents. Emissions from pesticides and fertilisers have effects of ecotoxicity and human toxicity. Finally, we include the direct pesticide use and fertiliser use as environmental indicators. Therefore, for the protein chains, we define five emission indicators: (i) CO_2 equivalents for global warming, (ii) NH_3 equivalents for acidification, (iii) N equivalents for eutrophication, (iv) pesticide use and (v) fertiliser use.

In addition to the environmental indicators, we define resource use indicators, because agriculture requires land and water as inputs. The consideration of land use is relevant, because there is a competition for available cropland (De Haan et al., 1997; Bradford, 1999). It is true that land use has other functions such as providing landscape, amenity and biodiversity. However, land use for crops also reduces the opportunity of land being used for other purposes. ‘Saving land for nature’ is advocated and the best quality farmland is already used for agriculture. This means that future land expansion would occur on marginal land that is vulnerable to degradation (Tilman et al., 2002). Therefore, land use can be viewed as an important resource indicator. Water use also is an example of natural resource use. Therefore, we include two resource use indicators: land use and water use.

We use 1,000 kg of protein consumption for both chains as a functional unit in the comparative LCA study. Table 10.1 shows the results of the study.

Table 10.1 Emission and resource use indicators per functional unit (1,000 kg consumable protein in both cases)

	Pork	NPFs	Ratio (pork/NPF)
Acidification (NH_3 equivalent, kg)	675	11	61
Global warming (CO_2 equivalent, kg)	77,883	12,236	6.4
Eutrophication (N equivalent, kg)	2,491	417	6.0
Pesticide use (active ingredient, kg)	18	11	1.6
Fertiliser use ($N+P_2O_5$, kg)	485	144	3.4
Water use (m^3)	36,152	10,912	3.3
Land use (hectares)	5.5	1.95	2.8

Source: Zhu and Van Ierland (2004).

The resulting LCAs show that the pork chain contributes to acidification 61 times more than the NPFs chain, to global warming 6.4 times more, and to eutrophication 6 times more. The pork chain also uses 1.6 times more pesticides, 3.4 times more fertilisers, 3.3 times more water and 2.8 times more land than the NPFs chain. According to these environmental indicators, the NPFs chain is clearly more environmentally friendly than the pork chain. So replacing animal protein by plant protein shows promise for reducing environmental pressures, in particular acidification.

However, some caution is needed for generalisation of the results to animal protein foods. For example, in the literature a much higher water use was reported for animal production than crop production, because pig feed (such as mixed corn-soybean feed) requires 10-16 times more water than grains and pulses in addition to the pigs’ direct water consumption (Smil, 2000). Dutch pig feed used in our study consists of grains and pulses and food industry by-products. We consider water use for feed production and direct water consumption of pigs, but for simplification we did not include water use for processing. It should be realised that the difference in water use could be considerably larger if all water use categories would be included.

Economic modelling

Introducing more environmentally friendly foods such as NPFs to replace animal products seems promising for environmental improvement according to LCA. A limitation of LCA, however, is that it cannot show how the rest of world will react if consumers in the EU partly replace pork by NPFs. As long as pork is highly demanded in the whole world and feed is imported from the rest of the world, the pork issue remains an international issue. If eastern Asian countries have an increasing demand for meat (Keyzer et al., 2003), what would be the implications for meat producers in the EU? To answer such questions, we need a more extensive economic analysis, to understand how international trade and resource allocation will change if more NPFs consumption will take place in the EU.

The international dimension of EU animal protein production means that substantial changes in the pig production sector in the EU have a direct impact on agricultural producers and traders elsewhere in the world. For this study we have chosen to use an Applied General Equilibrium (AGE) model, because AGE models are suitable for studying world-wide issues (Shoven and Whalley, 1992; Ginsburgh and Keyzer, 1997). In order to include the environmental aspects in the economic model, we refer to the relationship between economic activities and the environmental system (Figure 10.1).

For an economic system consisting of production and consumption, we use the environmental resources as input, and we also emit some substances to the environment. In the environmental system, resource stocks and emission inflows from economic activities change the quality of the environment following the distribution and conversion in biophysical processes. The environmental quality supplies feedback to the economic system by influencing the amenity values of the environment and through impacts on economic productivity, resulting in interactions between the economic system and the environmental system (Costanza et al., 2000).

Our AGE model is a four-region global model. The model includes consumers' life style change, different production systems, and emissions from agricultural sectors. For the model simulations we consider a change in behaviour of consumers, because health and safety concerns have become pivotal in purchasing food products. For a large number of consumers, these concerns become manifest in the selection of products, as seen in increased purchases of diet and low-fat foods. In the final years of the millennium, more people in the developed countries have begun to change their attitudes towards animals, and an increasing number of consumers share the view that the meat industry does not care enough for animal welfare and is responsible for severe environmental damage. This tends to increase the demand for meat products that are produced in an animal-friendly way, or for meat substitutes (Miele, 2001; MAF, 1997; Jin and Koo, 2003). These concerns reflect that the consumers' attitudes towards food

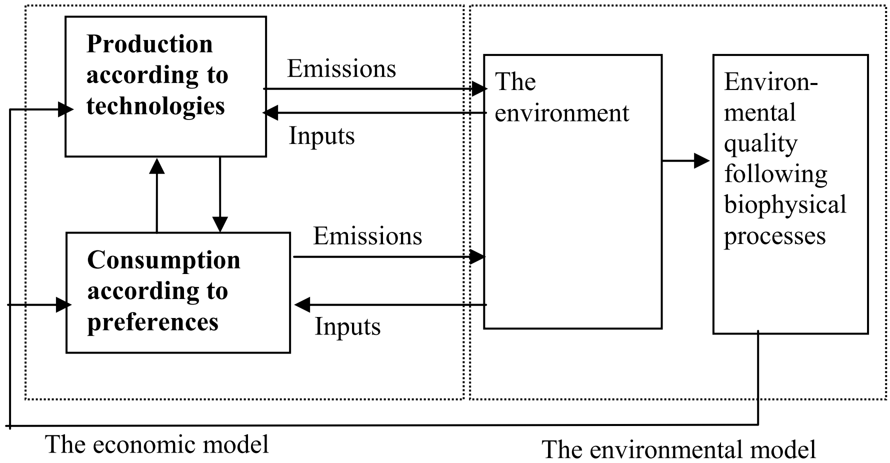


Figure 10.1 Links between the economic model and the environmental model

consumption, or in general, their lifestyles are changing. To analyse the potential impacts of these changes in consumer behaviour, we applied the model to simulate different levels of replacements of meat by NPFs in the protein consumption of 'rich' consumers.

In our applied model, we focus on the environmental emissions from the agricultural sector. Agricultural activities including manure storage, soil fertilisation and animal husbandry are important sources of ammonia (NH_3), methane (CH_4) and nitrous oxide (N_2O) emissions. The CO_2 emissions from agricultural processes are not covered in this study as agriculture itself is considered both a source and a sink. For example, in the Netherlands the CO_2 emission from agriculture is only 4% of total national CO_2 emissions in 1998 and largely related to glasshouse horticulture (CBS, 1999). For the same reason, SO_2 and NO_x emissions are not considered because NO_x emissions from agriculture are only 2% of the total emission of NO_x and SO_2 from agriculture was negligible in the Netherlands in 1998 (CBS, 1999). It was therefore decided to focus on three gases: NH_3, CH_4 and N_2O.

The model simulation shows that substitution of NPFs for meat as a preference change will decrease meat demand. This substitution will also change the relative prices of meat and NPFs and thus consumer food expenditures. As an overall effect, the meat demand in the EU, other high-income, middle-income and low-income regions will decrease. The extent of the change is greater in the EU and other high-income regions than in the other two regions, because there is higher meat consumption largely due to the increased incidence of 'rich' consumers.

Results show that the higher the replacement of all meat (including pork, beef and poultry) by NPFs, the lower the NH_3 emission. For the emissions of N_2O and CH_4, the same trend holds. See Figure 10.2 for the development of emissions under different replacement levels of meat by NPFs by the rich consumers. The reason is obvious, because the emissions are lower for the production of peas (the primary crop from which NPFs are assumed to be made) than for meat production. However, the emission reduction through life style change is very limited if only a small fraction of meat consumption is replaced by NPFs. This result can be explained by the restriction that only 'rich' people will currently switch to NPFs. Since the meat consumption of 'intermediate' consumers is increasing, the total meat production and consumption does not decrease so much. As a result, the production of meat still takes place in intensive livestock production systems.

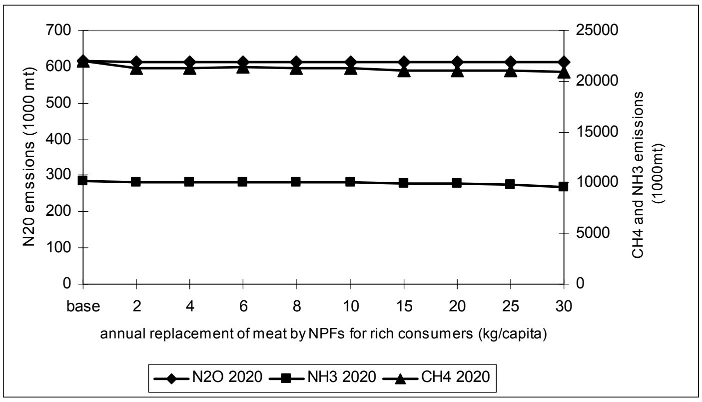


Figure 10.2 Development of emissions under different replacement levels of meat by NPFs by the 'rich' consumers

LOCATION OF PLANT PROTEIN PRODUCTION SYSTEMS

Crop growth modelling

Pea (*Pisum sativum* L.) production was chosen as the model crop for the plant protein chain, primarily because of its protein content, its ability to grow in Western Europe, the absence of unwanted substances in pea and the availability of scientific expertise on its characteristics (Linnemann and Dijkstra, 2002). It was the objective of the project to design a tool for understanding how genotypes of peas respond to different environments, so that an optimal pea production system can be defined, with respect to quantity and quality of product and to resource use efficiency. Subsequently, potential pea producing areas are identified.

The complexity of primary production systems and the need to fulfil multiple objectives call for a systems approach to better understand the chain of production processes. The method to achieve this goal is based on ecophysiological modelling. To this end, the model has to be robust, being capable of predicting crop growth responses to genotypic characteristics and environmental variation. Based on potentially useful elements from existing models, such an innovative model was developed. In addition, the main processes specific to leguminous crops (such as symbiotic nitrogen fixation) and to the *PROFETAS* programme (such as seed protein production) were identified. Once the model has been evaluated and proved robust, it can be a powerful tool for designing a sustainable primary production system at the field level.

Three major developments of modelling physiological components are to determine:

- the growth function;
- generic relationships between leaf area index and canopy nitrogen; and
- a new equation for electron transport in leaf photosynthesis.

Further, modelling the individual processes has been elaborated for nitrogen fixation, root senescence in analogy to leaf senescence, the formation and remobilisation of stem and root carbon reserve pools, and seed protein predicted from the amount of nitrogen partitioned to seeds. New methods reported in the recent literature for simple mechanistic modelling of canopy photosynthesis and crop respiration have also been incorporated. Integration of these individual model components resulted in the new, innovative generic crop growth model GECROS (Genotype-by-Environment CROp Simulator) (Figure 10.3).

The model is generic, applicable to any crop at any production level free of pests, and requires only minimum parameter inputs, which can be readily obtained in general. In addition to yielding characteristics that most existing crop models predict, crop quality aspects such as seed protein are also predicted by GECROS. Interestingly, the model predicts that within the range of seed protein percentage reported in the literature it is impossible to increase total seed protein production per ha by using pea cultivars of high protein concentration, because such cultivars would have lower seed biomass yields. The underlying reason is that for accumulation in high-protein seeds nitrogen needs to be withdrawn from the leaves. Such withdrawal causes faster leaf senescence and a shortened crop photosynthetic duration.

Application to land-use aspects

In order to assess the potential for pea production in Europe, the model was applied to a range of European conditions for pea crops, based on parameters for the standard cultivar 'Solara', which has been used in other *PROFETAS* projects. Since nitrogen is usually not a limiting factor for peas, the model was run with three water supply scenarios: supply as crop demand versus 200 mm and 100 mm initial soil available water. These three water supply scenarios represent pea cultivation with ample water supply (i.e. irrigation), pea cultivation on loamy clay soil without irrigation, and pea cultivation on sandy soil without irrigation, respectively. Simulations used climate data (1991-2000) from the Environment

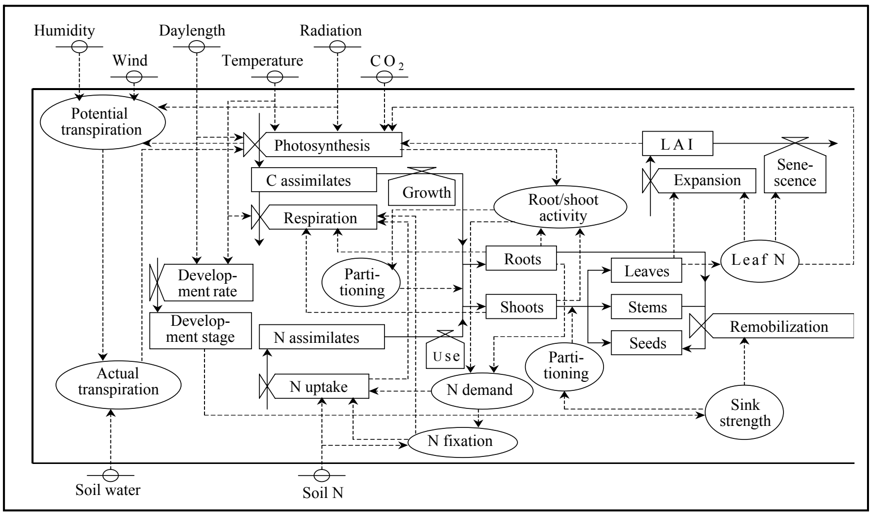


Figure 10.3 The relational diagram of the GECROS crop growth model

and Sustainability Institute of the European Commission for 66 pre-selected locations in Europe. Using GIS, the 10-year average seed yields were mapped for all three water supply scenarios (Figure 10.4).

Not surprisingly, predicted crop productivity depends strongly on water supply for all sites. Annual variability in predicted crop productivity was greater under water-limited conditions than under non-limiting conditions. Areas with potentially high predicted productivity, such as Scotland, Denmark, North Germany, and part of France are, indeed, regions in Europe where peas are currently grown. The Netherlands seems to be well suited for growing peas. The higher productivity in North Western Europe and South Scandinavia compared to Southern Europe was basically due to a longer crop growing period as a result of a cooler environment. However, caution should be taken, since the simulations were done without considering geographic information on soil quality and landscape. Furthermore, the simulation concerned only 66 sites, and in some areas (such as Scandinavia) mapping was merely the result of extrapolating just a few points. Therefore, improved simulations should incorporate local specific soil and landscape information and more locations.

In actual practice, pea performance appears to be sensitive to excess water or drought during flowering and harvesting. Peas easily lodge in heavy rains, presenting a major risk for harvesting (lodged crops remain wet for longer, are susceptible to fungal attack, whereas combine harvesters have difficulty reaping plants that are lying flat on the soil surface). Improved straw stiffness has been a major focus in pea breeding. The effect of drought and lodging severity in reducing canopy photosynthesis and seed set can be well assessed by GECROS.

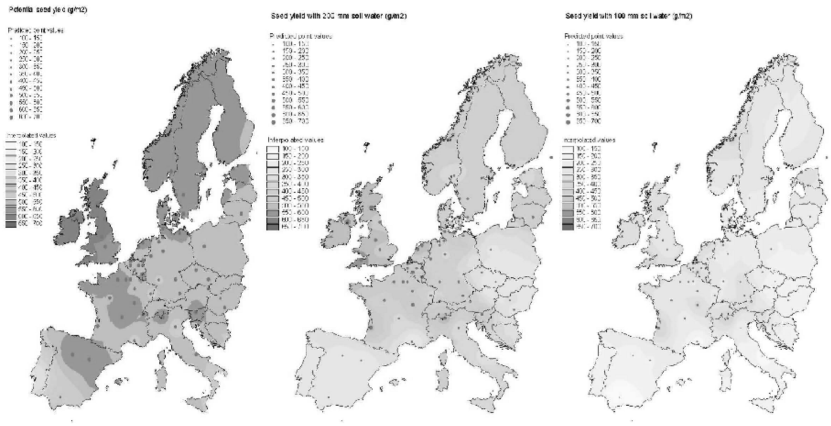


Figure 10.4 Map of pea seed yields under three water supply scenarios (decreasing from left to right, see the text) from interpolation of point model simulation for 66 sites

However, it has been beyond the reach of the current project to rigorously quantify the effect of excess water and lodging incidences per se, because of a lack of data. Soil-borne fungal diseases are a second practical problem of pea. Root rot diseases, in particular 'near wilt', caused by the fungus *Fusarium oxysporum* needs to be mentioned. Since no cure exists, prevention is the only measure that can be taken. The best prevention is to grow a crop of peas on a field only once every six years. In summary, the validated model could be a powerful tool in:

- predicting responses of global environmental change on crop production and cropping systems;
- defining crop ideotypes adapted to a target environment;
- optimising management strategies for specific crop genotype and environment; and
- designing sustainable cropping systems.

If the model is linked to a GIS environment, it can be used for studies on land use, greenhouse gas emissions and water (precipitation) requirements, while providing valuable suggestions for geographic location and fine-tuning in order to optimise sustainable production of crops.

PROTEIN CROP OPTIONS AND CLIMATE CHANGE

A conservative estimate shows that direct human consumption of plant protein, rather than indirect (via meat), has the potential to reduce the claim on natural resources such as land and fossil fuels 4-6 fold (Smil, 2000; Pimentel and Pimentel, 2003). It should be realised, however, that the meat chain has been optimised for thousands of years, resulting in efficient use of almost the whole animal (meat as well as skin, hairs, bones, gut, etc.). When replacing meat with NPFs, by analogy, all parts of the protein crop should be put to use, in order to remain competitive with respect to sustainability. Consequently, it is of the utmost importance to consider what options exist for the non-protein fraction of the raw material. Any crop that is used to produce protein-rich food products will also produce residues that cannot be used for the NPFs, for seed protein content is just 20-40%. These residues may arise in various different forms and may have different compositions depending on the crop used, the part of the production process where they arise, and the actual production techniques used. This means that both the environmental impact and the economic value of the non-protein fraction can vary greatly.

To study the non-protein fraction, information is needed on the constituents of any crop that could potentially be used for its protein. Of the main commercial food crops the main constituents other than protein are carbohydrates (starch and - to a lesser extent - sugars) and oil or fat. If we widen the scope to more unusual sources of plant protein there may be a need to include a cellulose/lignin fraction. In Europe, crop options might include lupin, pea, quinoa, triticale, lucerne, grasses, rapeseed/canola and potato (Linnemann and Dijkstra, 2002). Outside Europe, at least soy should be added.

For each constituent of the non-protein fraction there are different options. Firstly, for commercial food crops (such as pea or soy) the options are likely to be food, feed, industrial raw materials and energy production, whereas for the crops that are high in cellulose/lignin (such as grass) the options will be feed (cellulose only), industrial raw materials and energy production (Table 10.2). For all of these options estimations must be made with regard to their economic value, in order to be able to judge how realistic any given option is. Furthermore, economic value is also important when it comes to attributing environmental impacts to the different fractions of a given crop.

Table 10.2 Possible uses of the non-protein fractions

	Food	Feed	Raw materials	Energy
Carbohydrates	+	+	?/+	?/+
Oil/fat	+	+	+	+
Cellulose/lignin	-	+/-	?/+	+

A possible tool for assessing uses that are available for the non-protein fractions would be a kind of scorecard. An example for such a scorecard is given in Table 10.3 for an imaginary crop X, with 25% protein, 25% carbohydrates, 25% oil/fat and 25% cellulose/lignin. Please note that, although the scorecard is given here as a 2-dimensional table, a multidimensional, spreadsheet-based card is envisaged, allowing for easy calculation of economic values and environmental impacts.

Table 10.3 Non-protein scorecard for imaginary crop X

		Food	Feed	Stock	Energy
Carbo-hydrates	Main use 1:	syrup	pig feed	syngas	biocrude
	replaces:	corn syrup	maize	mineral oil	mineral oil
Oil/fat	Main use 1:	cooking oil	chicken feed	cleaning agent	biodiesel
	replaces:	sunflower oil	maize oil	palm oil	mineral oil
	Main use 2:	-	-	plasticiser	-
	replaces:	-	-	mineral oil	-
Cellulose/ lignin	Main use 1:	unsuitable	unsuitable	unsuitable	co-firing
	replaces:	-	-	-	coal

In every use/replace combination various aspects can be addressed. Technical aspects must be considered, possibly leading to the verdict unsuitable, if there are very high technical barriers. Likewise economic aspects need to be taken into account, since unrealistically high costs could also rule out options. From the environmental perspective, the same scheme would serve to find the best combination of environmental benefits. Each prospective use can be given an estimated environmental impact, which can then be compared to the environmental impact of the substance it replaces. The information required to use the scorecards is:

- Information on the composition of a specific crop, such as peas.
- Information on the economic attributes of the crop's production chain.
- Information on possible uses for non-protein agricultural products in general, to serve as a backbone for more crop-specific investigations.
- Information on the environmental impacts of the crop production chain.
- Information on the environmental impacts of the replaced product chain using the same methodology as the crop chain.

The contribution of this analysis to sustainability is evident. For without useful application for the non-protein fraction a protein transition is simply not feasible for environmental reasons, because the potential 4-6 fold gain mentioned above would be largely offset by the added waste (up to 80% of the crop). The future results of the project are therefore likely to primarily influence crop selection. As a preliminary result, generally, oil crops seem preferable over starchy crops with regard to biofuel production.

Combined production of plant protein and biomass was the basis for this particular analysis. Since the EU is striving for self-sufficiency in both areas they will be interested. The protein transition and the biomass transition going hand-in-hand towards more sustainable production of protein and energy, respectively, is a clear example of a 'win-win' situation and it illustrates that transitions rarely go alone. If, indeed, the non-protein fraction of a protein crop is utilised for sustainable energy production, no additional, dedicated crop will be required. The converse is also true: it would be a waste to burn the high-quality protein in a dedicated energy crop. Combining sustainable production of protein and energy in one crop seems ideal to combat agricultural resource depletion and pollution, as well as climate change.

DISCUSSION AND CONCLUSIONS

To make food production more sustainable, a stepwise improvement is required, a so-called transition (Green et al., 1999; Weaver et al., 2000). In the past many food transitions have taken place (Grigg, 1995), but they always evolved passively, as products of a multitude of chance factors. In particular a transition from animal to plant protein would be highly beneficial to the environment, due to the inherently inefficient conversion step from plant protein to animal protein (Aiking and Vellinga, 2000; Delgado et al., 1999; Smil, 2000). It is currently thought in The Netherlands that active transition management should be sought by the government (Kemp and Loorbach, 2003). However, many actors are involved, all of which will perceive their own barriers and opportunities. Aiking (2003) identified at least four barriers to such a transition towards decoupling protein production from concomitant environmental impacts:

- social forces opposing change are strong, because meat has a high status (Beardsworth and Keil, 1997);
- economic forces opposing change are strong, because established interests in the meat chain are powerful;
- technological know-how on novel (plant) protein foods is lacking; and
- for centuries the meat chain has been optimised for exhaustive use of all by-products, potentially offsetting a large part of the theoretical environmental gain.

Consequently, important actors include consumers, retailers, food processors, farmers, NGOs and policymakers. Interestingly, opportunities and obstacles for a transition turn out to be strongly different depending on the level (from local to global). In Asia, for example, incentives, crops and consumer taste are different. Therefore, regional approaches to a protein transition are called for (Aiking, 2003).

The present chapter demonstrates that, from an environmental point of view, there is no doubt that Novel Protein Foods are environmentally more friendly than meat. But the real environmental benefits of NPFs depend on their acceptance by the consumers. Even in developed countries, only a minority of the consumers is prepared to avoid meat and if they do, health issues are a much stronger underlying motivation than environmental issues (Beardsworth and Bryman, 2004). In contrast, in developing countries the proportion of meat in the diet is rising rapidly (Bruinsma, 2002). Our economic analysis indicates that if only the ‘rich’ consumers switch to consume more NPFs to replace part of all meat, the meat production and the concomitant emissions will hardly be reduced because of increasing demand of meat of ‘low income’ and ‘middle income’ consumers in developing countries. So NPFs only offer a partial solution for reducing environmental emissions (by less than 1%, unless all meat were replaced with NPFs entirely and all over the world).

Therefore, in a consumer-driven economy, stimulating consumers’ environmental concern and changing consumers’ behaviour are essential to achieve a transition from animal protein foods to plant protein foods. Another option for reducing the environmental emissions from agriculture may be found in environmental policies such as tradable emission permits for greenhouse gases and local emission bounds for local pollutants. Although it may be difficult to implement these policies in practice, they may turn out to be more effective and achieve a higher level of emission reduction than the simulated change in consumer preferences.

LCA shows that a transition from animal to plant protein might result in a threefold lower requirement of agricultural land and freshwater. World-wide, there is potential for an additional reduction in water use by at least another factor of 10. The geographic location of these and other environmental benefits will, however, depend very much on the actual selection of crops to be used as raw materials. Crop growth modelling was applied to pea growth under 3 different soil water availability scenarios. The results suggested that in the EU with low resource input high pea crop yields could be anticipated in Scandinavia (in addition to current production in France and the UK). The same model can be used for other protein crops, thus revealing optimal geographic locations for sustainable protein production.

Finally, a study on protein crop options argued that, in Europe, potential raw materials might include lupin, pea, quinoa, triticale, lucerne, grasses, rapeseed/-canola and potato, and that outside Europe at least soy should be added. However, the feasibility to be a suitable source for NPFs was shown to be an insufficient condition. Since just 20-40% of the seeds is protein, extra waste from the non-protein fraction (up to 80% of the crop) would largely offset the potential 4-6 fold environmental gain from replacing indirect (meat) with direct plant protein consumption. Therefore, useful application of the non-protein fraction is indispensable to a protein transition, and should influence crop selection. As a general result, oil crops seem preferable over starchy crops with regard to biofuel production. In this respect, it was evident that combining sustainable production of protein and energy in one crop would simultaneously mitigate agricultural resource depletion, agricultural pollution, as well as climate change.

In summary, first the necessity and impacts of a protein transition was substantiated by economic-environmental modelling. Second, the expected concomitant geographic location of land-use changes in Europe was addressed by crop growth modelling. Third, alternative crop options were dealt with and led to the conclusion that combining sustainable production of protein and energy could effectively be combined and would benefit both agricultural resource depletion and pollution, and climate change. Taken together, these three projects provide us with a preview of environmentally desirable changes in consumption patterns and the concomitant changes to be expected in land-use patterns beyond 2015. Thus, the present chapter contributes to the book’s objective to delineate the major interactions between agriculture, climate change and changes in land-use patterns to be expected in the near future. In conclusion, this chapter argues that:

- changes in consumption patterns are required for environmental reasons (including climate change and shortages of agricultural land and freshwater);
- even a partial transition from meat to NPFs would constitute an important step in that direction;
- such a transition will lead to huge changes in land-use during one generation (20 years);
- the location of these land-use changes depends on the crop choice; and the crop choice depends on the demands for both NPFs and biofuel, and is also related to available technology.

Since climate, crop choice, environmental impacts and land use are so clearly and inextricably intertwined, the consequences of a transition will be far-reaching in every respect.

ACKNOWLEDGEMENTS

PROFETAS is supported by generous grants from NWO (Netherlands Organisation for Scientific Research) and LNV (Ministry of Agriculture, Nature and Food Quality). In addition, the authors would like to thank all their colleagues within the *PROFETAS* programme for continued support and feedback.

REFERENCES

Aiking, H. (2003) The protein food transition. *Open Meeting of the Human Dimensions of Global Environmental Change, October 16-18.* Montreal (Canada).

Aiking, H., G. Meerdink, W.M.F. Jongen and P. Vellinga (2000) PROFETAS: Protein Foods, Environment, Technology And Society. In: R. Häberli, R.W. Scholz, A. Bill and M. Welti (Eds) *Proceedings International Transdisciplinarity 2000 Conference, Vol. 1, February 27 - March 1.* ETH, Zurich (Switzerland), pp. 326-330.

Aiking, H. and P. Vellinga (2000) Environment and food in a changing world: Research issues. In: A. Boekestein, P. Diederen, W.M.F. Jongen, R. Rabbinge and H. Rutten (Eds) *Towards an Agenda for Agricultural Research in Europe.* Wageningen Pers, Wageningen, pp. 199-207.

Beardsworth, A. and A. Bryman (2004) Meat consumption and meat avoidance among young people: An 11-year longitudinal study. *British Food Journal*, Vol. 106 (4), pp. 313-327.

Beardsworth, A. and T. Keil (1997) *Sociology on the Menu: An invitation to the study of food and society.* Routledge, London.

Bolsius, E. and J. Frouws (1996) Agricultural intensification: Livestock farming in the Netherlands. In: P.B. Sloep and A. Blowers (Eds), *Environmental Problems as conflicts of interest.* Arnold, London, pp. 11-36.

Bradford, E. (1999) *Animal agriculture and global food supply.* Available from <www.cast-science.org>, Council for Agricultural Science and Technology, Washington, DC.

Bruinsma, J. (2002) *World agriculture: Towards 2015/2030, An FAO perspective.* FAO, Rome.

CBS (1999) *Milieucompendium 1999: Het milieu in cijfers.* CBS/RIVM, Voorburg, Heerlen, Bilthoven (The Netherlands).

Costanza, R., C. Cleveland and C. Perrings (2000) Ecosystem and economic theories in ecological economics. In: S.E. Jorgenson and F. Muller (Eds), *Handbook of Ecosystem Theories and Management.* Lewis Publishers, Boca Raton, London, New York, Washington D.C., pp. 547-560.

De Haan, C., H. Steinfeld and H. Blackburn (1997) *Livestock and the environment: Finding a balance.* FAO, Rome.

Delgado, C., M. Rosegrant, H. Steinfeld, S. Ehui and C. Courbois (1999) *Livestock to 2020: The next food revolution.* Available from <www.ifpri.cgiar.org/index1.asp>, IFPRI/FAO/ILRI, Washington, DC.

European Commission (2002) *Prospects for agricultural markets 2002-2009.* Available from < europa.eu.int/ comm/agriculture/ publi/ caprep/ prospects 2002/ fullrep. pdf >, Directorate General for Agriculture, Brussels.

Evans, L.T. (1998) *Feeding the Ten Billion: Plants and population growth.* Cambridge University Press, Cambridge.

Ginsburgh, V.A. and M.A. Keyzer (1997) *The Structure of Applied General Equilibrium models.* MIT Press, Cambridge (Mass.).

Green, K., L. Vieira and H. Aiking (1999) Food. In: P. Vellinga and N. Herb (Eds) *Industrial Transformation Science Plan.* IHDP, Bonn (Germany), pp. 26-33.

Grigg, D. (1995) The pattern of world protein consumption. *Geoforum*, Vol. 26 (1), pp. 1-17.

Guinee, J.B. (1995) *Development of a methodology for the environmental life-cycle assessment of products.* CML Centre for Environmental Science, Leiden University, Leiden (The Netherlands).

Jin, H.J. and W.W. Koo (2003) The effect of the BSE outbreak in Japan on consumers' preferences. *European Review of Agricultural Economics*, Vol. 30, pp. 173-192.

Kemp, R. and D. Loorbach (2003) Governance for sustainability through transition management. *Open Meeting of the Human Dimensions of Global Environmental Change, October 16-18.* Montreal (Canada).

Keyzer, M.A., M.D. Merbis, I.F.P.W. Pavel and C.F.A. Van Wesenbeeck (2003) *Diet shift towards meat and the effects on cereal use: Can we feed the animals in 2030?* Working Paper WP-01-05R, Centre for World Food Studies, Vrije Universiteit, Amsterdam.

Kloppenburg, J., S. Lezberg, K. De Master, G.W. Stevenson and J. Hendrickson (2000) Tasting food, tasting sustainability: Defining the attributes of an alternative food system with competent, ordinary people. *Human Organization*, Vol. 59 (2), pp. 177-186.

Lindblom, C.E. (1990) *Inquiry and change. The troubled attempt to understand and shape society.* Yale University Press, New Haven.

Linnemann, A.R. and D.S. Dijkstra (2002) Towards sustainable production of protein-rich foods: Appraisal of eight crops for Western Europe. - PART I. - Analysis of the primary links of the production chain. *Critical Reviews in Food Science and Nutrition*, Vol. 42 (4), pp. 377-401.

MAF (1997) *Meat, meat eating and vegetarianism: A review of the facts*. MAF Policy Technical Paper 97/16, Ministry of Agriculture and Fisheries, Wellington (New Zealand).

Mattsson, B. (1999) *Environmental Life Cycle Assessment (LCA) of agricultural food production.* PhD Thesis SLU Swedish University of Agricultural Sciences, Alnarp.

Miele, M. (2001) Changing passions for food in Europe. In: H. Buller and K. Hoggart (Eds), *Agricultural Transformation, Food and Environment: Perspectives on European rural policy and planning, Vol. 1.* Ashgate Publishing Ltd, Aldershot (UK), pp. 29-50.

Millstone, E. and T. Lang (2003) *The atlas of food.* Earthscan Publications Ltd, London.

Pimentel, D. and M. Pimentel (2003) Sustainability of meat-based and plant-based diets and the environment. *American Journal of Clinical Nutrition*, Vol. 78, pp. 660S-663S.

PROFETAS (2005) *Protein Foods, Environment, Technology And Society*. Up-to-date information available from <www.profetas.nl>, Vrije Universiteit, Amsterdam.

Shoven, J.B. and J. Whalley (1992) *Applying General Equilibrium.* Cambridge University Press, Cambridge.

Smil, V. (2000) *Feeding the world: A challenge for the twenty-first century.* MIT Press, Cambridge (Mass.).

Smil, V. (2001) *Enriching the earth: Fritz Haber, Carl Bosch, and the transformation of world food production.* MIT Press, Cambridge (Mass.).

Smil, V. (2002) Worldwide transformation of diets, burdens of meat production and opportunities for novel food proteins. *Enzyme and Microbial Technology*, Vol. 30, pp. 305-311.

Tansey, G. and T. Worsley (1995) *The food system: A guide.* Earthscan, London.

Tilman, D., K.G. Cassman, P.A. Matson, R. Naylor and S. Polasky (2002) Agricultural sustainability and intensive production practices. *Nature*, Vol. 418, pp. 671-677.

Vellinga, P. and N. Herb (1999) *Industrial Transformation Science Plan.* IHDP, Bonn (Germany).

Verbeke, W. (1999) *Factors influencing the consumer decision-making process toward meat.* PhD Thesis, University of Gent (Belgium).

WBCSD (2004) *World Business Council for Sustainable Development*. Available from <www.wbcsd.org>.

Weaver, P., L. Jansen, G. Van Grootveld, E. Van Spiegel and P. Vergragt (2000) *Sustainable Technology Development.* Greenleaf Publishing Ltd, Sheffield (UK).

Zhu, X. and E. Van Ierland (2004) Protein chains and environmental pressures: A comparison of pork and Novel Protein Foods. *Environmental Sciences*, Vol. 1, pp. 254-276.

Participatory Approaches for a Transition in Agriculture: the Case of the Netherlands

11

Jan Ros, Matthijs Hisschemöller, Floor Brouwer and Gert-Jan van den Born

INTRODUCTION

What does climate change imply for the agricultural sector and the long-term agricultural policy agenda in the Netherlands? Which climate options are particularly interesting for agriculture? And, what are the implications of far reaching reductions of green house gas emissions for the transition to a sustainable agriculture? The 4th National Environmental Policy Plan for the Netherlands (VROM, 2001) concluded climate change was one of the persisting problems – next to energy, mobility, agriculture and the management of natural resources – that requires a new type of policy. Transition management including systems innovation over a generation time was considered vital to resolve such persisting problems.

Besides its contribution to greenhouse gas emissions, agriculture does also face environmental problems (e.g. high nitrogen loads) and animal diseases, and needs to respond to increasing requirements regarding animal welfare. A process of a societal transition may take several decades. Preparing for a change requires the identification of adequate options, including research and development, experiments and the design of proper institutions. It is about climate options, but it essentially explores options for the agricultural system. The involvement of many stakeholders is essential.

This chapter first explores new tools to evaluate the progress of transition processes. We examine how to measure progress and identify indicators describing the process of change. It might be regarded as a top-down perspective on the process of system innovation. However, numerous activities are observed in the transition process. Some initiatives to reduce greenhouse gas emissions from agriculture are reviewed, and we will explore the relevance of co-operation in the attempt to implement them. The stakeholders involved in the policy process are identified.

F. Brouwer and B.A. McCarl (eds.), Agriculture and Climate Beyond 2015, 191-210.

A FRAMEWORK FOR ANALYSING TRANSITION PROCESSES

Introduction

Transition processes are including activities like debate, research, experiments, co-operation and policy design. A framework that includes the relevant activities is presented in Figure 11.1. It offers an overview of the process as a whole. The activities in society are interrelated, although, in a parallel process as opposed to a serial process. As an example, the activity output of first movers (new options for system change) may have a direct impact on steps that have to be taken to change the system. They can also feed the debate on 'images of the future' or lead to a new R&D programme.

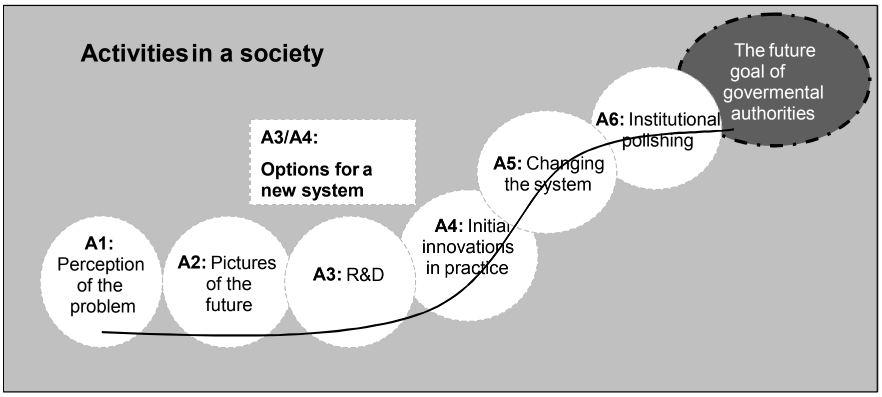


Figure 11.1 Activities in the system innovation process

Perception of the problem

The overall problem is a base for system innovations, and comprises many related smaller problems. In fact, it envelops all the aspects of the broad concept of sustainable development: people, profit and planet. This base includes short-term and short-distance aspects but also points to problems of future generations, here and elsewhere, the global ecological system and developing countries. Many of these aspects are interdependent, sometimes in win-win situations but quite often in win-loose situations. An overview of key challenges in agriculture and the food chain is presented in Table 11.1. By no means, it pretends to be complete, but it indicates the diversity of issues at stake.

Agreement among the parties involved on the seriousness of problems and priorities is important for acting efficiently. However, many actors are involved, with differences regarding on views, experiences and interests. The key element of problem perception is to reach agreement on the need to change the system. A

Table 11.1 A survey of main challenges in agriculture and the food chain using the sustainability matrix

Feature	People (social/human perspective)	Profit (economic perspective)	Planet (ecological perspective)
Here and now	food safety effects of eating habits on health odour nuisance on farms	vulnerability for veterinary diseases	ecological value of agricultural land animal welfare environmental quality with short-term ecological effects
Here and later (conditions relevant for the future system)	vital societal structure for farmers landscape values	reservation of agricultural land agricultural knowledge	Contribution to environmental conditions: eutrophication acidification groundwater pesticides and GHG
Elsewhere; now and later (people and profit in developing countries)	hunger in the world virtual water use in countries with shortages	global loss of soil quality trade regulations guidelines for food safety and environmental protection	ecological footprint risks of biotechnology

Source: VROM (2002).

proper perception of the problem can be measured by asking the relevant actors. However, for transition management it is important to analyse why actors perceive the problems the way they do. The perception of problems has several inputs, as itemised below:

- Results from physical monitoring. Although monitoring presents facts, the number of measurements in every monitoring system is limited and therefore determinative of the cogency of the results.
- Perception is also based on scientific knowledge, including uncertainty. Scientific knowledge allows us to understand relationships in the system and potential future developments. But the inevitable uncertainties in

understanding complex systems will always maintain the subject of scientific and public discussion.
- Calamities or incidents result in shock effects and a high level of problem perception directly subsequential to the event; however, these effects fade with time, sometimes slowly, sometimes quickly.
- The way this information is communicated is also an essential element. Conferences, scientific journals and Internet play an important role in the scientific world, although this is no guarantee for scientific agreement. Dispersion and colouring of information by the media also influences the public awareness in the perception of problems.

Images of the future

It is important to create an attractive image of a better future as a stimulating factor to overcoming future barriers. Again, agreement between the most important actors is paramount. However, as reaching agreement on vague goals is easy but not very meaningful; agreement should first be based on well-defined goals. To follow-up a clear image of technology and institutions is needed. However, defining too many details in the early stage of an innovative process might discourage players in the field and hinder creativity: this is why an optimum level of agreement must be found. This optimum will change with the progress of the process.

As might be expected, goal impulses tend to be stronger than the means impulses. Most transition processes start with goal setting. It is not a general matter of course to obtain agreement on the goals. This will require networking and participation. Agreement on goals only is the first step, for it is especially the clearness of and consensus on the technologies and institutions that allow a transition process to advance. In this respect one of the key issues in VROM (2001) was to keep all options open. This is only a proper strategy in a specific phase of the transition process. Such a strategy is argued as being ineffective when major investments are required that need to be covered by several investors. These investors depend on each other to profit from their individual investments. They will only take action if there is agreement on a clear approach.

There is no formal agreement yet on the best options for agriculture and the food chain in the Netherlands. More information is needed on the options or they might have to be improved to advance the process. It would be counterproductive for authorities to enforce this process too intensively. Clearness without consensus will not provide the necessary stimulus.

Research and development

Transition needs new technical and institutional options to change the system, but they still have to be developed. Chances for a breakthrough of new technologies need to be assessed, along with the remaining time for development and possible impacts. Technologies may be based on characteristics of the technology itself, the developers, the synergy between researchers and potential users, government support and the R&D budget. All such factors can be monitored and in some cases assessed by expert judgement (Ros et al., 2003). Technology seems to be the dominant factor in many system innovations. However, the institutional part of new system options requires even more attention in the development phase. At least three steps can be distinguished in this development phase:

- Step 1: generation of a new idea for institutional reform;
- Step 2: description of the institutional concept, in which the new idea is embodied;
- Step 3: detailed plan for introducing the new institutional concept, at least for experiments in practice.

Institutional options can be classified in this stepwise approach, and they might include ideas like 'taxes on biodiversity' or even 'biodiversity rights with a trade system for consumers' (VROM, 2001). Step 2 has been applied in Hees et al. (2003) in an assessment of three options for the institutional design of land-related agricultural activities in the future. Besides the more traditional concept of small individual farms (sometimes working together), two new options are introduced. The first is the farm as a franchise of large companies in the agrifood chain. Technological progress on the farms will form part of the company strategy. Agricultural and industrial processes will be more attuned to each other. Specialisation is foreseen to be more advanced, in combination with related R&D. Matters of ecology and landscape will be discussed between the national authorities and the large companies, and then set down in agreements. The second option is the farm as company, which sells all kinds of land-related products and services. These may be agricultural products but also recreational services. An important part of the farm's cash flow is related to the quality of the landscape. The benefits of this service are especially advantageous for citizens living near these farms. A landscape tax will be paid by the inhabitants to these farmers, depending on the landscape characteristics and the location of their livings. In general, long-term institutional options receive too little attention. Good ideas will have to be worked out in more detail before even the discussion on experiments can start.

Initial innovations in practice

In a transition process first movers are essential. In general, they will combine awareness on the problems with courage to experiment with innovations. They will need the courage to take risks and also support. These experiments can be monitored and results presented under the following six groups:

- Sufficient R&D results, but to date no experiments in practice started up.
- Some experiments started up, but the going is quite difficult.
- Some experiments started up and going quite well.
- Successful experiments (at technological and institutional levels) performed.
- Experiments performed, but many of them terminated.
- Experiments performed, but all applications terminated.

Especially in case experiments have not started up or are proceeding slowly, it might be useful to analyse the conditions in which new movers operate. These conditions are partially determined, usually positively, but sometimes negatively, by all kinds of policy instruments. Where one actor or actor group (i.e. pig farmers or coffee producers) plays the most important role, analysis may be focused on the driving forces (e.g. policy instruments) for this actor group. In other cases, network analysis could be fruitful; this applies to situations in which several actors will have to participate in a combined experiment. Ros et al. (2003) provide results of both approaches.

R&D and experiments in practice provide the options for system innovation. Every option implies a shift in the production structure and consumption patterns, more so than the more traditional approach of process optimisation. The progress in the development of these options for system innovation should be evaluated integrally at the system level, showing the effects for all the problems mentioned in the sustainability matrix of Table 11.1. Currently, this is partly achievable only in a quantitative way through models for production and consumption (Idenburg and Wilting, 2000; Wilting et al., 2001; Rood et al., 2003). The results for two options are presented in Table 11.2. The options distinguished include a full transition into the production of eco-milk in the Netherlands and healthier food consumption.

Table 11.2 Possible effects of system options in the Netherlands compared to the present situation

	Organic milk production on all dairy farms	Healthier food consumption pattern by the population
Effects at national level:		
Eutrophication	-8.6%	-9.7%
Land use	neutral (assumption)	-17.3%
Use of pesticides /herbicides	-12.1%	-2.2%
Animal welfare	++	+ (less meat)
Veterinary diseases	+(?)	less (?)
Public health	neutral (perception +)	++
Added value (nationallevel)	-0.5%	?
Energy use	-0.5%	+4.0% (rebound effects)
Effects on the global scale:		
Land use	+45%	less

Source: Ros et al. (2003).

Change in the system

The main challenge in a transition process is how to overcome the barrier of a less efficient system which is a mix of the old and the new systems. A method has been applied to analyse and even quantify this resistance against change on the grounds of a model for the efficiency of policy instruments based on driving forces (Booij et al., 2000). These driving forces include all factors playing a role in the decision process. Table 11.3 presents a survey of these forces with examples of underlying factors. These forces are based on a mixture of facts (monitoring of instruments, costs etc.) and expert judgement.

Table 11.3 Driving forces and examples of underlying factors related to a specific action

Driving force	Underlying factors
Financial consequences	Investment costs; subsidies; operational costs; taxes; policy on competitors
Pressure of policy goals	Goals for the country or the sector; legal standards (related to the action or to the effect)
Juridical pressure	Intensity of control; sanctions
Public pressure	Kind of problem or risk (health, ecology, here or elsewhere, now or later); attention in the media; activities of NGOs
Characteristics of the action (technology)	Knowledge about it; completely new or already in other applications; availability
Market pressure	Impact on product quality (labels); policy pressure on consumers or clients in industry
Attitude within the sector or group of actors	Internal competition due to the action; agreements between the sector and the authorities

AGRICULTURE AND THE CHALLENGE OF CLIMATE CHANGE

Introduction

This section explores options for the reduction of greenhouse gas emissions and explores the achievements made with illustrative example of stakeholder involvement in transition processes. Four options are selected and explored through close consultation with stakeholders from agribusiness, NGOs and knowledge institutes:

- An integrated assessment in fan meadow areas.
- Food consumption and climate change.
- Biomass, a glooming perspective for agriculture policy?
- Glasshouse production as a source to supply energy.

The selection of options was based on a high reduction potential after 2010, the open windows they offer for the transition in Dutch agriculture, as well as the controversy or scepticism among stakeholders and government institutions. Stakeholders must be willing to discuss their differences in view. Such a consultation with from science, society and government is vital to the process.

Brouwer and Berkhout (2001) identified options to reduce greenhouse gas emissions from food and the rural countryside and to be achieved by 2010. They focus on consumer behaviour, agricultural production, rural areas, as well as business, management and technology.

Options for the period until 2010

Consumer behaviour

An increase in income generally increases energy demand. It is therefore a substitute for 'time'. A further increase of food-related energy demand is foreseen. Changes in the demographic composition of society play an important role in this. It is expected that the number of households could increase by a third during this period. In addition, energy demand per capita is also foreseen to increase. The demand for food is expected to diversify, and the range of convenience foods such as ready-to-eat meals has expanded considerably in recent years. This trend is expected to continue. The preparation of these products generally brings about an increase in energy consumption. It is not only the growing supply of convenience food that is important here, but also the trend of more frequent dining outside of the home.

Eating habits are linked both directly and indirectly to energy consumption, and therefore influence CO_2 emissions. Meat and dairy products are particularly significant sources of increased greenhouse gas emission, as are vegetables produced in greenhouses. Currently, approximately 20% of household energy consumption relates to the consumption of food (and is therefore linked to CO_2 emissions). The consumption phase corresponds with 30% of the total energy consumption within the agricultural chain, i.e. as much as the share of the farming phase which is the other end of the chain.

Agricultural production

Further internationalization of the agricultural sector is expected in the nearby future. The application of new technologies (information and communications technologies in particular) will affect the logistical and distribution-related aspects of the agricultural sector. The Netherlands is expected to further develop itself into a logistical centre for international trade in agrofood products. An increase of production is expected in particular in greenhouse horticulture (especially ornamental plant cultivation) and open air vegetable cultivation. The current milk quota may stabilise dairy farming. The increase of organic farming has been promoted to a large extent by market developments, as well as by government-funded transition payments. The recent food scares (such as animal diseases) are an influential factor, potentially resulting in a reduction in meat consumption.

The emission of greenhouse gases is influenced by a number of developments in the agricultural sector:

- Transport of agricultural products currently has a share of 40% of all domestic road transport, and a similar share of the transport-related emissions of CO_2. The tendency to increase internationalization of the agricultural sector is expected to increase trade and transport flows and thus to increased greenhouse gas emissions from agriculture.
- The adoption of new technologies within agro logistics. The application of information and communication technologies reduce could reduce transport flows, thereby contributing to a reduction in emissions.
- The use of fertilizers and the development in the fertilizer industry. The production of nitrogenous fertilizer is associated with the use of large amounts of natural gas. The production of nitrogen fertilizers in the Netherlands is exported for the foreign market.

The layout of green space

Developments like emancipation, individualization, multicultural society and the ageing of the population bring about changes in spatial use and the different interests involved in the layout of green space. The area covered by forest and natural environments in the Netherlands is once again on the increase, while agricultural land use is under pressure due to the demand for land for other purposes. The land based character of dairy farming is coming under pressure as a result of demands made on behalf of the abovementioned other land-use purposes. The establishment of agro-production in industrial zones is being considered as a possibility in order to be able to reduce the amount of space taken up by agriculture. This could also limit transport flows. Water management may take up more and more space during the coming years, potentially resulting in a considerable area of land being used for water storage, coupled with extensive operational management. The aim of this is to combine the land-use types of water storage, agriculture, recreation and nature.

The increase in the amount of land intended for residential purposes, employment, recreation and infrastructure (as opposed to agricultural uses) generally leads to an increase in greenhouse gas emissions. Concentrated agricultural production generally results in a reduction of transport flows and can therefore also result in a reduction of emissions.

Business, management and technology

In the coming years, greenhouse horticulture is expected to make a significant transition towards high-quality products. The development of livestock production will be determined to a great extent by livestock diseases and the subsequent social and political debate. To a greater extent in the future, livestock production is expected to be characterized by product differentiation and added value, reduced long-distance transportation of live animals and a distinction in government policy with regards to land based and intensive livestock production.

Land based livestock production will play an important role in the management of open spaces, while intensive livestock production will be faced with a licensing system and strict rules regarding the sale of animal manure. A section of the agricultural world will become more extensive when making the transition to organic operations or the implementation of measures within agricultural nature management.

Developments in greenhouse horticulture (the scale of production and energy consumption per unit of the product) are determining factors for CO_2 emissions in primary agriculture. For livestock production, the development of the stock and the feed management (quantity and use) are important factors for emissions of CH_4 and N_2O. The emission of methane is chiefly related to the number of animals (particularly cows) through their digestion of feed; the manner of storing manure also influences emissions of methane. The emission of nitrous oxide is closely related to the use and application of manure and artificial fertilizer.

Options beyond 2010

COOL (Climate Options for the Long term) carried out four dialogue groups for four sectors of Dutch economy: housing, industry and energy, agriculture and transport. For each of these sectors, the dialogue addressed the following question: What is needed to realize reductions up to 80% by 2050 (as compared to 1990 levels) for greenhouse gas (GHG) emissions in The Netherlands? Dialogue participants did *not* address the issue as to whether such an emission reduction would be desirable as a climate policy target. Whereas the realization of –80% for The Netherlands by 2050 was taken as a point of departure, the dialogue explored implementation trajectories for reduction options using a method, which is known as back casting. It is also important to note that the dialogue groups were asked not to fake consensus in their strategic recommendations. The dialogue groups were supported by major research institutes. Table 11.4 summarizes the findings with respect to emission reduction trajectories for agriculture. The range in figures is caused by different expectations as regards the volume of primary production by 2050.

The following trajectories are distinguished:

- Implementing measures related to primary production renders an emission reduction of 12-18Mt CO_2 equivalent. This yields 60-80% reduction in the remained emissions (5-10 Mt CO_2 equivalent) compared to 1990 level.
- Energy production and optimisation of wood consumption renders an additional reduction in the order of 6-8.5 Mton CO_2-equivalent (this is 25-35% of the overall emissions from the sector in 1990).
- Sinks could render another 7-9 Mton CO_2 (also 25-35% of the sector's emissions in 1990).

This means that, in total, the sector can be able to reduce 100-150% of its own emissions by 2050. Interventions in the food chain are not included in this figure.

Table 11.4 Contribution to emission reductions by the sector agriculture (reduction potential in Mton CO_2-equivalent)

	Reduction potential[a]
Reduction primary production	
CO_2 neutral greenhouse	9-14
Closed stables	2-3
Emissions per cow	0.5-1.5
Organic fertilizers	Uncertain
High efficient use of fertilizers	1
Total primary production	12-18
Sustainable energy and materials Netherlands	
Utilisation of residuals from agriculture	0.5-1
Manure fermentation	0.5-1
Combustion of (dry) manure	1
Bioenergy production NL	1
Wind farms on shore	1-1.5
Total sustainable energy and materials Netherlands	4-6
Sustainable energy sources and materials from abroad	
Chain optimisation of wood consumption	2
Bioenergy production imported (400-500 PJ)	38
Total sustainable energy sources from abroad	40
Sinks	
Increase groundwater level in peat pastures (450,000 ha)	?5-7[b]
New forest (350,000 ha)	?1
Forest and land management	?1
Total sinks	?7-9

Note: [a] The reduction potential of the options cannot simply be added because of overlap; [b]? means that the net effect is uncertain.

Most remarkable is the sector's contribution to reductions in other sectors. The shift from artificial to organic fertilizer, in combination with efficiency in use, will, if this measure is applied outside The Netherlands as well, probably render a reduction in the order of 8-11 Mton CO_2 equivalents (N_2O and CO_2). This branch of industry will be likely to shift its core business in The Netherlands. Cement production will be affected by a chain optimisation of wood consumption, as the use of concrete in construction will be reduced. In total, agriculture may reduce 14-19 Mton CO_2-equivalent in other sectors.

Approach adopted

Policymakers in the Netherlands tend to consider that measures taken in agriculture and in rural areas have no significant impact on emissions. However, the reduction potential of options might be uncertain or even contrasting among the stakeholders involved. Measures in agriculture may reduce emissions from transport. However, such measures may no longer be needed in case transport fuels are available that are CO_2 neutral. Measures to promote the use of organic manure may replace the use of inorganic fertilizers. However, such options may no longer be needed from a climate perspective if industry starts using CO_2 neutral feedstocks (e.g. implementing CO_2 removal and storage). Even if the options' potential seems obvious, there maybe persistent uncertainties and sceptics with respect to their feasibility in terms of behaviour change, monitoring or international agreement. Measures related to the fen meadow (peat pastures) areas provide a major example. Large scale implementation of biomass may raise ethical questions as well. Stakeholders may have to be consulted to identify options that have in common a shared notion of their long term potential. Stakeholders from the agricultural sector and research - with conflicting views and expectations - may have to be involved to identify the range of options. We will now explore options to reduce greenhouse gas emissions in four cases, including the fen meadow region, food and consumption, biomass and greenhouse production.

Four options to reduce emissions

An integrated assessment of the fan meadow areas

Peatland is like a forest an ecosystem where lots of carbon is sequestered. For centuries peatlands have been used for agriculture and have been a source of energy. In the Netherlands only a small portion of the original peat area is left. The area studied is about 350,000 ha. For centuries, it is mainly in use for agriculture, meadow in particular. Agricultural intensification since the beginning of the 20th century required deeper drainage causing peat mineralization, which in turn requires further drainage, starting a cycle that leads to continually lower drainage levels, which ultimately may end into a situation where all peat is mineralised, at least in some areas. Peatland areas that are managed as nature conservation are not subject to mineralization and might under certain conditions even sequester carbon.

By changing the drainage depth to a level just below the surface the mineralization of peat can be reduced significantly. Under even more extreme conditions where the water table is near or above the surface, the peat area can become a sink of carbon instead of a source. This is very relevant from policy perspective that is aimed at a reduction of carbon emission and sequestration of carbon.

One of the consequences of increasing the water table to a level below or at the surface level is the emission of CH_4. Methane is produced under anaerobe conditions and the amount of emissions is dependent of soil temperature, surface or groundwater level and the primary production of the ecosystem. Next to CO_2 and CH_4 also N_2O is produced. Nitrous oxide is a product of microbial nitrification and denitrification in soil and aquatic ecosystems. Emissions increase with the use of manure. The contribution of methane and nitrous oxide are rather relevant because of the higher global warming potential (GWP) of these gases compared to CO_2. The impact of CH_4 is 21 times greater than CO_2 and N_2O 320 times.

To show the net contribution of fan meadows to the emission of greenhouse gases under different management options an emission budget is made for each of the options. The selected options include past and current fan meadows management, including its accompanied drainage levels and a few alternative land uses. The management options are:

- fan meadows with deep drainage levels (business as usual);
- fan meadows with undeep drainage levels (historical);
- swamps, high water levels;
- swamp forest, high water levels; and
- swamps used for biomass production (short rotation willows for the production of renewable energy).

The emission budget shows the net result of the emission or sequestration of carbon and the emission of CH_4 and N_2O. Changes in water level and subsequent changes in land use have a positive impact on the greenhouse gas emissions budget and fan meadows area have a potential to contribute to reduce emissions and even might contribute to sequester carbon. This, however, very much depends on the conditions that are required for regrowth of peat. Precise figures on emissions remain largely uncertain. Stakeholders agreed that choices for the long term are necessary, because policy goals with respect to climate, water, nature and spatial planning currently might not be consistent. An integrated assessment may clarify the interplay of policy targets for these issues, the possibilities for win-win options and criteria for evaluating policy development and implementation.

Food consumption

Too little attention is devoted to consumer behaviour in climate policy. Better insight into consumer eating patterns and behaviour is important for the process of transition towards sustainable agriculture. No complete image of this is available, but we may assume that better use of materials and energy is an important factor. Here, emphasis is given on the perspective of reducing greenhouse gas emissions through changes in eating patterns and behaviour.

Approximately 10% of the total emissions of greenhouse gases in the Netherlands are food-related. Primary production makes up a 40% share of this, while processing and transport contribute about 35% and the remaining 25% is related to the consumption phase. Table 11.5 provides an overview of the total greenhouse gas emissions related to the consumption of foodstuffs by Dutch households (Kramer, 2000). The greenhouse gases examined here are CO_2, CH_4

and N_2O. Agriculture and the consumption phase account for more than half of the emissions of greenhouse gases that are related to food consumption.

Table 11.5 Relative contribution of the various links in the food chains in total CO_2 equivalent (%)

	Share
Farming	39.0
Industry	17.0
Packaging	5.0
Transport	6.0
Wholesale and retail trade	10.0
Consumption (preserving, preparing, washing up)	23.5
Waste	-0.5
Total	100.0

Table 11.6 Emissions of greenhouse gases per household per year related to food (in kg CO_2-equivalent)

Category	Emissions
Indirect emissions, consumption at home	2,851
Direct emissions, consumption at home	914
Indirect emissions, consumption outside the home	262
Direct emissions, consumption outside the home	135
Total	4,162

Table 11.6 shows that annual emissions per household for the purpose of consuming food exceed 4 tonnes of CO_2 equivalents. With approximately 6 million households in the Netherlands, this equates to total emissions of over 24 million tonnes of CO_2 equivalents. This corresponds with approximately 10% of the total emissions in the Netherlands. This amount is not solely emitted in the Netherlands, because part of the products is produced elsewhere.

Approximately a third of food production is lost during the process between production and consumption, and households have a large share in this. There is also a great deal of wastage in the chains. The consumers' choice is strongly influenced by public concerns such as health and food safety. Convenience is also an important factor.

Aspects like health and food safety are important for consumers. Conversely, consumers consider the role of environmental and climate-related aspects to be unimportant. The consumption of meat causes various environmental problems (e.g. acidification, GHG emissions). The consumption of meat by Dutch households contributes almost 30% of the greenhouse gas emissions (CO_2, CH_4, and N_2O) emanating from Dutch annual food consumption (Kramer, 2000). Meat consumption has increased greatly in recent decades. Meat consumption has increased by 60% per head of the population. The production of grain – the basis of feed for the animal sector – lags a long way behind. During the last 20 years, global grain production has actually decreased per head of the population. Tilman et al. (2002) indicate that between 3 and 10 kg of grain are required for the production of 1 kg of meat. In view of the possible scarcity of feed raw materials on the global market, coupled with the environmental requirements regarding the application of animal manure, they indicate that extensive production systems may become more important. This could provide an incentive to land based livestock production (and to cattle farming in particular), whereby feed crops with relatively low protein content are converted into products with high protein content (such as dairy products and beef).

The total losses in the food chain, from the food producer to the food consumer, are estimated at 32 to 39% of the food production. Households account for 10 to 15%. Private households therefore account for approximately a third of the total losses incurred through the food chain. According to table 1, almost 40% of food-related greenhouse gas emissions come from the agricultural sector. In total, 12% is emitted 'for nothing' due to the losses incurred throughout the chain. By preventing wastage in the chain, the emissions from the agro-complex can be reduced by 12%.

Energy consumption and greenhouse gas emissions are strongly linked with the country of origin. Imports of foodstuffs contribute to the consumption of energy and the emissions of greenhouse gases in foodstuff chains. Approximately 40% of domestic road transport is connected with agricultural products.

A movement emerged at the end of the 1980s, arguing the case for regional products. The rediscovery of locally-produced food is seen as an important counterpart of the international standardization of food quality. The rapid spread of McDonalds restaurants through Italy was a major *raison d'être* for this movement (Miele, 2002). In view of the great interest in regional cuisine in northern parts of Italy, this is hardly surprising. In addition to the spread of information about local dishes, the emphasis has more recently been placed on reinforcing relations with restaurants. Maintaining a varied range of vegetables, fruit, meat and regional dishes is important for these restaurants. At present, the movement has about 70 thousand members, spread across 45 countries. Its roots are in Europe (Germany and France), but new members (USA, Australia, Japan and China) joined during the 1990s. The consumption of locally-produced foodstuffs reduces emissions. What are the possible actions that could be taken?

- Active advantage can be taken in the short-term of regional products, which are bought principally for reasons of quality. These products put less pressure on the environment, although environmental considerations are not the direct reasons for sales. Supermarket chains and organizations for agriculture and horticulture are important players in this. In collaboration with the catering industry, the possibility of incorporating organic meat (which requires less energy during production) and regional dishes into the meals on offer could also be explored.
- In the longer term, a system of transferable emission rights could be introduced for consumers. Such a consumer-oriented instrument may not be likely in the short term, but could be achieved over time. The main advantage

is the freedom of choice for consumers within the limiting conditions of CO_2 emissions. It is as yet unclear how consumers would react to such a system.

The consumption of meat requires a great deal of energy and is coupled with considerable greenhouse gas emissions. Meat substitutes in low energy products would seem to have potential. There are a few conditions that would need to be met in this regard, such as technological expertise. The views of consumers with regards to meat substitutes in combined products also need to be investigated.

Biomass, a glooming perspective for agricultural policy?

If biomass is used as an energy supply source the net impact of CO_2 emissions is zero. This makes biomass a sustainable source of energy. It can be used for

- supply of electricity and heat;
- transport fuel; or
- raw material for production in chemical industry (bio-plastics etc).

There is broad range of organic materials that can be used for bioenergy purposes (such as grass and wood) and as many ways to transform these into fuels or into raw materials for other products.

The debate on biomass is rather complex, as pros and cons may be situated on different levels of scale (global, national, local) and in different regions. Bioenergy may also have impacts on other issues and policy fields. Technological, economic and governance aspects are closely intertwined.

The European Union (EU) promotes the development and use of bioenergy, and issues related to biomass touch upon all priority areas of the Ministry of Agriculture, including arable farming and horticulture, the greenhouse sector, fertilizers, nature and landscape, international cooperation and environment. Biomass issues affect the three pillars of the agro-food complex in the Netherlands, including innovation, corporate sustainability and international markets, and some recommendations are developed regarding the contribution to national and international policies.

- The potential of biomass in the transition to a sustainable energy system is widely acknowledged. In all energy scenarios, biomass is considered rather crucial. Current global energy use is 400 EJ, while bioenergy could provide more than double that amount. The achievability of such potentials depends on factors that remain as yet uncertain. National government aims for a share of 10% of the national energy consumption from sustainable sources for the year 2020, of which at least half to originate from biomass. Given the high population density, bioenergy production as a monoculture would not be competitive at this moment. However, multifunctional cultures and multifunctional land use, agro-forestry and the use of organic wastes might even under these economically unfavourable circumstances provide 10% of the national energy supply (circa 300 PJ, including 150 PJ from production and 150 PJ from wastes).

- The large scale production and use of biomass for energy meets considerable objections and uncertainty. Experts and stakeholders articulate different points of view around, which also affect the image of bioenergy. On the one hand, scepticism relates to the competitiveness of bioenergy as compared to fossil and other sustainable options. On the other hand, there is doubt with respect to its sustainability. Limits on the availability of land for the cultivation of biomass are a concern. Although calculations are available to show that this may not be a problem, concern remains as regards rival land use claims between biomass and food. Another issue is the possible harmful effects for biodiversity. Apart from concerns with respect to ecological sustainability, there are concerns with respect to social impacts of large scale biomass production, especially in developing countries. Is it possible to develop an international regulation and monitoring system to guarantee that production, transport end use of bioenergy meet standards of sustainability? Next to these questions uncertainty remains regarding the best species and varieties as well as the most efficient and environmentally sound technological processes. Stakeholders and experts articulate different assumptions and views in this respect. For policy makers, the question is how to deal with the different views and knowledge claims in a way that there is some progress and a shared development of knowledge at the same time.

Without disregarding uncertainty and conflicting views, there is also the observation that the EU and countries like Sweden, Germany and France, have taken the lead in applying biomass for energy. The trend is toward a bigger share of bioenergy in the total energy supply, electricity as well as transport fuels. Specific measures, such as the exemption from tax for bio diesel in Germany, will undoubtedly foster an increase of biomass import and stimulate production in Central and Eastern-Europe, Asia and Latin-America. This development is likely to restrict the alternatives for Dutch policy with respect to the implementation of sustainability criteria as well as technology innovation. At the same time, the urgency to address the uncertainties in an international context has considerably increased. From this perspective, as well as from the perspective of stakeholder from Dutch agriculture, environmental NGOs and industry, reluctance of Dutch agricultural policy makers may have undesirable consequences in the near future.

The Ministry of Agriculture is advised to concentrate on:

- Initiate the development of mechanisms that safeguard sustainable production, transport and use of biomass for energy. This also includes the barriers in national policy that hampers the successful implementation of bioenergy.
- Promote and support further research into the cost-effectiveness of different biomass options and technologies.

Put in a somewhat broader context, the challenge for the Ministry of Agriculture might be to develop an integrated view on biomass, by bridging the gaps between the worlds of agriculture, energy and climate. Links might be established between biomass and policy themes related to the use of agrochemicals, the development of countryside and rural landscapes, transition sustainable agriculture, corporate business and nature conservation. The Ministry has been advised to install a task force on developing vision. This task force might consult stakeholders, which might be critical in enhancing public support.

Greenhouse production as a supply source of energy

Some initiatives are launched to develop a system change in the greenhouse production that does supply energy rather consume energy like is currently the case. The initiative is a response to the criticisms that greenhouse production currently is unsustainable because of its share in greenhouse gas emissions (large amounts of energy used, and the release of CO_2 from open greenhouses) as well as the use of chemicals. Based on recent experience, the sector organisation has become increasingly aware that such major innovations are not achievable through incremental steps. Hence, the sector has become open to welcome a major breakthrough, which is based on a combination of new technologies but which may have a far-reaching impact on the entire system (production, spatial planning and consumption).

A technological concept has been developed which may help to implement the concept Greenhouse as an energy supply source within a foreseeable future. The concept uses a combination of technologies, including a fine wire heat exchanger, and underground storage of water (27° Celsius). Solar is used for heating the water. The heat exchanger and the underground storage of water make it possible to cool the greenhouse in the summer and warm it during the winter period. Sufficient quality CO_2 can be delivered by the chemical industry. In effect, the greenhouse might reduce the use of fossil energy (natural gas) by more than 90% and can deliver low value heat to surrounding offices. The initiators have asked for financial support from Dutch government to set up a demonstration project. The Ministers of Economic Affairs, Agriculture and Environment have spoken out a political willingness to support the project but as yet, some practicalities have not been overcome.

A participatory technology assessment was initiated and several stakeholders have been interviewed. Generally, the interviewees supported the initiative. The idea of a pilot was endorsed, even by those who were quite sceptical about the concept, and several arguments have been offered:

- Strengthen the sector in global competition;
- Technological breakthrough, with advantages like an almost zero use of chemicals (thanks to the fact that the greenhouse remains closed, even in summer), the expected increase in production by lowering costs and an improved public image for the sector.

Criticism and doubts remained as well. Some people were sceptical about the high investment costs involved for the producers; others had doubts on the feasibility of the technological concept, especially under extreme weather conditions. Specific questions and concerns relate to legal and spatial planning issues. Especially interesting are the possible implications of the concept for the location of greenhouse production. It is now moved to low population areas, whereas the concept suggests integrating them in either suburbs or business areas.

A political issue raised was whether this initiative could be used by the sector to avoid or delay its obligations to reduce energy, laid down in the national energy agreement (the so-called GLAMI agreement). This agreement is important in the context of the Kyoto targets. There was some serious concern as to whether this project was not a bridge too far and the sector might end up with nothing. Instead of a complete system innovation, an emission reduction of 5% would already be a major achievement.

Government involvement might be limited to some financial support, and recommendations are made for the Ministry of Agriculture:

- support a pilot to test the technology;
- investigate costs and benefits for the individual producer;
- map out to what extent the concept contributes to achieving the national Kyoto targets;
- identify institutional and legal issues that can only be addressed by regulation. This includes any implications the concept has for spatial planning and the desirability of integrating greenhouses in populated areas rather than expelling these what is current practice;
- an open dialogue about the results of these trajectories with stakeholders, especially those who are sceptical about the initiative.

CONCLUSIONS

The analysis in this chapter addressed two strategic questions:

- The available evidence from research to assess the potential contribution from agriculture to the climate problem.
- The steps that could be taken in order to achieve progress. Options are selected and explored in close consultation with stakeholders from agro-business, NGOs and knowledge centres.

Agriculture can make a difference indeed, if it would only on the options identified. However, there is neither certainty nor consensus with respect to the feasibility and desirability of the options identified.

A shared view on a better future is helpful for a radical transition process. The clearness of this vision, the clearness of the image of the future system as well as the consensus about it might be very relevant process indicators for the progress of a transition process, especially in its phase of preparation. However, such a view cannot be forced. Consensus takes time. In the beginning several options for a better system are developed and the present system still is a good alternative for many stakeholders, especially those who have the power.

The options identified are more than just a technology. Chain analysis is important to understand the implications of the system innovation as is shown for some of the presented options. All options for an alternative system have plusses and minuses. So, transition management should focus on two things. On the one hand, system option should be improved by stimulating research, supporting first mover to experiment with important parts of system options and working on institutional improvement as well. On the other hand the process of selection needs facilitation, eventually leading to the most desired system option for all stakeholders as a first step to break down the resistance against change.

To conclude, it is not a simple process. From the example of climate change it might be suggested that, in order to take the implementation of climate options seriously, the practice at the level of ministries should change. In order to address the important issues more effectively, it might be necessary to address the conflicting viewpoints in society, and not to avoid tough debate.

REFERENCES

Booij H., J.P.M. Ros and M.M.P. van Oorschot (2000) Beschrijving Model Effectiviteit Instrumenten. Versie 2.0 (MEI 2.0). RIVM (report 773401001), Bilthoven.

Brouwer, F. and P. Berkhout (2001) De klimaatdimensie van voedsel en groen: Opties voor vermindering van de emissies van broeikasgassen (The climate dimension of food and green space: Options for reducing emissions of greenhouse gases). LEI (Agricultural Economics Research Institute), The Hague, LEI-rapport 3.01.09.

Hees, E.M., J. Ros, H. Westhoek, W.J. van der Weijden and C.J.A. Hin (2003) Duurzame landbouw 2030 in drie organisatievormen. Beelden voor de toekomst. CLM, Utrecht.

Idenburg, A.M. and H.C. Wilting (2000) DIMITRI: a Dynamic Input-output Model to study the Impacts of Technology Related Innovations. Available at: http://policy.rutgers.edu/cupr/iioa/Idenburg&Wilting_DMITRI.pdf.

Kramer, K.J. (2000) Food Matters. On reducing energy use and greenhouse gas emissions from household food consumption. Center for Energy and Environmental Studies, University of Groningen, Groningen.

Miele, M. (2002) The slow food movement. *Newsletter of the European Society for Agricultural and Food Ethics (EurSafe)*, Vol. 4 (3), pp. 2-4.

Rood, G.A., J.P.M. Ros, E. Drissen and K. Vringer (2003) A structure for future projections of environmental pressure due to consumption. *Journal of Cleaner Production*, Vol. 11, pp. 491-498.

Ros J.P.M., G.J. van den Born, E. Drissen, A. Faber, J.C.M. Farla, D. Nagelhout, P. van Overbeeke, G.A. Rood, W.R. Weltevrede, J.J. van Wijk and H.C. Wilting (2003) Methodiek voor de evaluatie van een transitie. Casus: transitie duurzame landbouw en voedingsketen. RIVM (report 550011001), Bilthoven.

Tilman, D., K.C. Cassman, P.A. Matson, R. Naylor and S. Polasky (2002) Agricultural sustainability and intensive production practices. *Nature*, Vol. 418 (8 August 2002), pp. 671-677.

VROM (2001) Where there's a will there's a world. Working on sustainability. 4th National Environmental Policy Plan. Ministry of Housing, Spatial Planning and the Environment (VROM), The Hague.

VROM (2002) National Strategy for Sustainable Development. Review of Government Policy. Ministry of Housing, Spatial Planning and the Environment (VROM), The Hague.

Wilting, H.C., W.F. Blom, R. Thomas and A.M.Idenburg (2001) DIMITRI 1.0: Beschrijving en toepassing van een dynamisch input-outputmodel. RIVM (report 778001005), Bilthoven.

Options and Trade-offs: Reducing Greenhouse Gas Emissions from Food Production Systems

12

Sanderine Nonhebel

INTRODUCTION

Agriculture is producing food for the worlds' population and is therefore a sector of vital importance. The amount of food required depends on the size of population and consumption per capita. The FAO (Bruinsma, 2003) estimates that a 50% increase in global food production in the next 30 years is needed to feed the global population. This increase in needs is caused by an increase in the global population (from 6 to 8.3 billion people) and by a change in consumption patterns. The change in consumption includes not only the consumption of more food per person, but also an increase in the consumption of more luxurious products like livestock products as milk and meat. Since it requires 4 kg of wheat (as feed) to produce one kg of pork (Nonhebel, 2004), the increased consumption of meat requires yet a larger increase in agricultural production.

The present agricultural practices, however, already put an enormous claim on the local and global environments. Agriculture is the main cause for pressures on the environment, including deforestation, loss of biodiversity, land degradation, salinization, over extraction of water, emission of some categories of greenhouse gasses and ammonia, leaching of nitrates etc. The 50% increase in food production without a large increase in environmental impacts will be a challenge for the coming decades.

Food production can occur in very different ways, varying from so called extensive systems, where hardly any external inputs are used to very intensive production systems which require large amounts of external inputs (chemical fertilizers, pesticides, machinery etc.). The extensive systems are characterized by low inputs and low yields per ha and the intensive systems by high inputs and high yields per ha. Different systems have different effects on the environment. Low input systems show low emissions but require vast amounts of land, while the high input systems show large emissions to the environment but require a smaller acreage to produce the same amount of food.

In principle, an increase in food production can be obtained via different routes: increase of the land used for food production or increase in the production per hectare (intensification). The FAO estimates that 80% of the required food

F. Brouwer and B.A. McCarl (eds.), Agriculture and Climate Beyond 2015, 211-230.

production increase will be obtained from intensification, while the other 20% will be obtained through expansion of land use (Bruinsma, 2003). This implies that with respect to the environmental impacts of increased food production, the environmental effects associated with intensification will be the most important.

To obtain an impression of the possible environmental implications of this increase in global food production, the history of agriculture in Western Europe can serve as an example. In the last 30 years intensification in West European agriculture took place. As a result of the technical improvements in agriculture, the yields per ha nearly doubled (FAO, 2003). The technical improvements included a variety of activities like improvements of crops through breeding, expanded use of chemical fertilizers and pesticides, better water management, increased knowledge of the farmer etc. However, this yield increase per hectare came along with the increase of the emissions of nitrates and ammonia causing regional eutrophication and acidification.

In the 1980s environmental regulations were introduced in agriculture to reduce its effect on the environment. In The Netherlands, these regulations resulted in a 30% reduction in agricultural emissions of nitrates and ammonia (RIVM, 2001). This shows that changes in farming practices can lead to a large reduction in emissions.

Agriculture has recently been recognized to be an important source of the greenhouse gasses methane and nitrous oxide. Not much research has yet been done on options to reduce these emissions. The FAO estimates that a 50 percent increase in production will therefore come with a similar magnitude increase in methane and nitrous oxide emissions.

The purpose of this chapter is to inventory options to reduce greenhouse gas emissions related to the production of food. Experience obtained in the past decade with respect to reduction of the nitrate and ammonia emissions shows that such reductions require changes in production techniques and substitution of other resources. These other production techniques may lead to unwanted effects in other parts of the system. To prevent problems arising elsewhere attention must be paid to trade-offs with other environmental themes as well as trade-offs with food security. This chapter will present such an analysis with the situation in the Netherlands used as the starting point.

DESCRIPTION OF THE NETHERLANDS AGRICULTURAL SYSTEM

The Netherlands agricultural system can be characterized as a high input system (large inputs per ha resulting in high yields). The inputs per ha (fertilizers) are the highest in the world, and so are both crop yields per ha, and milk production per cow (LEI, 2003; FAO, 2004). Agriculture and food production put a large claim on available resources and cause large emissions to the environment. In the Netherlands, about 60% of the land is in use for agricultural production and agriculture is the largest fresh water user. Further, agriculture is the major cause of the eutrophication and acidification problems (RIVM, 2001). About 90% of the nitrogen and phosphorus emissions originate from agriculture due to fertilization of crops, both by applying manure and chemical fertilizer. With respect to acidification over 40% of the national NH_3 emissions are due to the application of manure.

During the last decade several measures were taken to reduce the environmental impacts of agriculture. An example is the so called sod-injection technique. During the application of manure to soils large amounts of ammonia are emitted. To reduce these emissions the so-called sod injection technique was developed. With this system, manure was applied in the soil (at a depth of 5 cm) instead of on the soil surface. The adoption of this technique led to an enormous decline in the ammonia emissions (a 30% reduction). Another example is the mineral accounting system (MINAS) - a management system which gives farmers insight in the phosphorus and nitrogen surpluses on their farm that involves limits to emissions to the surroundings. The introduction of this system led to a 30% reduction of the phosphorus and nitrogen emissions (RIVM, 2001).

In addition to these adaptations in conventional production systems, an increased interest in other, more environmental friendly production systems can be observed. Subsidies are available to support farmers changing from intensive production systems to organic production systems. A policy goal states that by 2010 10% of the Netherlands agricultural production should be organic, rising from a level of 3% in 2004 (LNV, 2004).

The fact that agriculture is also a source for methane and nitrous oxide is only recently recognized. Inventories are currently being undertaken to the sources of these emissions (Novem, 2004). No overview exists with respect to the possible of the trade-offs of the potential greenhouse gas reduction options with other environmental emissions and food production.

ENVIRONMENTAL IMPACTS OF THE PRODUCTION AND CONSUMPTION OF FOOD

To gain insight in the trade-offs of GHG emission reduction options, methodologies developed in environmental sciences are applied. This section starts with a short description of the applied methods.

Environmental impacts of a production process can be studied from production and consumer side viewpoints. Approaching the problem from the production side implies that one determines the emissions related to a specific production process or a production sector. Approaching the problem from the consumer side implies the determination of the emissions related to consumption of certain products. Studying it from the production side implies that one is interested in the emissions occurring in a region (including the emissions required for the production of exports). Studying the problem from the consumption side implies that one is interested in all the emissions required to produce and transport items that are consumed/purchased in a region. This starting point includes the emissions abroad required for the imported goods.

Since production only occurs when there is consumption, on a global scale the total emissions calculated from the production side are equal to the total emissions calculated from the consumption side. At the level of a nation, imports and exports interfere with these results. A country that produces a lot for export will show large emissions in the production side analysis, but the emissions analyzed from the consumption side will be much lower. On the other hand, a country that imports all of its consumption will show no emissions in a production side analysis but large emissions from a consumer side analysis.

Greenhouse gas emissions from the production side

Examination of the Netherlands greenhouse gas (GHG) emissions from the production side results in the following observations. Total GHG emissions in the Netherlands are 220 10^9 kg CO_2 equivalent (RIVM, 2001) of which CO_2 is the most important. The CO_2 emissions arise mainly due to the use of fossil energy sources for needed production energy. Figure 12.1 shows CO_2 emissions by production sector. Energy production, transport and industry produce the largest amounts. The emissions by the agricultural sector are only 5% of the country total. Within this sector the heated glasshouses in horticulture are the largest emitters.

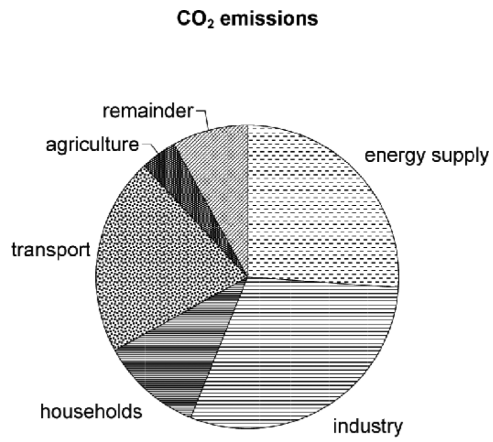


Figure 12.1 Contribution of the various production sectors to the total national CO_2 emissions in the Netherlands
Source: RIVM (2001).

When we focus on other greenhouse gasses, we find that the agricultural sector plays an important role with respect to the emissions of CH_4 and N_2O. Figures 12.2 and 12.3 show these emissions by sector. Nearly 50% of the national N_2O emissions occur in agriculture. This is mainly due to de-nitrification processes in soils resulting from application of manure and chemical fertilizers. Emissions from grasslands (dairy production) hold the largest share. A large part of the N_2O

emitted in industry is also associated with agriculture: the production of chemical fertilizer involves substantial emissions of N_2O (Kramer, 2000).

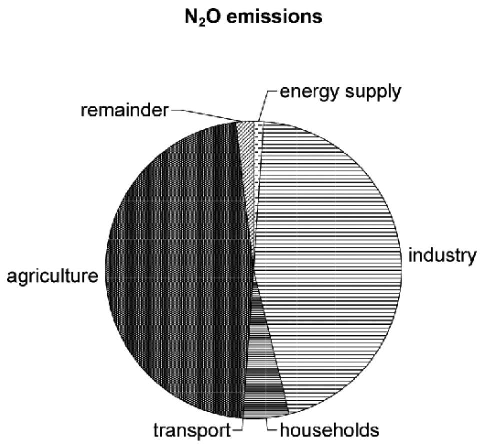


Figure 12.2 Contribution of the various production sectors to the total national N_2O emissions in the Netherlands
Source: RIVM (2001).

In terms of methane, 42% of the national CH_4 emissions originate from agriculture (figure 12.3). Enteric fermentation processes in ruminants (cows and sheep) are the largest suppliers, with again dairy farming being the largest contributor.

The above information is suggestive of several options to reduce national GHG emissions. The most extreme option is cessation of agricultural production in the Netherlands. The information in Figures 12.1, 12.2 and 12.3 indicates that this would result in a decline of 5% in CO_2 emissions, 50% in N_2O emissions and 40% in the CH_4 emissions. It is obvious that this is only a theoretical option, but in an analysis of possible trade-off's it is interesting to evaluate the consequences. It should be realized that options as 'decline production' in general or 'decline of the number livestock' are just milder forms of this option.

Another option involves greenhouse gas emission reducing improvements in the production system. Agricultural production can take place via various routes and up to now improvements were focused on the reduction of the acidification and eutrophication problems related to agriculture. The reduction of the GHG emissions from this sector has not received a lot of attention, and thus it is likely that there are opportunities that will lead to reduced emissions.

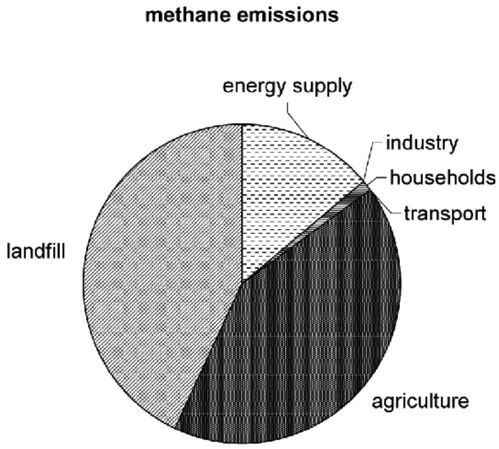


Figure 12.3 Contribution of the various production sectors to the total national CH_4 emissions in the Netherlands
Source: RIVM (2001).

Greenhouse gas emissions from the consumer side

The production side data were obtained from environmental statistics. Estimation of emissions related to consumption requires quite different methodologies. Life cycle analysis (LCA) methodologies (Rebitzer et al., 2004) are the most suitable tools. Initially LCA was developed to assess the environmental impacts of industrial processes; recently the method is also applied to agriculture (Audsley et al., 1997). It determines the environmental impacts of a product from cradle to grave, accounting for all the processes involved in manufacturing, transport and consumption of the product, this includes the extraction of the raw materials to possible waste treatments. Conducting an LCA involves a lot of information and a lot of work. To give an example: to calculate the environmental impacts associated with consumption of a litre of milk it is necessary to determine all the impacts required to get a litre of milk on the table of the consumer. This includes consideration of the impacts of farming practices; producing the fertilizers used on the farm; cooling, processing, packaging and transporting the milk from the farm via the dairy factory and the supermarket to the consumer; along with the waste treatments required to discard the packages.

In principle, when the environmental impact of all consumer goods is known the environmental impact of the total consumption can be determined by multiplying the environmental impact per unit of the product by the number of units of the product purchased.

The large amount of work involved in such an analysis makes it practical for only a limited number of products. This implies that there is no overview for the total environmental impact of the total consumption bundle. Only an energy based LCA exists with respect to the total consumption bundle. Namely, Kok et al. (2001) analyzed the energy requirements of over 350 products and services (including food, music lessons, bicycles, clothing etc.) starting with the energy required to extract the raw materials to the energy involved in the waste treatments. Figure 12.4 shows some of their results. Half of the energy attributed to households concerns heating, electricity, and transport (petrol for the car) and the other half has to do with product consumption and accounts for energy that was used elsewhere in society. In this 'consumption half' food is a major player.

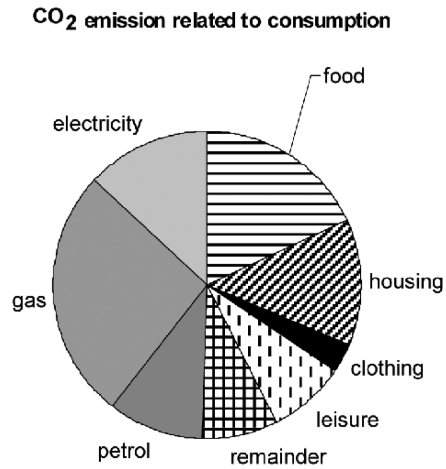


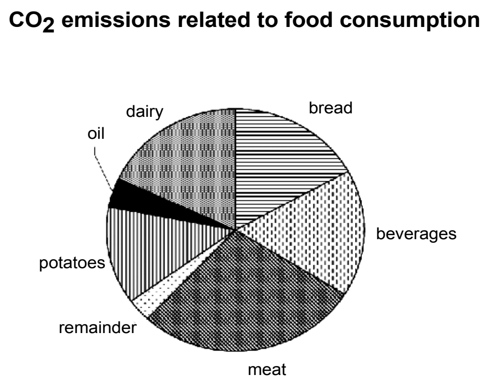
Figure 12.4 Distribution of the CO_2 emissions related to consumption over the different spending categories
Source: Vringer and Blok (2000).

This large contribution of food to total energy requirements is quite in contrast to what is found in the production perspective (where agriculture only accounted for 5% of the national energy use). This is because energy used in other sectors than agriculture is substantially used in association with consumed food. In a consumer oriented approach the energy used for transporting food is attributed to food, while in a production-oriented approach it is attributed to the transport sector. A comparable situation exists for the industrial sector. In a consumer oriented approach, the energy used in the food industry is attributed to food as is the energy used in the fertilizer industry.

With respect to food a detailed study exists in which CO_2, CH_4 and N_2O related to over 150 food items were examined (Kramer, 2000). In that study, greenhouse gas emissions along the complete production chain were analyzed and those results will be discussed in detail.

The 150 food commodities are grouped into categories. ‘Bread’ aggregates products where grains (wheat, rice, maize) are the major ingredients like breads, cakes and pastry, but also pastas. ‘Potatoes’ represents potatoes and vegetables and fruits, ‘Beverages’ aggregates beer, coffee, tea, fruit juices, but also confectioneries. The category ‘Meat’ concerns all meat and fish products, ‘Dairy’ includes milk, yogurt, butter and cheese, the ‘Oil’ category involves vegetable oils and fats to fry, ‘Remainder’ includes spices and ready to eat meals.

Figure 12.5 shows the emissions related to these different categories. One should realize that emissions related to consumption depend on both emissions per unit and the amount consumed. The emissions related to an exotic fruit can be very high, but when the volume consumed is small then the contribution to national emissions is low. This also holds the other way round: the emissions of for instance a unit of milk may be low, but since it is consumed in very large quantities the overall impact can be high.



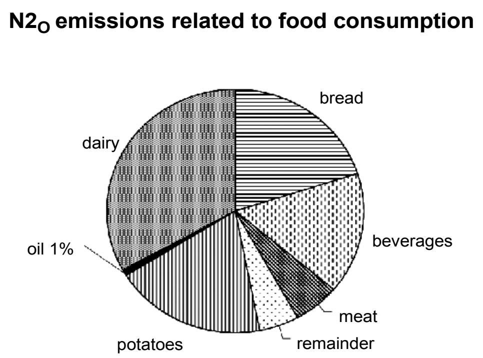
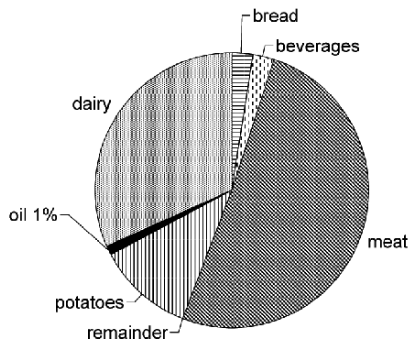


Figure 12.5 Distribution CO_2, CH_4 and N_2O emissions and CO_2-equivalents over various food product categories in the Dutch food consumption package

Source: Kramer (2000).



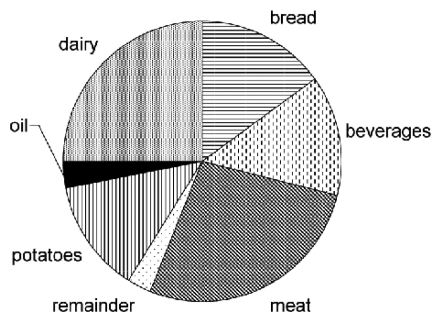


Figure 12.5 Continued

The emissions are not distributed evenly over the categories and gasses. With respect to CO_2, bread, beverages, meat and dairy provide the largest contribution (80%). With respect to CH_4, meat and dairy are responsible for 80% of the emissions. For N_2O the largest share arises from dairy, bread, beverages, and potatoes. For all greenhouse gasses, dairy consumption plays the largest role. More detailed analysis of the emissions attributed to dairy shows that the CO_2 emissions arise from chemical fertilizer production (this fertilizer is used to fertilize grasslands), production of livestock feed (a large part is from imported soybeans, which are transported over large distances) and in milking, cooling, transporting and packaging. The CH_4 emissions attributed to milk are mainly due to the CH_4 emitted by the cows in enteric fermentation. The N_2O emissions occur during the production of chemical fertilizer and as a result of de-nitrification processes in grasslands. So different parts of the production chain are responsible for the emissions.

This also accounts for the other commodities including food packaging. With respect to CO_2 20% of the emissions occur as part of primary production, and the remaining 80% arise outside the agricultural production system, either through delivery of inputs, processing and transport of food, retailing or in the households (cooling and cooking). The emissions of N_2O and CH_4 show a different picture with 80% of these emissions occurring in association with primary production.

The differences in environmental impact of the various consumption items imply that there are options to change emissions under alterations in consumption patterns. From Figure 12.5 it is apparent that for CH_4 the consumption of milk, cheese and meat is of importance. For N_2O the emissions are spread more evenly over the consumption items (all agricultural production requires chemical fertilizer), but dairy holds the largest share. Refraining from milk and meat, for instance, would result in a 75% reduction of CH_4 emissions, related to food consumption, for N_2O refraining from milk and meat results in a reduction of about 40%.

Another option to reduce the environmental impact from consumption is the purchase of products which are produced using processes with lower environmental impacts much like those discussed in the production side analysis. However, a change in production techniques from the consumer point of view may involve other changes. To give an example: the use of vegetables grown in heated greenhouses involves large amounts of energy. Improvement of the production techniques from the producer side would include the use of better-insulated greenhouses. From a consumer perspective a switch to vegetables grown in the open air is also an option. A comparable situation exists for transport: from a producer perspective reduction in energy use in transport can be obtained from more efficient trucks. From a consumer perspective less transport is also an option (increasing consumption of locally grown products).

Potential greenhouse gas reduction options

The previous analysis shows three different routes to reduce greenhouse gases emitted during the food production. The first is a national production reduction with the complete close down of the agricultural sector as its most extreme alternative. The analysis presented in this chapter shows that this leads to a 50% reduction of the national N_2O and CH_4 emissions. The second originates from the consumption side and involves changes in consumption patterns (a switch away from products creating large greenhouse gas emissions). Refraining from meat and dairy would lead to significant greenhouse gas reductions. The third route involves improvement of production techniques, this route emerges both in the consumer and production side analyses.

The routes suggested involve changes in production processes and/or in consumption patterns. These changes require other inputs and result in other emissions. The next section pays attention to the consequences of implementing the suggested changes for food security and the other environmental themes.

DETERMINING THE CONSEQUENCES OF THE REDUCTION OPTIONS

Effects and trade-offs when reducing agricultural production

Since the agricultural sector has large effects on the environment a reduction in production or even a complete close down of the production sector is expected to have large effects on the environment. Agriculture is the main cause for eutrophication, acidification and a large emitter of N_2O and CH_4, a decline of this sector will reduce these problems. So it seems that there are no local trade offs to the other environmental themes (they even benefit from it).

However, the trade-offs with respect to global environmental conditions are large. In the coming decades, agricultural production has to increase to fulfill the needs of the global population. A local decline in production is only possible when production is increased somewhere else. A local reduction of the production will lead to local reduction of the acidification and eutrophication problems, however since production has to increase somewhere else, these 'increased production regions' will encounter increases in their acidification and eutrophication problems. On a global scale this implies that the environmental effects (such as acidification) are simply moved to other regions. Global greenhouse gasses emissions will not be affected only emissions on a national level.

Focusing on local food to requirements in more detail shows an extra trade-off. When a nation decides reduce its agricultural production to reduce the environmental effects, this will imply that the displaced food has to be imported from somewhere else. Such imports require transport and transport requires energy and the use of energy results in the emissions of greenhouse gasses. To obtain an impression of the magnitude of these emissions it is calculated what happens when the Netherlands agricultural production is moved to Eastern Europe and the products are transported back.

If we assume that the production process remains the same across countries, this would imply that emissions in the agricultural part of the production chain remain the same, but arise somewhere else. The remainder of the production chain changes since the transport distances from the producer (farm) to the consumer increases. If we assume that food is transported by truck over 1,000 km, the emissions related to this transport have to be added to the present emissions.

Table 12.1 shows the results for milk and potatoes (using data from Kramer, 2000). In the present situation, when milk is produced in the Netherlands, it requires 1.5 kg CO_2 equivalent to produce and deliver 1 litre of milk to the consumers table. To produce and deliver a kg of potatoes 1.23 kg is required. Emissions involved to transport 1 kg food over 1,000 km include 0.24 kg CO_2 equivalent. So when the food for the Dutch population is imported from Eastern Europe this would imply a 15-20% increase in the greenhouse gas emissions related to food.

Here an interesting trade-off can be observed. Based on the analysis from the production perspective the complete removal of the Dutch agricultural system would mean a reduction of the national greenhouse gas emissions with about 5-10% (in CO_2 equivalents, based on Figures 12.1-12.3). From a national perspective closing down agriculture might be an option and it is seems that a lot of the other national environmental problems will be simultaneously solved. However, from a global environmental point of view another picture arises. The close down of the agricultural sector implies that all the food has to be imported. When Dutch consumers stick to the same food consumption pattern this would mean an increase in the GHG emissions attributed to the Dutch food consumption patterns by 15-20%. Thus while national GHG emissions decline, increasing production in other countries increase their emissions (since they replace lost Dutch production) and the resultant transport to meet Dutch consumer needs makes the overall GHG emission effect negative (on a global scale the greenhouse gas emissions will even increase).

Table 12.1 The greenhouse gas emissions attributed to 1 litre milk and 1 kg potatoes purchased by the Dutch consumer (produced in the Netherlands) and the emissions that come together with the transport by truck over 1,000 km

	CO_2 (kg)	CH_4 (g)	N_2O (g)	CO_2 equivalent (kg)
1 litre milk	0.8	26	0.46	1.49
1 kg potatoes	0.9	1.	1.	1.23
1,000 km transport	0.22	0.34	0.05	0.24

Note: Data obtained from Kramer (2000).

Possible adaptations in consumption patterns and associated trade-offs

The consumption of meat and dairy comes together with large emissions of greenhouse gasses (Figure 12.5). Altering diets to reduce consumption of these products would theoretically reduce GHG emissions. (Refraining from eating meat and dairy would lead to a 50% decline of the CO_2 equivalents related to food.) However, dairy and meat play important dietary roles with meat being important for protein supply and milk for its calcium. So just refraining from dairy and meat is not possible, replacements have to be found to fulfill the nutritional requirements of the human body. The design of these replacements is complicated as food also has emotional and cultural values. In the Kramer study mentioned earlier, options to reduce greenhouse gas emissions through changes in the consumption patterns are examined, taking the nutritional and social/emotional values into account.

Kramer (2000) designed 7 sets of changes in the menu (without changing the nutritional value of the menu) and calculated the reduction greenhouse gasses obtained with these changes. Table 12.2 shows a summary of the results.

Table 12.2 Possible changes in food consumption patterns and related reduction of the greenhouse gasses (in CO2 equivalent)

Set	*Description of the changes with respect to the present menu*	*Reduction (%)*
1	20% less meat, replaced by vegetables	3.3
2	As set 1, and twice a week vegetarian meal	5.4
3	As set 2, and no glasshouse vegetables, replaced by import	7.9
4	As set 3, but replaced by locally grown	8.8
5	As set 4, and 20% less rice and pasta, replaced by potatoes	8.9
6	As set 5 and 20% less milk, replaced by coffee and tea	10.5
7	As set 6 and 20% less cheese, replaced by jams	11.9

Note: Data obtained from Kramer (2000).

Set 1 involves a 20% reduction in meat consumption. Since we eat more meat than is necessary, a 20% reduction is possible without introducing a protein shortage. In set 1 only the caloric value is replaced with vegetables. In set 2 the meat is replaced by a vegetarian alternative (cheese or a vegetarian burger). Since consumer research has shown that a change to complete vegetarian lifestyle is not feasible (Nonhebel and Moll, 2001) the analysis involves a vegetarian meal twice a week. This twice a week a vegetarian meal involves a larger reduction of the meat consumption than the 20% in set 1. However the production of the vegetarian replacements also leads to emissions of greenhouse gasses, so that the net gain is smaller (2.1%).

Set 3 focuses on glasshouse vegetables. Heated glasshouses require large amounts of energy to produce tomatoes, peppers etc. In warmer climates (Spain), these vegetables can grow in open air systems, hardly requiring energy. A change from glasshouse vegetables to imported open air vegetables is therefore an option. However, in that case the vegetables have to be transported from the production area to the consumer. When this extra transportation is included the change from glasshouse to import will involve a GHG emission reduction of 2.5%. Replacing glasshouse vegetables with locally grown open air vegetables leads to a far larger decline in emissions: 3.4%. This option seems promising (just replace the vegetables in the meal), however one should realize that such a change involves the use of other vegetables since not all vegetables can be grown in the open air. A change to locally grown ‘open air’ vegetables also implies large changes in seasonal menus. In the summer season not many changes are expected, but in the winter season the consumption of locally grown vegetables involves a menu with only cabbages, unions and carrots.

The change from rice and pasta to potatoes (set 4) had hardly any effect on emissions. With respect to milk and cheese some gain is expected. In the sets studied (6 and 7) the nutritional value is not replaced (the present consumption allows a reduction of 20%; see the discussion in set 1 for meat). Milk is replaced by coffee or tea and cheese is replaced by jam.

Table 12.2 shows that a substantial change has to be made to obtain a 10 percent emission reduction. To obtain this reduction meat consumption is nearly halved and in winter season vegetables in the menu include only onions, carrots and cabbage. This is in contrast with the analysis at the start of this paragraph that indicated that refraining from eating meat and drinking milk would result in a 50% decline of the emissions. The difference can be explained by the fact that just refraining is not possible, replacements are needed to fulfill the needs for food and these replacements also require emissions.

Cleaner production techniques and their trade-offs

The option of reducing emissions through applying cleaner production techniques emerged both from the production and consumer points of view. We will first analyze the improvement options from the production side analysis and focus on the options to reduce the CH_4 and N_2O emissions by changing production techniques in the agricultural sector, followed by an analysis from the consumer perspective.

Options to reduce CH_4 emissions

Agriculture is an important source for CH_4 with dairy farming the largest contributor. CH_4 emissions associated with dairy farming come from the cow itself as a result of the enteric fermentation and from sub floor manure storage. Veen (2001) estimates that 70-80 % emissions come from the cow and the remainder from the manure. The emissions per cow are in the order of 100 kg per year and are influenced by among others the digestibility of the feed, but are independent of the milk production. This implies that increase of the production per cow leads to a decline in the emissions per liter. The milk production per cow in the Netherlands is 7,400 liter milk per year, while in other European countries this value is much lower (4,387 in Ireland, 4,451 in Poland (FAO, 2003)). This shows that one liter of milk from a Dutch cow goes together with the emissions of 14 grams of methane, while the milk from an Irish cow goes together with the emissions of 23 grams of methane. A further increase of the production per cow provides a reduction option.

Another reduction route involves feed composition. More digestible feed and addition of extra fats to the feed are potential options to reduce the CH_4 emissions due to enteric fermentation (Veen, 2001). However, for a proper functioning digestive system about 20% of the feed should consist of roughage (Veen, 2001, CVB, 2003). In the intensive dairy farming systems in the Netherlands, the percentage of roughage is very near to this percentage, so that not much room for improvement can be found here. The addition of extra fats to the feed also shows some complications. Since the BSE-crisis, animal fats are no longer allowed in feed and the addition of vegetable fats to the feed has been found to have negative effects on milk quality (protein and fat concentrations). This implies that not many improvements can be expected with respect to changes in feed composition in the short term.

There may be options to reduce manure related emissions, with research on possible options now being carried out (Novem, 2004). However, presently not enough information exists to estimate the magnitude of the reductions in this category.

A change in the opposite direction (increase of the CH_4 emissions), however, is also possible. As mentioned in the introduction of this chapter a shift to less intensive production systems (organic) could be employed. This change to less intensive production systems is a method to reduce the large effects of production systems on the other environmental themes.

De Boer (2003) did a comparative analysis of the environmental impacts associated with conventional versus organic milk production systems. She showed that the impacts on acidification and eutrophication per hectare were lower in the organic systems. However, her results showed that CH_4 emissions increased. Huis in 't Veld and Monteny (2003) show similar results. The increase was caused by lower production per cow, the higher percentage of roughage in the feed (organic agricultural practices require 80% roughage in the feed) and the other type of stable (bedding) practiced in organic farming. Huis in 't Veld and Monteny (2003) also showed that in the organic system the CH_4 emissions per litre milk more than doubled (from 20 g per litre to 50 g per litre milk), however this measurement involved only one farm, rendering such values therefore only an indication.

Less extreme changes in intensive dairy farming than a switch to organic farming also have negative effects on CH_4 emissions. To reduce nitrate emissions, farmers tend to fertilize less, which results in a slower start of the crop, which makes farmers harvest later to obtain the same yield. But later harvesting results in a lower digestibility of the feed (Veen, 2001). Here an important trade-off between different environmental themes becomes evident, namely methods to reduce eutrophication tend to increase the emissions of methane.

Options to reduce N_2O emissions

N_2O emissions result from de-nitrification processes in soils and in slurry on the farm. Most N_2O emissions occur from soils after application of manure/fertilizer. The highest emissions are found when manure is applied with sod injection techniques (Velthof et al., 2003). The simplest way to reduce N_2O emissions is to apply fertilizer to the soil surface, instead of injecting it into in the soil. However, these sod-injections techniques reduce NH_3 emissions by about 30% relative to soil surface application. Here a trade-off between acidification and climate change is observed.

Presently only a small part of the nitrogen applied to the soil is actually taken up by the crop (at a maximum 70% but frequently values in order of 20% of the applied nitrogen are found - Meisinger and Randall, 1991). The nitrogen that is not taken up by the crop, nor is stored in the soil is lost to the surroundings, causing eutrophication as nitrate, acidification as NH_3 or climate change as N_2O. Better nitrogen management practices that increases the fraction of the nitrogen that is taken up by the crop seems the best route to go since all environmental themes benefit.

Cleaner production from the consumers perspective

From the consumer perspective cleaner production involves changes in the complete production chain instead of developments only in agriculture as analyzed in the previous paragraph. The Kramer study mentioned earlier also provides information on this. He analyzed options to reduce emissions within the complete production chain including: agriculture, industry, packaging, transport, trade, consumption and waste management. His analysis is based on the agreements between the various sectors and government with respect to energy use efficiency improvements. Table 12.3 shows some of the outcomes.

Table 12.3 Greenhouse gas reduction percentage along the food production chain (%)

Sector	*Reduction*
Agriculture	6.0
Industry	8.4
Retail	3.0
Transport	0.6
Kitchen appliances	5.5
Sustainable energy	3.0

Source: Kramer (2000).

The changes in agriculture involve increasing production per cattle (reduction of the CH_4 emissions, more efficient use of fertilizers (reduction of the N_2O and CO_2) and large energy savings in horticulture. In industry they involve a general increase in energy use efficiency with 30-35% gains by the year 2010 relative to 1990. In the retail sector this general energy efficiency improvement leads to an energy reduction of 3%. The improvements in transport are the results of a combination of more energy efficient trucks, better driving practices, etc these measures lead to a reduction of 7% of the emissions related to transport. Transport improvements play a minor role in the overall reduction amounting to 0.6%.

The use of energy efficient kitchen appliances (refrigerators etc.) in households is estimated to result in a 5.5% reduction. A national shift to sustainable energy is expected. Assuming that by 2010 that 5% of the total Dutch energy consumption originates from renewables, this would result in an extra 3% reduction in the greenhouse gas emissions related to food. The simultaneous implementation of all these options results in a 26% reduction of the greenhouse gas emissions associated with food.

It is striking that reduction in the non-agricultural parts of the chain has the largest impact on the emissions related to food. The effects of changes in household consumption are of the same magnitude as the changes in agricultural production. This consumer side analysis provides new insights in options to reduce emissions. It might be far easier to exchange all refrigerators in the households with more efficient units than to introduce large changes in the agricultural production systems that also have negative trade-offs to the other environmental themes.

CONCLUSIONS

Several options exist to reduce greenhouse gas emissions related to the production of food. At first glance their impact on the total emissions seems large (over 50% reduction), however a more detailed analysis shows that for most trade-off's to other parts of the system are very large. When the effects in other parts of the system are also taken into account, the overall reduction potential turns out to be small.

From the production perspective discontinuing agricultural production would imply an important decline in national greenhouse gas emissions, but it was shown that as a consequence of this decision, food would be grown elsewhere and then transported over a longer distance, which in turn implies an overall increase of the emissions related to food.

From the perspective of the consumer it was shown that refraining from eating meat and dairy would lead to an important decline in emissions, but since meat and dairy fulfill important nutritional and emotional functions in the food package these goods can only be replaced to a certain extent. It was estimated that at most 10% reduction of the emission could be expected through changes in the food package.

The analysis in this chapter also identifies the existence of options in between the agricultural production sector and the consumer: the production chain in between, which includes the food industry, retail and a consumer with respect to cooking practices. Analysis shows that this 'in between' sector shows the largest potential to decrease the greenhouse gas emissions related to food production. Finally it was shown that presently recognizable developments in the agricultural system like a shift to organic agriculture, and the implementation of techniques to decrease ammonia emissions tend to increase emissions of methane and nitrous oxide.

These findings are developed within the context of the Dutch production system. Since this is an a-typical system the findings here are not entirely applicable to the global situation. The food consumption patterns studied are relatively luxurious. Reduction of the meat consumption as analyzed in this chapter is not an option on a global scale since largest share of the world population is hardly eating meat. Globally a shift in the other direction is likely to be observed, namely an increase of the meat consumption.

Also the shift to organic or less intensive production systems as observed in the Netherlands agricultural sector is a-typical for the global situation. As mentioned earlier, the Dutch production system is one of the most intensive production systems in the world. The largest share of global food production originates from extensive production systems. On a global scale food production is likely to intensify (generating higher yields per production unit). This intensification is of importance with respect to the methane emissions related to meat and dairy production. Emissions of methane are related to the number of the livestock and more or less independent of the production of an individual animal. Increasing the milk production per cow, as is expected to happen, will reduce methane emissions per litre.

A third important difference is the fact the rice is not cultivated in the Netherlands. On a global scale rice is an important crop and its cultivation goes together with large emissions of methane.

A fourth difference is the existence of a large food industry which uses a lot of energy. In less industrialized countries this industry hardly exists. Households buy basic agricultural products (grains, milk) and convert them into food items themselves (Home baking etc.). The potential for energy reduction as is found for the Dutch system does not exist outside the developed world. In practice, it can even be expected that with increased development within the developing world such food industries will emerge, leading to increased energy use related to food.

The fact that the Netherlands system is a-typical, however, does not imply that relations found in this chapter are of no use. As mentioned in the introduction, global food production has to increase to fulfill the demands of the growing population and the consumption shifts induced by income growth. The largest share of this increase has to be met through production intensification. The lessons revealed in the Netherlands study with respect to the environmental consequences of agricultural intensification can provide tools to prevent these errors from being made on a global scale.

In the Netherlands, only several decades after the introduction of chemical fertilizers it became clear that the emissions to the environment associated with the use of chemical fertilizers caused acidification and eutrophication. In turn, measures were taken to reduce the effects. Only recently the N_2O emissions associated with chemical fertilizer use were recognized portending future measures.

The global agricultural intensification will go together with increased use of chemical fertilizers. To prevent that the Dutch mistakes from being made on a global scale attention to improved fertilizer management is essential.

With respect to CH_4 emissions increased per animal milk production reduces the emissions per litre. The values used in this chapter indicate that the difference between extensive and intensive production may be 50%. This would imply that intensification may reduce the emissions associated with the production of milk.

In the Netherlands the shift to more luxurious diets came together with the emergence of a large food industry. This industry uses a lot of energy, and plays an important role with respect to the CO_2 equivalent emissions attributed to food. A global shift to more luxurious diets may not only imply an increased agricultural production but also a large increase in energy used in the food supply chains. Up to now increased energy requirements of the more luxurious diets gained limited attention.

The above analysis shows that a lot of effort is needed to prevent increases in food production and consumption from having adverse effects on the global environment. However, it also shows that agricultural intensification can result in a large increase of the food production in a relative short time span. The intensification in the Netherlands led to a doubling in production in less than 50 years. This is an indication that the required 50% increase of the global food production in the coming decades is not impossible.

REFERENCES

Audsley, E., S. Alber, R. Clift, S. Cowell, P. Crettaz, G. Gaillard, J. Hausheer, O. Jolliet, R. Kleijn, B. Mortensen, D. Pearce, E. Roger, H. Teulon, B. Weidema and H. van Zeijts (1997) *Harmonisation of Environmental Life Cycle Assessment for Agriculture*. Final Report, Concerted Action AIR3-CT94-2028, European Commission DG VI, Brussels, Belgium.

Boer, I.J.M. de (2003) Environmental impact assessment of conventional and organic milk production. *Livestock Production Science*, Vol. 80, pp. 69-77.

Bruinsma, J. (2003) *World Agriculture Towards 2015/2030; An FAO perspective*. Earthscan, London.

CVB (2003) *Tabellen boek veevoeding 2003*. Lelystad, Centraal Veevoeder Bureau. FAO (2003) http://apps.fao.org/default.htm.

FAO (2003) http://apps.fao.org/default.htm.

Huis in 't Veld, J.W.H. and G.J. Monteny (2003) *Methaanemissies uit natuurlijk geventileerde melkveestallen*. IMAG, Wageningen.

Kok, R., R.M.J. Benders and H.C. Moll (2001) *Energie-intensiteiten van de Nederlandse consumptieve bestedingen anno 1996*, IVEM-onderzoeksrapport no.105, Groningen.

Kramer, K.J. (2000) *Food Matters*. PhD thesis University of Groningen.

LEI (2003) *Land- en tuinbouwcijfers 2003*, Landbouw Economisch Instituut, Den Haag.

LNV (2004) http://www.minlnv.nl/thema/plant/biolog/

Meisinger, J.J. and G.W. Randall (1991) Estimating nitrogen budgets for soil–crop systems. In: Follett, R.F., D.R. Keeney and R.M. Cruse (Eds.), *Managing Nitrogen for Groundwater Quality and Farm Profitability*. Soil Sci. Soc. Am, Madison, WI, pp. 85-124.

Nonhebel, S. and H.C. Moll (2001) *Evaluation of options for reduction of Greenhouse gas emissions by changes in Household consumption patterns*. IVEM OR 106, Rijksuniversiteit Groningen, 136 pp.

Nonhebel, S. (2004) On resource use in food production systems: the value of livestock as 'rest-stream upgrading system'. *Ecological Economics*, Vol. 48, pp. 221-230.

NOVEM (2004) http://www.robklimaat.nl/.

Pennington, D.W., J. Potting, G. Finnveden, E. Lindeijer, O. Jolliet, T. Rydberg and G. Rebitzer (2004) Life cycle assessment Part 2: Current impact assessment. Practice. *Environment International*, Vol. 30 (5), pp. 721-739.

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.-P., Suh, S., Weidema, B.P. and D.W. Pennington, (2004), "Life cycle assessment, Part 1: Framework, goal and scope definition, inventory analysis, and applications". *Environment International*, Volume 30, Issue 5, July 2004, Pages 701-720.

RIVM (2001) *Milieucompendium 2001*. Kluwer, Alphen aan de Rijn.

Veen, W.A.G. (2001) *Veevoedermaatregelen ter vermindering van methaanproductie door herkauwers*. De Schothorst. Lelystad.

Velthof, G.L., P.J. Kuikman and O. Oenema (2003) Nitrous oxide emission from animal manures applied to soil under controlled conditions. *Biology and Fertility of Soils*, Vol. 37, pp. 221-230.

Vringer, K. and K. Blok (2000) Long term trends in directs and indirect household energy intensities: a factor in dematerialisation? *Energy Policy*, Vol. 28 (10), pp. 713-727.

U.S. Agriculture and Forestry Greenhouse Gas Emission Mitigation over Time

13

Heng-Chi Lee, Bruce A. McCarl, Dhazn Gillig and
Brian C. Murray

INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) asserts the Earth's temperature rose by approximately 0.6°C (1°F) during the 20th century (Houghton et al., 2001) and projects that temperature will continue to rise projecting an increase of 1.4 to 5.8°C by 2100 (McCarthy et al., 2001). The IPCC also asserts that anthropogenic greenhouse gas emissions have been the dominant causal factor (Houghton et al., 2001). In response to these and other findings society is actively considering options to reduce greenhouse gas emissions. In 1992, 165 nations negotiated and signed the United Nations Framework Convention on Climate Change (UNFCCC), which sets a long-term goal 'to stabilize greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous human interference with the climate'. Subsequently, a number of programs or policy directions have been formed that are directed toward achieving emissions reductions including the Kyoto Protocol, and the U.S. Presidential level Clear Skies and Global Climate Change Initiatives (Bush, 2002).

Emission reductions can be expensive. In the United States, the majority of emissions come from fossil fuel energy related sources use with about 40% of total GHG emissions coming from each of electricity generation and petroleum usage. A large emissions reduction would require actions such as:

- a large reduction in energy production and use, which could be economically disruptive;
- development and use of new technologies that reduce the net GHG emissions arising in fossil fuel usage; or
- fuel switching to less GHG emissions intensive energy sources.

Such actions are widely argued to be expensive and time consuming. These arguments were used in support of the U.S. rejection of the terms of the Kyoto Protocol. Nevertheless, as manifest in the Kyoto Protocol and the President's

F. Brouwer and B.A. McCarl (eds.), Agriculture and Climate Beyond 2015, 231-247.

Clear Skies initiative (Bush, 2002), the U.S. and other countries have announced intentions to limit greenhouse gas emissions.

Achievement of emission reductions through technological development or fuel switching takes time. Interim strategies may need to be developed to allow emission reductions while such developments proceed. Agricultural and forestry activities offer an opportunity to buy such time (McCarl and Schneider, 1999). Known management and land use manipulations may be employed to reduce emissions, offset fossil fuel emissions, and enhance carbon sequestration. This chapter reports on the results from a study that examined the dynamic potential for greenhouse gas emission reduction development in the agricultural and forestry sectors.

In terms of the overall theme of this book this chapter makes several contributions. Namely it shows:

- The way that land use change and management might contribute to a societal wide effort to mitigate climate change in the near and longer terms.
- The way land use based modelling may be used to address such questions.
- A perspective of how mitigation may be pursued in a land rich country like the United States.

AGRICULTURAL AND FORESTRY MITIGATION POSSIBILITIES

The agricultural and forestry sectors present a number of possibilities that can be employed to mitigate net GHGE additions to the atmosphere. As summarized by McCarl and Schneider (1999, 2000), these include activities directed toward reducing emissions, enhancing sinks, and offsetting emissions.

In terms of reducing emissions the agricultural and forestry sectors particularly agriculture are important emitters of:

- methane largely through rice cultivation, ruminant livestock enteric fermentation, and manure management;
- nitrous oxide largely through nitrogen fertilizer use induced emissions, legumes, and manure; and
- carbon dioxide mainly through land use change from grass lands or forests to cultivated uses. In addition, smaller levels of emissions also arise through direct fossil fuel use. Indirect emissions also arise in conjunction with the production and transport of fertilizers and other inputs as well as in product transport and processing.

In terms of enhancing sinks, ecosystems involved with the agricultural and forestry sectoral production are large reservoirs of carbon and exhibit large annual exchanges of carbon with the atmosphere (see Lal et al., 1998 for discussion on stock magnitude and the carbon cycle). Sink enhancement can be achieved by strategies that increase the carbon input or slow the rate of decomposition. Some such strategies involve:

- Altering forest management by increasing forestry rotation ages or using added inputs like fertilization.
- Changing agricultural land management by adopting less intensive tillage methods.
- Altering crop mix using more perennials that involve lessened soil disturbance.
- Altering land use from cultivated agriculture to grasslands or forests.

In terms of offsetting emissions, agricultural and forestry products may be used in industrial processes offsetting the use of more emissions intensive inputs and/or providing an opportunity to recycle many emissions. The principal opportunities in this category involve the use of agricultural and forestry products, to replace fossil fuel use in electricity generation and as inputs to processes transforming them into liquid fuels replacing fossil fuels use in transportation and other usages.

ANALYSIS REQUIREMENTS

Several features of the above mentioned agricultural and forestry activities imply particular approaches that must be used in a total analysis of their potential for participating in a greenhouse gas emission mitigation program. Notable features involve dynamics, multiple GHG implications, mitigation alternative interrelatedness, market/welfare implications, co-benefits, and differential offset rates.

Dynamics

Agricultural and forestry activities develop over time. Sinks accumulate as long as the rate of carbon addition to an ecosystem exceeds the rate of decomposition. However, as carbon accumulates the decomposition rate rises. Eventually under a sequestration increasing altered management or land use alternative, all systems will eventually come to a new equilibrium with accumulation stopping. Furthermore, crops are annuals but trees can last for many years with 50+ year rotations common in some U.S. regions. This implies that the role of agricultural and forestry activities in a total greenhouse gas emission mitigation environment requires attention toward dynamic rates of participation.

Multiple greenhouse gas implications

The agricultural and forestry related strategies towards reducing greenhouse gas emissions jointly have impact on the net emissions of carbon dioxide, nitrous oxide, and methane. These three gasses have significantly different causal climate change forcing effects. Equivalency rates have been established through the global warming potential (GWP) concept as discussed in the IPCC assessment reports (IPCC, 1991, Houghton et al., 2001). To develop gas equivalency and express trade-offs we used the IPCC's 100-year global warming potentials as suggested in Reilly et al. (1999).

Mitigation alternative interrelatedness

Agricultural and forestry mitigation alternatives are highly interrelated because of a number of interdependencies that characterize these sectors. Consider three of the principal ones:

- Land competition. Agricultural and forestry activities compete for a common land base and expansion of land used for forests or biofuels generally implies reduction in the land used for crops or pasture and in the agricultural production from those lands.
- Intermediate products. Many agricultural and forestry activities requires use of the output of other activities as intermediate inputs. This is particularly true in the case of livestock consumption of crop products.
- Product substitution. A number of agricultural and forestry products can be used in place of one another where for example beverages can be sweetened with sugar or corn sweeteners.

The important consideration here is that modeling must be complex and involve competition for land, intermediate products, and product substitution among other factors across the agricultural and forestry sectors (Table 13.1).

Market/welfare implications

The U.S. encompasses a large market for most commodities produced by the agricultural and forestry sectors. It is also an active, sometimes dominant, player in world markets for a number of agricultural and forestry commodities. As such the analysis needs to consider price and quantity implications for the commodities produced as well as welfare implications for domestic and foreign producing and consuming parties.

Co-benefits

In addition to generating emission offsets, greenhouse gas emission mitigation alternatives in agriculture and forestry also influence the environment by for example reducing erosion, improving land quality, altering wildlife habitat, and reducing chemical runoff changing water quality (McCarl and Schneider, 1999; Plantinga and Wu, 2003; Elbakidze and McCarl, 2004). Agriculture and forestry mitigation strategy adoption has, in prior studies, been shown to have substantial implications for producer income possibly offsetting the need for extensive farm income support as occurs under U.S. farm policy (McCarl and Schneider, 2001) along with increasing forest producer income (Shugart et al., 2003). As such attention to the environmental and income distribution implications of strategy use is important.

Table 13.1 Mitigation strategies in FASOMGHG

		Greenhouse gas affected		
Mitigation strategy	Strategy nature	CO_2	CH_4	N_2O
Afforestation	Sequestration	X		
Rotation length	Sequestration	X		
Timberland management	Sequestration	X		
Deforestation (avoided)	Sequestration	X		
Biofuel production	Offset	X	X	X
Crop mix alteration	Emission, sequestration	X		X
Rice acreage reduction	Emission		X	
Crop fertilizer rate reduction	Emission	X		X
Other crop input alteration	Emission	X		
Crop tillage alteration	Sequestration	X		
Grassland conversion	Sequestration	X		
Irrigated/dry land conversion	Emission	X		X
Livestock management	Emission		X	
Livestock herd size alteration	Emission		X	X
Livestock system change	Emission		X	X
Liquid manure management	Emission		X	X

Differential offset rates

Greenhouse gas emission strategies related to agriculture and forestry exhibit substantially different offset rates. Per unit area offset rates (e.g. tons/ha) vary by more than a factor of 10 while also having implications for complementary production. For example, tillage changes get somewhere in the neighbourhood of 5/8 metric tons of carbon equivalent offsets per ha while still producing crops. Employment of afforestation or biofuels can raise the offset rate to above 2.5 tons but loses the complementary crop production. Economic considerations would lead one to favour activities that preserve complementary traditional crop production if offset prices are low, but would cause a switch to the higher per unit offset producing alternatives losing crop production when offset prices become high.

In addition, greenhouse gas emission offset rates vary over time with for example West and Post (2002) reviewing evidence that tillage change induced agricultural soil sequestration ceases accumulation after the first 20 years, while data (Birdsey, 1992; Birdsey and Heath, 1995) show forest sequestration exhibits diminishing accumulation rates in the longer term. This implies a need to look at the optimum portfolio composition of offset strategies as influenced by offset price and time.

MODELLING

In order to investigate the time dependent role of agricultural and forest carbon sequestration as influenced by offset prices we need an analytical framework that can depict the time path of offsets from agricultural and forestry possibilities. To do this we will use the greenhouse gas version of the Forest and Agricultural Sector Optimization Model (FASOM) (Adams et al., 1996) as developed in Lee (2002) and hereafter called FASOMGHG. This model has the forest carbon accounting of the original FASOM model of Adams et al. (1996) unified with a detailed representation of the possible mitigation strategies in the agricultural sector adapted from Schneider (2000) and McCarl and Schneider (2001).

FASOMGHG (Lee, 2002) is a 100 year intertemporal, price-endogenous, mathematical programming model depicting land transfers between the agricultural and forest sectors in the United States. The model solution portrays a multi-period equilibrium on a decadal basis that arises from a modelling structure that maximizes the present value of aggregated producers' and consumers' surpluses across both sectors. The results from FASOMGHG yield a dynamic simulation of prices, production, management, and consumption within these two sectors under the scenario depicted in the model data.

Several aspects of FASOMGHG merit discussion including geographic scope, product scope, land transfers, agricultural management, forest management, terminal conditions, and soil and ecosystem saturation.

- Geographic scope FASOMGHG divides the U.S. into 11 regions where 9 of which produce forest products and 10 of which produce agricultural products.
- Product scope. FASOMGHG simulates the production of 50 primary crop and livestock commodities and 56 secondary or processed commodities along with 10 forestry commodities. Details on the commodity coverage can be accessed at the web site: agecon.tamu.edu/faculty/mccarl.
- Land transfers. Four types of land transfers are depicted. These are land transferred from (1) forestry to agriculture in period t into either the pasture or cropland categories; (2) agriculture to forestry in period t from either the pasture or cropland categories; (3) cropland transferred to pasture; and (4) pasture land transferred to cropland. Many forested tracts are not suitable for agriculture due to topography, climate, soil quality, or other factors so the model accounts for land that is not mobile between uses. Costs for converting forestland reflect differences in site preparation costs because of stump removal amounts, land grading and other factors.
- Agricultural management. The agricultural component depicts typical annual crop, livestock, processing, consumption and trade activity during a decade. Agricultural yields and factor usage vary by decade with historical trends in yield growth and input/yield interrelationships extrapolated (Chang et al.,

1992). Agricultural output is produced using land, labour, grazing and irrigation water accounted for at the regional level among other inputs. Once commodities enter the market they can go to livestock use, feed mixing, processing, domestic consumption or export. Imports are also represented. The model structure incorporates the agricultural sector model described by Chang et al. (1992), with Schneider's (2000) added greenhouse gas features. Demand and supply components are updated between decades by means of projected growth rates in yield, input usage, domestic demand, exports and imports. The model uses constant elasticity functions to represent domestic and export demand as well as factor and import supplies. In the first two decades, the production solution is required to be within a convex combination of historical crop mixes, following McCarl (1982) and Onal and McCarl (1991), but is free thereafter. Possibilities for greenhouse gas management are included by incorporating

  - 3 tillage possibilities for cropping;
  - 3 alternative fertilization levels for each crop;
  - livestock management possibilities for feeding based on Johnson et al. (2003a; b); and
  - manure management possibilities using digesters and methane recovery.

- Forest management. The basic form of the forest sector model is a 'model II' even-aged harvest scheduling structure (Johnson and Scheurman, 1977) allowing multiple harvest age possibilities. Multiple-decade forest production processes are represented by periodic regional timber yields from the Aggregate Timber Land Analysis System (ATLAS) (Mills and Kincaid, 1992). Logs are differentiated into three product classes (sawlogs, pulpwood, and fuelwood) for both hardwoods and softwoods, yielding six classes in total. Substitution is permitted between sawlogs and pulpwood, pulpwood and fuelwood, and between residues generated in sawlog processing and pulpwood. Upon harvest forestlands may be regenerated into forestry with possible improvements in management, or may migrate into agriculture. Forested land is differentiated by region, ownership class, age cohort of trees, forest cover type, site productivity class, timber management regime, and suitability of forestland for agriculture use.
- Terminal conditions. Given the model is defined for a finite period there will be immature trees at the end. Terminal conditions are imposed on the model that value ending immature trees and land remaining in agriculture. FASOMGHG assumes that forest management is, from the last period onward, a continuous or constant flow process with a forest inventory that is 'fully regulated' on rotations equivalent to those observed in the last decades of the projection (see Adams et al., 1996). The terminal value of land remaining in agriculture is formed by assuming that the last period persists forever.
- Soil and ecosystem saturation. Terrestrial carbon sinks accumulate, but are limited by ecosystem capability in interaction with the management system. In particular, carbon only accumulates until a new equilibrium is reached under the management system. FASOMGHG assumes that when cropland

tillage practice or land use (to pasture or grasslands) is altered, the carbon gain/loss stops after the first 30 years based on the previous tillage studies (West and Post, 2002) and opinions of soil scientists (Parton, 2001). On the forest side carbon accounting is based on the FORCARB model as developed by Birdsey and associates (1992, 1995) and the HARVCARB model of Rowe (1992). Forest carbon is accounted in four basic pools, soil, ecosystem, standing trees and products after harvest. Under afforestation, soil carbon initially rises rapidly, but levels off particularly after the first rotation. The ecosystem component (carbon in small vegetation, dropped leaves, woody dentritus, etc.) follows a similar pattern. The standing tree part is based in forest growth and yield tables from the Forest Service ATLAS model (Mills and Kincaid, 1992). The product accounting reflects products decaying over time. Thus saturation occurs as stands age while harvested pools decline as products age.

RESULTS AND IMPLICATIONS

The basic exercise in this chapter is to examine the mitigation strategies and associated land use/land management changes that arise in agriculture and forestry under different CO_2-equivalent prices. The CO_2-equivalent price is applied to CO_2, CH_4, and N_2O emissions/offsets after multiplying each quantity times the relevant GWP from the IPCC (Houghton et al., 1996) report. FASOMGHG is used to simulate the strategies chosen at CO_2-equivalent price incentives that are constant over time ranging from \$0 to \$50 per metric ton of carbon dioxide equivalent. Offset estimates are computed on a total U.S. basis relative to responses under a business as usual-zero CO_2-equivalent price-baseline scenario and are thus only those additionally stimulated by CO_2-equivalent prices.

Static mitigation quantity

The strategies employed vary over time. One way of looking at the strategies employed in a static setting is to compute the annuity equivalent amount. This is done by discounting the greenhouse gas emission increments by major category back to the present following the suggestion in Richards (1997). We do this using a 4% discount rate. The consequent results are in Table 13.2 and Figure 13.1. A number of trends appear in these results.

- At low greenhouse gas emission offset prices the first options chosen are agricultural soil carbon and existing forest stand management largely in the form of longer rotations.
- At higher greenhouse gas emission offset prices biofuel for power plants and afforestation dominates with agricultural soil share reduced from a peak at lower prices.
- Non-CO_2 related strategies largely in the form of livestock and fertilization (crop management and fossil fuel related emissions offsets are relatively small but rise as the greenhouse gas emission offset price rises.
- Liquid fuel replacement biofuels do not enter the solution.

Table 13.2 Emission reductions in million metric tons of CO_2-equivalent

	Price in $ per ton CO_2-equivalent				
	5	15	30	50	80
Afforestation	2	110	450	845	1,264
Soil sequestration	120	153	147	130	105
Biomass offsets	17	844	952	957	960
CH_4 and N_2O	13	34	65	107	159
Forest management	106	216	313	385	442
Crop management fossil fuel	29	56	74	91	106
All strategies	288	1,413	2,001	2,514	3,037

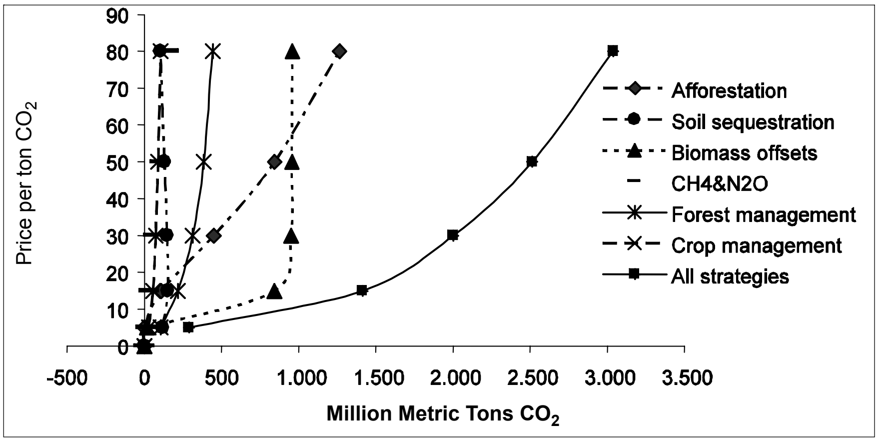


Figure 13.1 Annualized mitigation potentials of chosen mitigation tools at different greenhouse gas offset prices

These results basically show that at lower prices mitigation involves use of management alternatives that are highly complementary to current land uses. In such a case, the greenhouse gas emissio offset is largely complementary to the current land use and products produced thereon. However, the per land area production rates are lower being a quarter or smaller of the biofuel and afforestation activities. At higher prices, the larger per unit area offset production possibilities are adopted, but this displaces traditional production i.e. agricultural land that is afforested does not continue to grow crops. Thus, the higher price is needed to offset the value of the crops.

In addition, the biofuel result shows the dominance of power plant usage instead of liquid fuel production largely because the power plant replacement uses little energy in production relative to the offset quantity but the liquid fuel biofuel replacement uses substantially more.

Dynamic greenhouse gas emission mitigation

One can look at the results as they mature over time. Figures 13.2-13.4 present accumulated greenhouse gas emission mitigation credits from forest sequestration, agricultural soil sequestration, powerplant feedstock biofuel offsets, and non-CO_2 strategies as they vary over time for selected greenhouse gas emission offset prices.

At low prices and in the near term, the carbon stocks on agricultural soil and in existing forests grow rapidly initially and are the dominant strategies. However, the offset quantities in these categories later diminish and become stable with meaningful accumulation ceasing after about 30 years. Carbon stocks from the afforestation component of the forest sector grow for about 40 years at low prices. Non-CO_2 strategies continually grow throughout the whole time period. Biofuel is not a factor in the near term as it is too expensive to be part of a low greenhouse gas emission offset price mitigation plan.

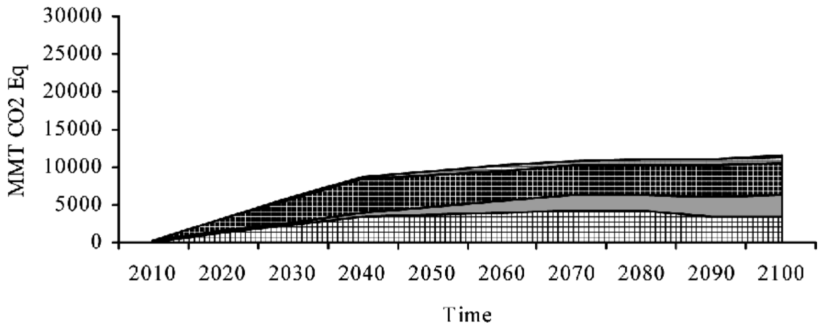


Figure 13.2 Cumulative mitigation contributions from major strategies at a \$5 CO_2 equivalent price

When the prices are higher, the forest carbon stock increases first and then diminishes; the agricultural soil carbon stock is much less important in the big picture especially in the later decades; and non-CO_2 mitigation credit grows over time but is not a very large player. Powerplant feedstock biofuel potential grows dramatically (ethanol is not used) over time and becomes the dominant strategy in the later decades. Across these and other runs several patterns emerge.

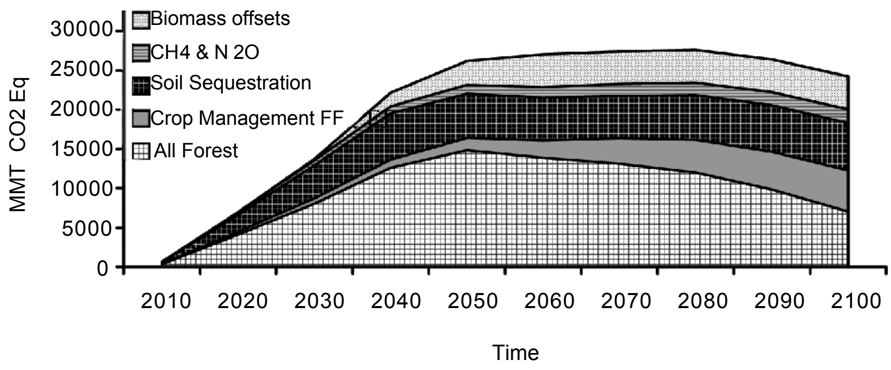


Figure 13.3 Cumulative mitigation contributions from major strategies at a $15 CO_2 equivalent price

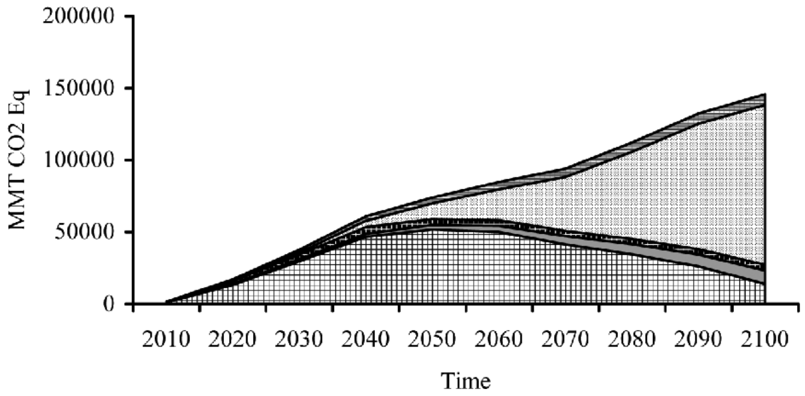


Figure 13.4 Cumulative mitigation contributions from major strategies at a $50 CO_2 equivalent price

- Carbon sequestration, including agricultural soil and forest carbon sequestration, and powerplant feedstock biofuel offsets are the high quantity mitigation strategies across all the results. The importance of these strategies varies by price and time.
- At low prices and in early periods agricultural soil carbon and existing forest management are the dominant strategies. When prices get higher the agricultural soil component is replaced by afforestation and powerplant feedstock biofuels as they have higher per acre carbon production rates.
- The sequestration activities tend to rise and then stabilize largely due to ecosystem holding capacity. Agricultural soil accumulation stops faster than

that for trees but in the longer run tree harvest begins and afforestation accumulation levels out.

- The higher the price the more carbon stored in the forests in the early decades, but the intensified forest sequestration comes with a price in that CO_2 emissions from forests increase later. When the forest carbon sequestration program starts, reforestation or afforestation is encouraged and the harvest of existing timber is slowed down. However, the future harvest increases because of the increased mature forests by the increasing inventory of reforestation, afforestation, and previous postponed harvests.

Regional effects

Because the U.S. landscape is quite heterogeneous, the adoption and effectiveness of greenhouse gas emission mitigating activities will not be uniform across regions within the country. The regional totals distribution for the price scenarios ($5, $15, and $30/ton CO_2) are illustrated in Figure 13.5. This figure summarizes the annualized GHGE mitigation quantities by major region, activity, and price scenarios.

The regions with the highest greenhouse gas emission mitigation fall in the South-Central, Corn Belt, and Southeast regions of the U.S. At lower offset prices, the Lake States and Great Plains are key contributors as well. The contributions of the Corn Belt, Lake States, and Great Plains are primarily in the form of agricultural soil carbon sequestration, whereas the South-Central and Southeast regions are primarily suppliers of carbon sequestration from afforestation and forest management.

The Rockies, Southwest, and Pacific Coast Regions generate relatively small shares of the national mitigation total in all price scenarios. From those regions, only forest management from Western Oregon and Washington (PNWW) produces appreciable mitigation. This can be attributed primarily to the fact that climate and topography significantly limit the movement of land between major uses such as forestry and agriculture in the western regions.

Biofuel production occurs primarily in the Northeast, South, Corn Belt, and Lake States. Table 13.3 presents a top 10 ranking by GHGE mitigation quantity of region–activity combinations. At the lowest two prices, the top-ranked combination is forest management in the South-Central region, followed by agricultural soil carbon sequestration in the Corn Belt and Lake States. As prices rise, so does afforestation in the South-Central and Corn Belt regions and biofuel production in the Corn Belt, South, and Northeast. Both the magnitude of the GHGE response and the portfolio of strategies undertaken vary substantially as GHGE offset prices rise.

Market effects and co-benefits

The introduction of the greenhouse gas emission offset prices causes changes in land use, tillage, fertilization, crop mix and other management practices,

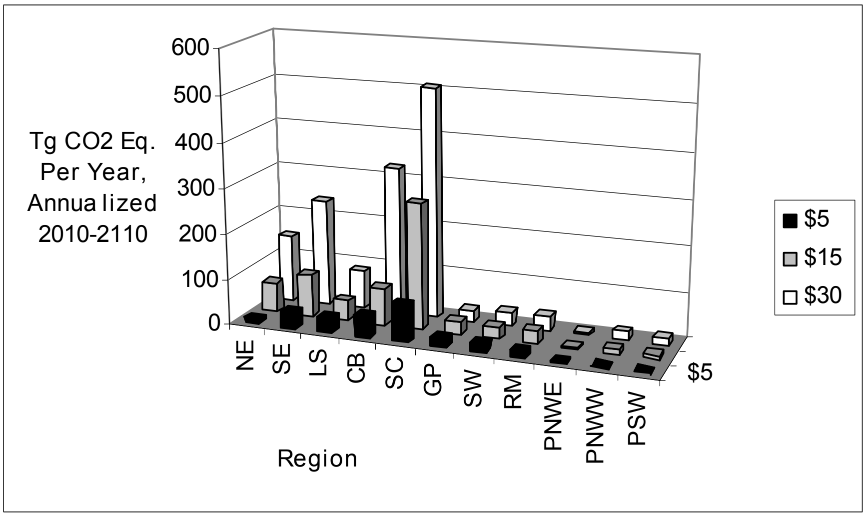


Figure 13.5 Annualized total forest and agriculture greenhouse gas emission mitigation by region at three greenhouse gas emission prices

Notes:
CB is Corn Belt and included states in vicinity of Illinois.
GP is Great Plains and includes states in vicinity of Nebraska.
LS is Lake States and includes states in vicinity of Michigan.
NE is North East and includes states in vicinity of New York.
PNWE is Pacific Northwest East Side – the eastern parts of Washington and Oregon.
PNWW is Pacific Northwest West Side – the western parts of Washington and Oregon.
PSW is Pacific Southwest and is in the state of California.
PSW is Pacific Southwest and is in the state of California.
RM is Rocky Mountains and includes states in vicinity of Colorado.
SC is South Central and includes states in the vicinity of Mississippi.
SC is South East and includes states in the vicinity of Georgia.
SW is South West and includes states in vicinity of Texas.

commodity production and consumption, and trade flows. In turn, this causes changes in market conditions and environmental loadings. Market related results found include:

- decline in production of traditional agricultural commodities;
- rise in agricultural and short term forest commodity prices;
- losses in consumer welfare due to higher prices;
- gains in producer welfare due to higher food prices and GHGE related offset payments; and
- losses in export earnings.

Table 13.3 Greenhouse gas emission mitigation quantity ranking by region–activity combination

Region	Activities	GHGE offset CO_2-equivalent price				
		$1	$5	$15	$30	$50
SC	Forest management	1	1	1	3	3
CB	Agricultural soil carbon sequestration	2	2	4	7	10
LS	Agricultural soil carbon sequestration	3	3	6		
GP	Agricultural soil carbon sequestration	4	5	7		
SW	Reduce crop Fossil fuel use	5	7			
RM	Agricultural soil carbon sequestration	6	8			
SC	Reduce crop fossil fuel use	7	6	8	10	
NE	Agricultural soil carbon sequestration	8	9			
CB	Reduce crop fossil fuel use	9	10			
CB	Agricultural CH_4 and N_2O mitigation	10				
SE	Forest management		4	3	6	8
SC	Afforestation			2	1	2
NE	Biofuel offsets			5	4	5
RM	Afforestation			9		
SW	Agricultural soil carbon sequestration			10		
CB	Afforestation				2	1
SE	Biofuel offsets				5	4
SC	Biofuel offsets				8	6
CB	Biofuel offsets				9	7
LS	Afforestation					9

Notes:
CB is Corn Belt and included states in vicinity of Illinois.
GP is Great Plains and includes states in vicinity of Nebraska.
LS is Lake States and includes states in vicinity of Michigan.
NE is North East and includes states in vicinity of New York.
RM is Rocky Mountains and includes states in vicinity of Colorado.
SC is South Central and includes states in the vicinity of Mississippi.
SC is South East and includes states in the vicinity of Georgia.
SW is South West and includes states in vicinity of Texas.

On the environmental side, the environmental impacts include:

- drop in the amount of traditionally cropped agricultural land;
- drop in irrigated area;
- increase in forested land;
- increase in biofuel land; and
- decline in loadings for nitrogen, phosphorous and soil erosion.

An interesting result is that the loadings decline substantially at low prices but in fact rise back up at higher prices due to intensification as more and more land is diverted. In a related study, Pattanayak et al. (2005) found such changes in loadings improved national aggregate average water quality about 2% moving the aggregate water quality measure into the swimmable range. They found that the Northern Great Plains, Southern Great Plains, Lake States, Corn Belt, and the Delta States experienced the largest water quality improvements. They also found that nitrogen loadings into the Gulf of Mexico decreased by about 9%.

CONCLUSIONS

This chapter conducted a modelling analysis regarding the optimal portfolio of agricultural and forest sector greenhouse gas emission mitigation strategies in response to alternative greenhouse gas offset prices. Focus is placed on the role of land use and land management alternatives within the portfolio in general and over time. Market and co-benefit effects are also discussed.

Our results show that the agricultural and forest sectors offer substantial potential to mitigate greenhouse gas emissions amounting to a share at high prices that could have met in the short run the magnitude of the suggested U.S. Kyoto Accord commitment. The optimal mitigation portfolio to achieve such offsets changes dynamically depending on price and time. Tillage based agricultural soil carbon sequestration and rotation length induced forest stand sequestration are the primary mitigation strategies implemented in the early decades and at low prices (below \$10 per ton CO_2) but then accumulation ceases as ecosystem capacity is reached and or forest harvest begins. These items even turn into sources after 40 to 60 years. On the other hand, power plant feedstock biofuel activities and afforestation become more important in the longer run or at higher prices. Crop and livestock management are small but steady contributors across the entire spectrum of prices and time periods.

The findings of this chapter support the argument that agricultural and forest carbon sequestration provides more time to find long-run solutions such as new technologies to halt the increasing ambient greenhouse gas concentration as discussed in Marland et al. (2001). It also shows that power plant feedstock biofuels are likely to be an important long run strategy under high GHGE offset prices.

The co-benefits and market results show that pursuit of such strategies can have positive effects on farm incomes and on environmental quality. Many of the practices employed reduce chemical and erosion related runoff.

ACKNOWLEDGEMENT

The work underlying this chapter was supported by USEPA, USDOE, SANREM and the Texas Agricultural Experiment Station.

REFERENCES

Adams, D.M., R.J. Alig, J.M. Callaway, B.A. McCarl and S.M. Winnett (1996) *The Forest and Agricultural Sector Optimization Model (FASOM): Model Structure and Policy Applications*. United States Department of Agriculture Forest Service Research Paper PNW-495, Pacific Northwest Research Station, Portland, Oregon.

Birdsey, R. (1992) *Prospective Changes in Forest Carbon Storage from Increasing Forest Area and Timber Growth*. United States Department of Agriculture Forest Service Publication, Washington, D.C.

Birdsey, R.A. and L.S. Heath (1995) Carbon changes in U.S. forests. In: L.A. Joyce (ed.), *Climate Change and the Productivity of America's forests*. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station General Technical Report, Ft. Collins, pp. 56-70.

Bush, G.W. (2002) Clear Skies & Global Climate Change Initiatives, February 14, 2002, http://www.whitehouse.gov/news/releases/2002/02/20020214-5.html.

Chang, C.C., B.A. McCarl, J.W. Mjelde and J.W. Richardson (1992) Sectoral implications of farm program modifications, *American Journal of Agricultural Economics*, Vol. 74, pp. 38-49.

Elbakidze, L. and B.A. McCarl (2004) Sequestration Offsets versus Direct Emission Reductions: Consideration of Environmental Externalities", draft article, Department of Agricultural Economics, Texas A&M University.

Houghton, J.T., L.G. Meira Filho, B.A. Callender, N. Harris, A. Kattenberg and K. Maskell (1996) *Climate Change 1995: The Science of Climate Change*. Cambridge, Cambridge University Press.

Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell and C.A. Johnson (2001) *Climate Change 2001: The Scientific Basis*. Cambridge, Cambridge University Press, 2001.

Intergovernmental Panel on Climate Change (1991) *Climate Change: The IPCC Scientific Assessment*, Cambridge, Cambridge University Press.

Johnson, D.E., H.W. Phetteplace, A.F. Seidl, U.A. Schneider and B.A. McCarl (2003a) Management variations for U.S. beef production systems: effects on greenhouse gas emissions and profitability, Presentation at 3rd International Methane & Nitrous Oxide Mitigation Conference, Beijing, China, December.

Johnson, D.E., H.W. Phetteplace, A.F. Seidl, U.A. Schneider and B.A. McCarl (2003b) Selected Variations in Management of U.S. Dairy Production Systems: Implications for Whole Farm Greenhouse Gas Emissions and Economic Returns, Presentation at 3rd International Methane & Nitrous Oxide Mitigation Conference, Beijing, China, December.

Johnson, R.N. and H.L. Scheurman (1997) Techniques for prescribing optimal timber harvests and investment under different objectives. *Forest Science Monograph*, Vol. 18.

Lal, R., J. M. Kimble, R.F. Follett and C.V. Cole (1998) *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect*, 128 pp., Sleeping Bear Press Inc., Chelsea MI.

Lee, H. (2002) The Dynamic Role for Carbon sequestration by the U.S. Agricultural and Forest Sectors in Greenhouse Gas Emission Mitigation. PhD Thesis, Department of Agricultural Economics, Texas A&M University.

Marland, G., B.A. McCarl and U.A. Schneider (2001) Soil carbon: policy and economics. *Climatic Change*, Vol. 51, pp. 101-117.

McCarl, B.A. (1982) Cropping activities in agricultural sector models: a methodological proposal. *American Journal of Agricultural Economics*, Vol. 64(4), pp. 768-772.

McCarl, B.A. and U.A. Schneider (1999) Curbing greenhouse gases: agriculture's role. *Choices*, First Quarter 1999, pp. 9-12.

McCarl, B.A. and U.A. Schneider (2000) Agriculture's role in a greenhouse gas emission mitigation world: an economic perspective. *Review of Agricultural Economics*, Vol. 22, pp. 134-59.

McCarl, B.A. and U.A. Schneider (2001) The cost of greenhouse gas mitigation in U.S. agriculture and forestry. *Science*, Vol. 294 (21), pp. 2481-2482.

McCarthy, J.J., O.F. Canziani, N.A. Leary, D.J. Dokken and K.S. White (2001) *Climate Change 2001: Impacts, Adaptation, and Vulnerability*. Cambridge, Cambridge University Press.

Mills, J.R. and J.C. Kincaid (1992) *The aggregate timberland assessment system — ATLAS: a comprehensive timber projection model*. General Technical Report PNW-GTR-281, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.160 p.

Onal H. and B.A. McCarl (1991) Exact aggregation in mathematical programming sector models. *Canadian Journal of Agricultural Economics*, Vol. 39, pp. 319-334.

Parton, W.J. (2001) Senior Research Scientist, Natural Resource Ecology Laboratory and Professor of Rangeland and Ecosystem Science, Colorado State University, Fort Collins, Colorado, Private communication.

Pattanayak, S.K., B.A. McCarl, A.J. Sommer, B.C. Murray, T. Bondelid, D. Gillig and B. DeAngelo (2005) Water quality co-effects of greenhouse gas mitigation in US agriculture, forthcoming in Climatic Change.

Plantinga A.J. and J. Wu (2003) Co-benefits from carbon sequestration in forests: evaluating reductions in agricultural externalities from an afforestation policy in Wisconsin. *Land Economics*, Vol. 79 (1), pp. 74-85.

Reilly, J., R. Prinn, J. Harnisch, J. Fitzmaurice, H. Jacoby, D. Kicklighter, J. Melillo, P. Stone, A. Sokolov and C. Wang (1999) Multigas assessment of the Kyoto Protocol. *Nature*, Vol. 401 (7 October), pp. 549-555.

Richards, K.R. (1997) The time value of carbon in bottom-up studies. *Critical Reviews in Environmental Science and Technology*, Vol. 27, S279-292, p. 385.

Rowe, C. (1992) Carbon Sequestration Impacts of Forestry: Using Experience of Conservation Programs. Paper presented at Symposium on Forest Sector, Trade, and Environmental Impact Models: Theory and Applications. April 30 - May 1, 1992, sponsored by CINTRAFOR, University of Washington, Seattle, WA.

Schneider, U.A. (2000) "*Agricultural Sector Analysis on Greenhouse Gas Emission Mitigation in the U.S.*", PhD-Dissertation, Department of Agricultural Economics, Texas A&M University.

Shugart, H., R. Sedjo and B. Sohngen (2003) *Forests & Global Climate Change: Potential Impacts on U.S. Forest Resources,* Pew Center on Global Climate Change.

West, T.O. and W.M. Post (2002) Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis, *Soil Science Society of America Journal*, Vol. 66, pp. 1930-1946.

Biosphere Greenhouse Gas Management: Transformative Change in Canadian Northern Great Plains Agriculture

14

Marie Boehm, Henry Janzen, Bob MacGregor and Murray Fulton

INTRODUCTION

The Northern Great Plains region (Figure 14.1) contains about 80% of Canada's agricultural land. It is a region of young soils and young agriculture. The landscapes were formed in the glacial deposits of the Pleistocene continental glaciation and as the glaciers retreated, forests and then grasslands covered the landscape. Over the last 10,000 years the mineral-rich glacial materials and grassland vegetation combined to produce the region's characteristic fertile soils.

The arrival of European settlers at the beginning of the 20th century began the transformation of the region from grassland to cropland. Crop production fundamentally altered the rates and patterns of energy and matter exchange among the prairie soil, air and water systems. One of the most significant changes was the loss from surface soils of about one-third of their organic matter content. This loss occurred for several reasons: tillage broke apart the stable soil structures that protected the organic matter from decay; more photosynthetically-trapped C was exported rather than returned to soil; and soil conditions (e.g., enhanced moisture) under arable crops often accelerated decomposition. The net loss of organic carbon was 'exhaled' as carbon dioxide (CO_2) to the atmosphere. There, it has joined with the other greenhouse gases added to the atmosphere by human activity to 'feedback' as potential climate change.

Most scientists agree that climate change will cause warmer average global temperatures (IPCC, 2001) but there is little consensus on other changes. According to Goody (2002), we cannot 'justify a claim to any quantitative knowledge of climate 50 years from now – except perhaps that anthropogenic activity will result in changes, and we may be surprised by what those changes are'. Uncertainty is a difficult challenge for policy-making and is one of the reasons why a global agreement on GHG emission reductions, an unprecedented application of the precautionary principle, has been so difficult to achieve. It is very difficult for people to change their behaviour before they are certain of the

F. Brouwer and B.A. McCarl (eds.), Agriculture and Climate Beyond 2015, 249-263.

impacts – it requires 'belief' in the predictions of climate change even while the scientists themselves still harbour reservations.

What can be assumed with some certainty is that the effects of climate change will vary and will produce winners and losers. Agriculture, land use, soil quality, water availability, crop productivity and sustainability, natural disturbance regimes (pests, diseases, storms and severe weather, droughts, invasion of alien species) transportation, markets, and food security could all be affected (Joyce and Hansen, 2001; Ogallo et al., 2000; Dale, 1997, Watson et al., 1996). Most of the world's population lives in developing economies that have limited resources for addressing impacts or adaptation. For them, the consequences of climate change are likely to be largely negative (Fankhauser, 1997).

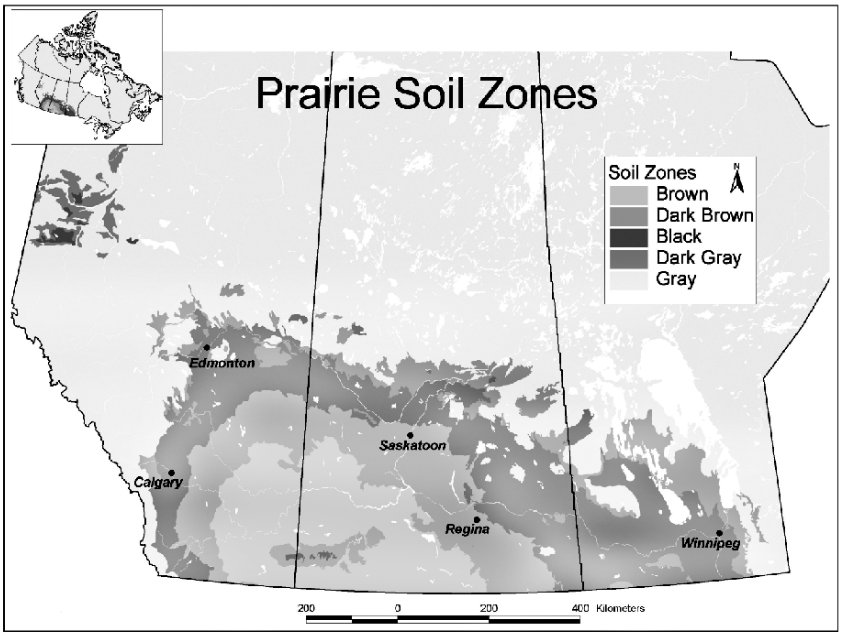


Figure 14.1 Most of Canada's agricultural land occurs in the Northern Great Plains or Prairie region. The five major soil zones of the region reflect the rate of potential evapotranspiration and soil organic matter content, ranging from the semi-arid Brown soils to the sub-humid Black and Dark Gray soils

Societies and individuals have two options for action in response to climate change - mitigation and/or adaptation. Adaptation is responses to change to reduce negative effects and take advantage of opportunities. Whereas mitigation is a planned process, adaptation is a more spontaneous reaction to perceived or actual risks (Adger, 2001). Adaptation looks for ways to minimize the impact of changes that are occurring; mitigation tries to prevent the change from happening in the first place. Farming is inherently about adaptation, so for farmers adaptation to climate change involves all of the short-term adjustments and agronomic decisions that they routinely make each year (Olsen and Bindi, 2002).

Adaptation can also involve 'top-down' approaches to achieve long-term adjustments and major structural change that cannot be achieved by individual responses alone, such as crop breeding to produce adapted varieties, or major infrastructure development, such as irrigation or transportation (Olsen and Bindi, 2002). The efficacy of top-down adaptation depends on how well new infrastructure developments and structural changes mesh with the needs of farmers on the ground – do proposed adaptations fit with on-going spontaneous actions and individual responses? For a sector like agriculture with so many individual decision-makers, adjusting to change is both a challenge (Timmer, 1998) and an opportunity (Jacobs, 2000). It is a challenge because the success of Canadian agricultural mitigation and adaptation policies depends on the decisions of about 200,000 individual farmers, each with their unique circumstances. However, each farm also offers an opportunity for experimentation, and taken together farmers apply a level of creative energy to finding workable adaptations that would be impossible to generate solely from the top down.

Whether climate change ultimately provides a challenge or an opportunity will depend on the degree to which it exacerbates the other ecological, social, economic and political challenges we face (population pressure, further industrialization, environmental degradation, migration, changes in land productivity) (Ogallo et al., 2000; Dale, 1997). Can we adapt fast enough to keep pace with climate change and are our systems resilient enough to withstand the impacts of climate uncertainty? The answers to these questions might separate the winners from the losers.

BIOSPHERE GREENHOUSE GAS MANAGEMENT

An approach to GHG abatement and adaptation being discussed in the context of Canadian agriculture policy is referred to as biosphere GHG management. Biosphere GHG management contains three components: remove, reduce, and replace[1] (Figure 14.2). 'Remove' refers to removals of carbon dioxide from the atmosphere through carbon sequestration (sinks) in agricultural soils. 'Reduce' refers to emission reduction and 'replace' is the substitution of renewable biomass energy sources for fossil fuels. 'Remove and reduce' are short and medium-term strategies whereas 'replace' represents new and innovative technologies that will become more important in the long-term. In the balance of this chapter, we extrapolate the biosphere GHG management strategies into the future with the aim of exploring how they could lead to a more environmentally benign agricultural system and a bio-based energy economy. We ask how the agricultural practices of the future might be shaped by the need for GHG

[1] The concept of biosphere GHG management based on remove, reduce, replace was first presented by the BIOCAP Foundation. More information is available at the website: www.biocap.ca.

mitigation and adaptation to climate change. We cannot predict how agriculture will change over the next decades and that is not our intent. Rather, we hope to gain some insight into the questions we should ask as we ponder how future farming systems might look and function.

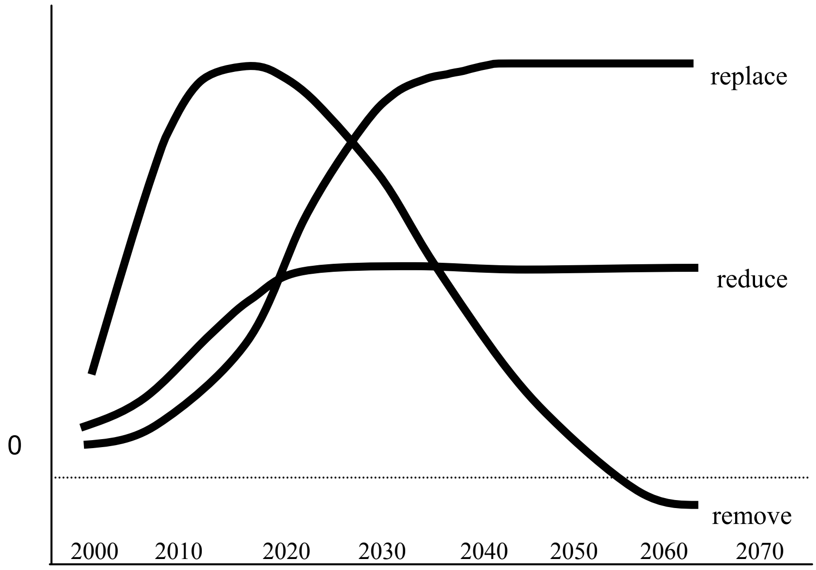


Figure 14.2 Relative annual rates of GHG abatement from remove, reduce and replace mitigation strategies

We have somewhat arbitrarily chosen to focus on two time periods: 2020 to 2050 and 2050 to 2080. In terms of the time required for change in a complex system like agriculture, 20 years is not very long but exploring the path beyond 2020 can provide some insight into where we can get from the trends and starting point of 2004. Even if agriculture in 2020 to 2050 is expected to mainly reflect a continuation of current trends, by the second period, 2050 to 2080, the influences of mitigation policy and adaptation to climate change could cause substantial changes in the systems of crop production.

While we recognize that other scenarios are just as possible, we based the future projections on the following assumptions about climate in 2050:

- Temperature, the rate of evapotranspiration, and the probability of drought have increased. In response, grasslands and forests continue the northward migration they began when the continental ice sheets retreated ten thousand years ago.
- Warmer and drier weather jeopardizes accumulation of snow in the Rocky Mountains, reducing snowmelt and waterflow in Prairie rivers that originate in the mountains. Without those rivers, which have been stable and reliable

sources of water, much of the biodiversity, the industrial activity and urban populations of the region face water shortages.

- Prairie climate is currently characterized by a growing-season moisture deficit (Conly and Van der Kamp, 2001) and the water balance is highly sensitive to climate. A small, sustained increase in the rate of evapotranspiration (because of warming temperatures or reduced precipitation, or both) will increase the risk of crop failure due to drought by 2050. Although it is not impossible to grow crops, in the driest regions the likelihood of obtaining break-even yields declines.

Transformative change in the short and medium-terms: 2020 to 2050

The path from here to 2020 will be shaped by many dynamic factors, such as markets, weather, policy, new technology, etc., but the mitigation practices that farmers use in 2020 will probably include the zero tillage and direct seeding systems that farmers are adopting now. They are 'no-regrets' GHG strategies that offer a range of economic and environmental benefits.

'Remove' strategies are based on the transfer of CO_2 from the atmosphere into plant biomass by photosynthesis and from there into carbon reservoirs such as soils. Removals occur when producers adopt farming practices that cause the amount of plant carbon retained in the soil as organic matter to increase. Increases in soil organic matter occur because the new practices increase plant biomass production and the amount of organic matter added to the soil or reduce soil disturbance and the rate at which added plant materials decays and is consumed by soil microorganisms. Carbon will be sequestered until the soil reaches a new equilibrium in which the rate of carbon additions is balanced by the rate at which soil carbon decays. It takes several years or decades for the soil to gradually approach an organic carbon equilibrium. At that point, changes in land management or the environment that cause carbon additions to decline or carbon losses to increase will unbalance the equilibrium and cause the soil to once again be a net source of CO_2 emissions. On the other hand, the soil will resume its function as a net sink if it is managed to increase organic matter additions relative to losses. The soil will act as a net source or net sink until it comes again into equilibrium with the new levels of carbon inputs and losses.

Prairie agricultural soils have the capacity to increase their organic carbon contents because they lost so much as a result of past farming practices – cropland soils have been a net source of CO_2 emissions for most of the past century. It is only during the past decade that a major shift from 'conventional' practices, especially those involving tillage and summer fallow, to soil conserving practices, such as zero tillage and reduced summer fallow use, have made the prairie cropland a net 'sink' for carbon.

In the first years following agricultural development on the prairies, soil scientists and agrologists recognized that the rich stores of organic matter in the grassland soils were easily depleted by the crop production practices of the time. Systems similar to the continuous cropping and reduced tillage systems that producers are now adopting were recommended, but they could not be profitably employed (Janzen, 2001). Producing crops without summer fallow and tillage for weed control became profitable only in the 1970s after farmers had perfected direct-seeding technology and low-cost, effective herbicides became available – too late to avert early organic matter loss, but well timed for GHG mitigation. (Had farmers early on had technology to avert carbon loss from soils, we might not be talking now about using soils for GHG mitigation.)

'Reduce' strategies are based on practices that reduce emissions of GHG. In most sectors, 'reduce' strategies are aimed at reducing emissions of CO_2 from fossil fuel combustion. However, agriculture is a biological production system and nitrous oxide (N_2O) and methane (CH_4) are the major GHG gases.

Nitrogen (N) additions, from fertilizer, manure, and other sources, are a major source of N_2O emissions from croplands. Emissions generally occur when there is more N available in the soil than the crop requires - either because the amount or timing of N applications does not match the crop requirement. Strategies to reduce N_2O emission usually involve better management of the N cycle to reduce the N 'leakage' from the system, whether as nitrate to water or N_2O to the atmosphere.

Most agricultural emissions of CH_4 are from enteric fermentation in ruminant animals and liquid manure storage. Methane emissions from croplands occur mainly when liquid manure is applied in large volume to the soil surface. Practices to reduce emissions include improving the quality of the ruminant diet (reducing the fiber content), adding amendments, such as ionophores, to diets, reducing the length of time that liquid manure is stored, recovering emissions from lagoons, and applying manure at rates that the soil can accommodate.

Land use patterns: 2020 to 2050

The strong southwest to northeast trend of decreasing potential evapotranspiration (Figure 14.1) that characterizes the Canadian prairies is the major influence on potential productivity. Crops, productivity, and production systems in the semi-arid southwestern prairies (the Brown soil zone) are considerably different than those of the more humid north and eastern regions (the Black and Gray soil zones) and the potential for carbon sequestration is substantially lower in the Brown soil zone than in the Black and Dark Gray soil zones.

Semi-arid Brown Soil Zone

Current land use ranges from pasture and forages to support livestock production in the driest areas of the Brown soil zone to production of grains in rotations that include summerfallow about once in every four years where there is less risk of drought (PFRA, 2000). If the climate is warmer and drier by 2050 (as we assumed for this exercise) and the risk of drought increases, adaptation will favour pasture and hay production rather than grains and livestock will become the dominant crop.

The development of a carbon market or offset trading system could also provide an incentive for shifting to mainly perennial crop production. Conversion from annual cropland to pasture and hay land could sequester carbon at rates of about 0.7 to 0.9 Mg CO_2/ha/yr for 20 years (Smith et al., 2001; McConkey et al., 1999). At a price of $10/Mg for CO_2 that would generate about $1/ha/yr, probably not enough revenue to drive the change itself but enough to offset some of the transition cost. Paradoxically, although a higher price for carbon would cause more land to covert from cropland to pasture, in the long run the lower price might have greater effect on GHG abatement. At issue is the non-permanent nature of sequestered carbon - removals of CO_2 from the atmosphere associated with biological carbon sinks can be released if the sequestering practices are not maintained. If practices that sequester carbon are adopted only in response to large incentive or market payments, there is a significant risk that if or when the incentive program stops or the market ends, practices will revert and the carbon sequestered in the soil will be released back to the atmosphere. Emission reductions on the other hand are permanent, so even if abatement practices are abandoned and emissions rates return to previous levels, the atmosphere is safe from the quantity of GHG not emitted in the interim. For carbon sequestration activities, a market value of carbon too low to drive the conversion to permanent cover but large enough help offset constraining transition costs might offer the most effective and assured GHG abatement in the long run.

The potential for net carbon sequestration from changes in land management is the balance between the new rate of removal and any increases in N_2O and CH_4 emissions that might also occur. Removals rates of 0.7 to 0.9 Mg CO_2/ha/yr were estimated taking into account expected changes in the non-CO_2 emissions but the N_2O and CH_4 emission estimates, which are still quite uncertain, will vary depending on:

- how the size of the livestock herd changes in response to increased hay land and pasture production;
- whether changes in feeding management, improved feed quality, and feed additives can reduce enteric fermentation emissions per animal;
- adoption of alternative manure handling and storage practices, such as composting, shorter storage times, and
- better fertilizer and manure application techniques; rates of nitrogen fertilization and denitrification on pasture and hay land compared to cropland; and
- fossil energy use (i.e., tillage, fertilizers and herbicides how about irrigation).

The net annual potential for carbon sequestration from conversion of annual cropland to pasture and hay land at current rates is projected to be about 4 Mt by 2008 for Canada, of which about half would occur in the semi-arid prairies (Boehm et al., 2004). The same analyses showed that if conversion rates were increased by one million ha and rotational and complementary grazing was practiced on 20% more grazing land, sequestration rates could reach an average of 5 Mt per year for Canada in 2008. Assuming that it will take 20 years to reach equilibrium, those rates of removal could continue to about 2020. The projections were made on the basis of the crop productivity potentials associated with long-term climatic norms and did not take into account possible changing climate patterns in the future.

Semi-humid Dark Brown and Black Soil Zones

In the semi-humid region of the Northern Great Plains, land is used mainly for continuous production of annual grain, oilseed, and pulse crops (PFRA, 2000) increasingly using zero tillage and direct seeding technology. It is not anticipated that the types of crops produced in this region will change over the next 20 to 50 years but it is expected that direct seeding/zero tillage/continuous-cropping will be the conventional crop production system by 2050.

Direct seeding, zero tillage systems are being adopted by farmers because they offer economic and environmental benefits under current production conditions, including carbon sequestration. Government policy aimed at GHG mitigation, including the development of a domestic market for carbon trading, offers an incremental incentive for their adoption but payments are not expected to be large enough to drive the change. Conversion from conventional tillage to zero tillage sequesters soil carbon at rates that range from about 0.4 to 1.3 Mg CO_2/ha annually for about 20 years (Smith et al., 2001, McConkey et al., 1999). A market price of \$10/Mg for CO_2 would provide about \$0.50 to \$1/ha/yr which could help offset some of the transition costs but would not be large enough to drive the change. As was discussed for the conversion of cropland to hayland and pasture, sequestered soil carbon can be released back to the atmosphere if the sink-enhancing practices are abandoned so it is not desirable to incent soil carbon sequestration through adoption of land management practices that would not be economically viable without the carbon payment. The amount of CO_2 removed from the atmosphere might be lower in the short-term, but in the long-term there is less risk of non-permanent removal. On the Canadian prairies, zero tillage and direct seeding practices have been adopted by many farmers over the past decade because of their economic and environmental benefits and without the need for direct incentive payments. The carbon market could further that adoption by easing the cost of transition for farmers for whom that has been a constraint over the past decade.

Carbon sequestration will not be sufficient to stabilize GHG concentrations in the atmosphere at levels that might minimize climate change – emission reductions are also required. Serious efforts to reduce emissions will likely increase energy prices. The consequent high prices for many purchased inputs, everything from fertilizers and pesticides to machinery and shipping commodities to market, is already exerting pressure on the grain production system. One adaptation to that price signal could be a greater integration of the grain and livestock production systems. For example, feeding hogs rather than exporting grain not only adds value to the production system and reduces fuel use for transportation, but if the nitrogen and carbon-rich manure is recycled back onto the cropland will reduce nitrogen fertilizer requirements and lower N_2O and CO_2 emissions.

Other opportunities that could be cost-effective by 2020 if investment is made in developing emission reduction technologies include use of:

- slow release nitrogen fertilizer and nitrification inhibitors to reduce N_2O emissions and increase N-use efficiency;

- better fertilizer application methods, such as precision farming techniques to match added nitrogen with specific crop requirements, timing of nitrogen applications to match crop nitrogen demand, and placement of nitrogen fertilizer placed within the soil to reduce volatilization and leaching losses;
- more efficient feeding of protein to livestock to reduce the nitrogen content of manure; and
- improved manure management to reduce storage time, match rates to local conditions, and deliver the nutrients more efficiently to crops.

Projections for Canada showed that if zero tillage adoption remains at 32% of cropland and summer fallow use declines to about 4 million ha, net carbon sequestration could reach 8 Mt per year by 2008, almost all in prairie croplands (Boehm et al., 2004). If zero tillage was used on 70% of cropland and summer fallow declined to 1.5 million ha, which are about the limits for those practices on the prairies, carbon sequestration in croplands could reach about 20 Mt per year by 2008 and remain at that level for about 20 years. A modelling exercise for United States agriculture suggests that by tightening the entire nitrogen cycle (better application techniques, fertilizer technology and delivery), application of synthetic nitrogen could be reduced to 72% of the estimated baseline by 2080 (Scott et al., 2002) with obvious benefits for profitability, the atmosphere, and water quality. Since soil organic matter contains nitrogen as well as carbon (at a C : N ratio of about 10:1), nitrogen availability gradually increases as carbon is sequestered. The combination of better management of the nitrogen cycle and increased stores of organic nitrogen could reduce use of chemical nitrogen fertilizer in the future. However, the sequestration estimates given in Boehm et al. (2004) assumed a small increase in nitrogen fertilization associated with zero tillage, thereby possibly underestimating net sequestration.

Dark Gray Soil Zone – agriculture to forest transition

Current land use in the grassland-forest transition area at the northern extent of prairie farmland is a combination of cereals, oilseeds, and pulses production on the best soils coupled with livestock production on the poor quality soils or along the forest fringe (PFRA, 2000). Moisture is not a major constraint for crop production but Dark Gray and Gray soils tend to have low nutrient status compared to the Brown, Dark Brown, or Black soils and high levels of nutrient inputs are required to sustain crop production. As the cost of nitrogen fertilizer and other inputs rises over time from 2020 to 2050, annual crop production in this region will gradually become less profitable, encouraging a shift to more extensive forestry and livestock systems, such as extensive livestock grazing, livestock, and timber (agroforestry) production or silvaculture.

The extent and rate of the transition from grains, oilseeds, and pulses to livestock or agroforestry systems will depend on the relative demand for products. The outcome could be influenced by the development of a market for sink credits, in which case the relative value of forest carbon credits (from afforestation and reforestation projects) compared to soil carbon credits (taking into account transaction costs and costs of measurement, monitoring, and verification) could affect which system is more profitable. It remains to be seen whether markets will distinguish between forest and soil carbon credits but there are differences between removals in forests and agricultural soils. Carbon sequestered in agricultural soils, although harder to measure, monitor, and verify, might be more resilient to loss than forest carbon. Short of catastrophic events like floods, soil carbon release requires deliberate human disturbance, such as tillage, and even then it would take repeated tillage operations over a period of years to release all of the sequestered carbon. Trees and forests, on the other hand, are more susceptible to natural disturbances such as fire, which are difficult to control and could cause an entire sink reversal in one event.

New technologies for making wood products, such as oriented strand board (OSB), are expanding the opportunities for combined farm production of wood and food crops. OSB uses wood fibers rather than lumber to manufacture building materials, so large trees are not required. Fast-growing hybrid poplar varieties suit the OSB market and, since they are ready for harvest in less than 15 years, they fit within the planning horizon of a farm.

The potential for enhanced carbon storage by shifting from agriculture to forestry varies depending on the quality of the land and is probably highest on landscapes that were originally forested. Reforestation, planting trees on land once forested, will probably increase ecosystem carbon stocks because organic carbon content tends to be low in forest soils so the aboveground biomass represents a relative carbon increase. Conversely, planting trees on soils with high carbon content, like those developed under grassland, can cause a decline, at least initially, in total carbon stocks if the disturbance causes greater losses from the soil than can be replaced by accrual in aboveground woody biomass.

Implications for environmental quality

'Remove' and 'reduce' are strategies aimed at tightening the carbon and nitrogen cycles and making agroecosystems less leaky, which benefits both the atmosphere and the terrestrial environment. Risk to water quality will decline if there is less movement of water with its dissolved nutrients, soil particles, and pesticides from cropland into surface and ground water. However, if more water is retained in the cropland, the number and size of water bodies, especially small sloughs, ponds, and ephemeral streams may decline (Hayashi et al., 2003; Kamp et al., 1999, 2003). Though many of the small and ephemeral water bodies and wetlands in the agricultural landscape are artifacts of past cropland management, they have become wildlife habitats and their decline could limit the numbers of some wildlife species.

Ironically, the most serious threat to carbon sequestered in agricultural systems might be the very phenomenon it is intended to forestall - climate change. Although opinion is still divided, a warming of the climate could release carbon sequestered in soil by accelerating the rate of decomposition of organic matter and by reducing the amount of organic matter added to the soil if crop productivity declines and droughts become more frequent (Amundson, 2001).

Transformative change in the long-term: 2050 to 2080

By 2050, farmers who are going to adopt the profitable “remove” and “reduce” strategies will have done so and croplands will begin to approach their limits for carbon sequestration. If agriculture is to help mitigate GHG emissions in the long-term, it will have to do more than manage the carbon and nitrogen cycles efficiently and reduce ‘leakage’ – it will have to help break societies’ dependence on fossil energy. By 2050, the sector could produce not only food and fibre, but also renewable feedstocks for the production of CO_2 emission-free energy to ‘replace’ fossil fuels (Caldeira et al., 2003; Hoffert et al., 2002).

The ‘replace’ strategies include production of a range of fossil fuel replacements, such as bio-diesel from oilseeds, ethanol from grain or cellulose, bio-oil from crop residues, methane captured from anaerobic digestion of liquid manure, and electrical power from woody crops or grasses. Bio-oil produced from biomass residues using thermochemical processes has less heating value than petroleum but it can be added to fuel diesel engines (NRCan, 2003). Ethanol is produced by fermenting grains or cellulose. Blends of gasoline with up to 10% ethanol (E10) are available in Canada and blends with up to 15% ethanol will likely soon be available soon. Waste products rich in C, such as liquid hog manure, can be treated in anaerobic digesters to produce methane, which can replace natural gas to produce electricity or heat. Organic matter remaining after digestion can be added to soils after composting (NRCan, 2003).

Although commercial production of bio-based energy still requires years of research and development, it could transform agriculture and agroecosystems. Diversity of production has historically meant growing different kinds of food on the same farm, for example, grain, milk, beef, and vegetables, but on future farms diversity could mean growing different kinds of products (pork, wood, methane and bio-oil, for example) aimed at different markets. The challenge will be to develop synergistic and efficient systems for producing food, fibre, and energy together.

How fast and how much land use and land management changes from 2020-2050 to 2050-2080 will depend on the degree and rate at which climate changes, how rapidly economies develop and adopt low CO_2-emitting and bio-based energy sources, and how the relative prices of the food, fibre and energy commodities change over time. If Canada develops domestic policy aimed at reducing GHG emissions to address climate change, the transition to a bio-based energy economy should be well underway by 2050 and some of the biomass produced on farms could be used for energy production. Early analyses indicate that the demand for crops for energy production could be greater than the demand in the food market. For example, Canada currently consumes 25 billion litres of diesel annually, mainly for use in off-road equipment like agricultural tractors and transport trucks.[2] Canada also produces 5 million tonnes of canola annually from which 2 billion litres of 100% biodiesel could be produced. Canadian per capita consumption of canola food oil is 30 litres, slightly less than half the canola we

[2] Dr. Andre Hucq, Director, Canadian Agricultural Energy Data Analyses Centre, University of Saskatchewan, Saskatoon, Canada, provided the information used in this example.

produce. Our consumption of diesel is about 700 litres per capita – clearly there is potential demand for biodiesel that agriculture could fill.

But before encouraging the widespread production of bioenergy crops, we may need to consider the broader effects. For example: What is the *net* saving of energy from energy crops, after subtracting energy inputs? How does the removal of carbon for energy affect the amount of carbon stored in the soil (and, hence, the atmosphere)? In a world with burgeoning population and food demand, can we justify using prime food-producing land to grow oil?

Land use and land management patterns: 2050 to 2080

How might the 'replace' technologies and a changing climate interact to alter land use and land management by 2050 to 2080? To explore this question, we speculate that by 2050 climate has warmed but there is still a great deal of uncertainty about future climate change.

In the Dark Brown soil zone, more land will be used for forage and pasture crops. Grain/oilseeds/pulse production will shift northward into the Black and Dark Gray soil zones.[3] The Brown soil zone will be more arid but land use will still be mainly for pasture, forages and extensive livestock grazing. In the driest areas, the frequency of drought by 2050 causes water and feed shortages making even extensive livestock grazing unprofitable. 'Wind' farming with large turbines erected for energy production might be the most suitable land use in the Brown soil zone.

The state of agriculture in 2080 might be an indicator of how seriously society acted to replace fossil fuels with biomass energy and its success at devising land management systems that integrate food and energy production. Although land use and land management patterns will change gradually over time, the most noticeable difference between the agricultural systems of 2080 and 2020 might be how commodities are marketed and used. For example, if by 2080 we are successful in developing renewable biomass energy systems, the crop biomass produced on prairie farms will be used to feed humans, animals and energy production. Our challenge will be to develop production systems and crop types that can meet food, energy and environmental health demands, perhaps by using the products we do not eat or require for maintaining soil quality for energy. Products like hog manure, now considered a source of microbial, nitrate, phosphate, odour, methane and nitrous oxide pollution, could be transformed into sources of energy and soil nutrients, both with clear environmental benefits.

CONCLUDING REMARKS

How agriculture changes over the next 80 years will depend on how individual producers and land managers respond to the pressures they will face, including the need to mitigate GHG and adapt to climate change. Farmers are not in the

[3] However, as an adaptation to climate change, northward expansion offers only limited potential because crop production will eventually be halted at the Precambrian Shield.

business of carbon sequestration, GHG emission abatement, or renewable energy production. They are in the business of managing land to produce crops with the aim of sustaining production over the long-term. Climate change will influence how farmers and other stakeholders in the agricultural sector align the resources of the ecosystem, the land, air, water, livestock, and people (Janzen, 2001) into a permanent food and energy production system.

If we are creative and diligent, we can find economical ways of reducing GHG emissions from agriculture while reducing the potential for climate change. However, since the residence times of GHGs in the atmosphere are decades to centuries and since even the most optimistic scenarios still show substantive GHG accumulations, farmers will still also have to adapt to climate change. We need to increase our understanding of how farming systems are buffered against climate change and uncertainty, and how they can be made more resilient.

If we are going to achieve a renewable energy economy by 2080, as a society we have to support the thinking and structural change required for producing workable alternatives to fossil fuels. In the agriculture sector, one way of moving from understanding to action might be to provide opportunity (or remove constraints) for innovation and experimentation at the farm level. At the same time, we need societal debate about whether there are ethical issues about using land to produce energy rather than food. But, in the end, even the replace strategies of GHG abatement are less about a grand cohesive response to mitigation or adaptation pressures and more like the decisions farmers make every day on their lands in response to shifting market opportunities and policy demands.

Biosphere GHG management for mitigation and adaptation is largely good land management, conservation of resources, and careful management of the carbon and nitrogen cycles. The progression from remove to reduce and replace GHG abatement strategies for Canadian prairie agriculture can be achieved through a mix of market-driven incentives, policy and adaptations, all aimed at moving toward more sustainable and economically viable crop production systems. For example, the goal should not be to maximize creation of carbon offsets for trading in a carbon market (given the risk that the sequestered carbon will be released if the carbon values declines) but rather to encourage the adoption of economically viable systems of crop production that sequester carbon and minimize other impacts of agriculture on the environment. The concept of biosphere GHG management allows GHG mitigation policy to be integrated into overall environmental policy for the agriculture sector.

REFERENCES

Adger, W.N. (2001) Scales of governance and environmental justices for adaptations and mitigation of climate change. *Journal of International Development*, Vol. 13, pp. 921-931.

Amundson, R. (2001) The carbon budget in soils. *Annual Review of Earth and Planetary Sciences*, Vol. 29, pp. 535-562.

Boehm, M.M., Junkins, B., Desjardins, R., Kulshreshtha, S. and W. Lindwall (2004) Sink potential of Canadian agricultural soils. *Climatic Change*, Vol. 65, pp. 297-314.

Caldeira, K., A.K. Jain and M.I. Hoffert (2003) Climate sensitivity uncertainty and the need for energy without CO_2 emissions. *Science*, Vol. 299, pp. 2052-2054.

Conly, F.M. and G. van der Kamp (2001) Monitoring the hydrology of Canadian prairie wetlands to detect the effects of climate change and land use changes. *Environmental Monitoring and Assessment*, Vol. 67, pp. 195-215.

Dale, V.H. (1997) The relationship between land-use change and climate change. *Ecological Applications*, Vol. 7, pp. 753-769.

Fankhauser, S. (1997) The economic costs of climate change and implications for land-sue change. In: W.N. Adger, D. Pettenella and M Whitby (Eds.) *Climate-change Mitigations and European Land-use Policies*. World Bank, Washington, D.C., USA, pp. 59-70.

Goody, R. (2002) Observing and thinking about the atmosphere. *Annual Review Energy and Environment*, Vol. 27, pp. 1-20.

Hayashi, M., G. van der Kamp and R. Schmidt (2003), Focused infiltration of snowmelt water in partially frozen soil under small depressions. *Journal of Hydrology*, Vol. 270, pp. 214-229.

Hoffert, M.I., K. Caldeira, G. Benford, D. Criswell, C. Green, H. Herzog, A.K. Jain, F.S. Kheshgi, K. Lackner, J. Lewis, H.D. Lightfoot, W. Manheimer, J.C. Mankins, M.E. Mauel, L.J. Perkins, J.E. Schlesinger, T. Volk and T. Wigley (2002) Advanced technology paths to global climate stability: energy for a greenhouse planet. *Science*, Vol. 298, pp. 981-987.

IPCC (2001) *Third Assessment Report. Climate Change 2001*. Working Group I: The Scientific Basis. www.ippc.ch.

Jacobs, J. (2000) *The Nature of Economies*. Vintage Canada. Toronto, Canada, 190 pp.

Janzen, H.H. (2001) Soil science on the Canadian prairies – Peering into the future from a century ago. *Canadian Journal of Soil Science*, Vol. 81, pp. 489-503.

Joyce, L.A. and A. Hansen (2001) Climate Change: Ecosystem restructuring, natural disturbances and land use. In: J. Rahm and R. McCabe (Eds.), *Transactions of the Sixty-sixth North American Wildlife and natural Resources Conference*. Wildlife Management Institute, Washington D.C. pp. 327-343.

Kamp, G. van der, M. Hayashi and D. Gallén (2003) Comparing the hydrology of grassed and cultivated catchments in the semi-arid Canadian prairies. *Hydrological Processes,* Vol. 17, pp. 559-575.

Kamp, G. van der, W.J. Stolte and R.G. Clark (1999) Drying out of small prairie wetlands after conversion of their catchments from cultivation to permanent brome grass. *Hydrological Sciences Journal*, Vol. 44, pp. 387-397.

McConkey, B.G., B.C. Liang and C.A. Campbell (1999) *Estimating gains of soil carbon over a 15-year period due to changes in fallow frequency, tillage system, and fertilization practices for the Canadian Prairies (An Expert Opinion)*. Misc. Publication #379M0209, Swift Current Semiarid Prairie Agricultural Research Centre, Agriculture and Agri-Food Canada. 9 pp**.**

NRCan, 2003. http://www2.nrcan.gc.ca/es/es/renewable_e.cfm.

Ogallo, L.A., M.S. Boulahya and T. Keane (2000) Applications of seasonal to interannual climate prediction in agricultural planning and operations. *Agricultural and Forest Meteorology*, Vol. 103, pp. 159-166.

Olsen, J.E. and M. Bindi (2002) Consequences of climate change for European agricultural productivity, land use, and policy. *European Journal of Agronomy*, Vol. 16, pp. 239-262.

PFRA (2000) *Prairie Agricultural Landscapes: a land resource review*. Prairie Farm Rehabilitation Administration, Agriculture and Agri-Food Canada. Regina, Canada.179 pp.

Scott, M.J., R. Sands, N. Rosenberg and C. Izaurralde (2002) Future N_2O from US agriculture: projecting effects of changing land use, agricultural technology, and climate on N_2O emissions. *Global Environmental Change*, Vol. 12, pp. 105-115.

Smith, W.N., R.L. Desjardins and B. Grant (2001) Estimated changes in soil carbon associated with agricultural practices in Canada. *Canadian Journal of Soil Science*, Vol. 81, pp. 1-7.

Timmer, C.P. (1998) The agricultural transformation. In C.K. Eicher and J. Staatz (Eds.) *International Agricultural Development.* Third Edition. Graduate School of International Relations and Pacific Studies, University of California, San Diego, USA. pp. 113-135.

Watson, R.T., M.C. Zinyowera and R.H. Moss (Eds.) (1996) *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical analyses*. Contribution of Working Group II to the Second Assessment Report of the IPCC. Cambridge University Press, Cambridge.

Policy Efforts to Achieve Sustainable Agriculture: An OECD Perspective

15

Wilfrid Legg[1]

INTRODUCTION

Achieving sustainable agriculture is now widely accepted as the over arching goal of agricultural policy in all OECD countries. The objective is thus to ensure that agriculture is not only economically efficient in meeting the demand for food and fibre, but that it does so in ways that are most beneficial to the environment, and respects the cultural, equity and ethical values in the society. In this context, while some countries are concerned that agricultural and trade policy reform could compromise the achievement of environmental goals for agriculture, others fear that domestic environmental policies could reduce the gains from agricultural trade liberalization. The policy challenge is to seek compatible solutions between these two positions.

On the basis of a decade of work in the OECD, this chapter concentrates on the policy efforts to enhance the environmental dimension of sustainable agriculture in cost effective and efficient ways, which is increasingly playing a major role in agricultural policy. It should be stressed that this chapter does not offer a review of non-OECD analyses of the policy linkages between agriculture and the environment, but readers can find many other relevant studies in the works cited in the list of references at the end of the chapter.

Agriculture has a special relationship with the environment, as overview studies on sustainable agriculture in the OECD have shown (OECD, 1995; OECE, 2001a). It is the major user of land and water resources in most countries, but its productive potential to a large extent depends on conserving those resources. Agriculture causes environmental damage, such as water and air pollution, soil erosion and loss of biodiversity, but also generates landscapes, sequesters carbon, controls water flows and provides species habitat. Farm structures, systems and practices, and farmer attitudes are diverse across and within countries as are ecological conditions. As a consequence the environmental effects of a given level of, or change in, agricultural production

[1] The views expressed in this chapter do not necessarily reflect those of the OECD or its Member countries.

F. Brouwer and B.A. McCarl (eds.), Agriculture and Climate Beyond 2015, 265-277.

also vary. Some environmental effects take a considerable time to appear - such as changes in soil quality. Others are not always easily observable - such as changes in biodiversity.

While farmers obviously have an interest in conserving resources and employing practices that are essential to ensuring their livelihoods, this does not at all mean that agricultural production will always achieve simultaneous economic and environmentally efficient outcomes. Firstly, many of the harmful environmental effects of farming are not confined to the farm and are often not taken into account by farmers when there are no markets or mechanisms for such externalities in place. Those who benefit from environmental services provided by agriculture but for which they do not pay are ‘free riders’, as are farmers who receive payments for environmental services they do not provide, whereas Legg (2003) has termed farmers who do not pay the cost of damage they cause off-farm as ‘free raiders’. Secondly, there are environmental benefits provided for society that are produced on the farm but for which farmers are not remunerated. Thirdly, farmers (and the public) are not always aware of the environmental impacts of their activities and may take a short rather than a long time perspective when establishing their planning decisions. Fourthly, it is not always clear as to what should (or can) be done in terms of attitudes, farm practices and technologies to address some environmental issues. Finally, policies have had a significant influence on agricultural practices, land use and production and thus environmental outcomes.

Sustainable agriculture and the OECD

Sustainable agriculture is part of the wider notion of sustainable development - the process of meeting society’s economic, environmental and social goals efficiently without impeding future production possibilities and welfare. Sustainable agriculture should satisfy consumer and public demands with maximum efficiency, while maintaining environmental quality and respecting social preferences. It is thus essentially a demand-driven concept. Policies can help or hinder the process through their effects on prices and other signals to producers, but potential conflicts can arise where policies and actions in one country in pursuit of sustainable agriculture are at the expense of achieving sustainable agriculture in other countries, in so far as country interests vary.

This chapter reports on the work in the OECD (which brings together 30 major market economies that account for around only one-sixth of the world’s population, but about five-sixths of its production and trade). The aim is to help governments take appropriate policy action, based on work that:

- Accounts for the effects of agriculture on the environment (indicators);
- Analyses the linkages between policies and environmental outcomes (cause and effect);
- Advises on the environmental effectiveness and economic efficiency of different mixes of policies and market solutions (identifying ‘what-if’ policy approaches); and
- Advocates actions to adopt in given circumstances (best policy practices).

AGRICULTURAL POLICIES IN OECD COUNTRIES

Many policies affect the environmental outcomes of agricultural activities. Some are intended to prevent harmful environmental effects, some focus on ameliorating or controlling existing pollution, while others are intended to encourage the provision of environmentally-related services (such as biodiversity, agricultural landscape features, carbon sinks, or flood and drought control). The policy measures used include economic instruments, regulations, voluntary or co-operative approaches, promotion of technologies, and dissemination of knowledge.

The driving force-pressure-state-response framework is a useful way in which to analyse the relationships between policies and environmental outcomes, recognising that this is a dynamic process, with many non-linear linkages and feedbacks involved. In the context of the linkages between policies, land use and climate change, attention is not only being paid to the effects of policies on land use and climate change, but increasingly on the effects of climate change on land used for agriculture and the possible policy responses that might be required.

Agricultural policies have impacted on the environment through changes in production incentives which influence farmer behaviour and practices – in terms of the types of the specific practices used, levels and composition of commodities produced, and location of production. Agri-environmental policies specifically address environmental effects of agricultural activities – sometimes placing conditions on the implementation of agricultural policies (e.g. cross-compliance), or directly targeting environmental outcomes (e.g. remunerating farmers for environmental services provided), or facilitating adoption of 'codes of good agri-environmental practice'. Environmental policies increasingly encroach on agriculture but are not specific to a sector and often involve regulations and penalties to reduce pollution. In addition, other policies play a part in influencing agri-environmental outcomes encouraging research and development, education, training and information; facilitating voluntary and co-operative approaches among groups of farmers; and imposing zoning regulations.

In most countries there is a mix of policy objectives, policy measures and environmental outcomes. This complexity makes it difficult to both identify the environmental impact of any one policy measure, and link a specific policy measure to attainment of a particular environmental objective. Rarely is policy coherence or integration to be found across the policy agendas in OECD countries in the area of agricultural and environmental policy: more often policies pull in opposite directions, with the result that additional policies are needed to counteract the negative spill over impacts of other measures.

Policies are of course put in place to address a particular need at a particular time. Policy intervention is justified to:

- correct for market failure (where private markets do not provide incentives to meet individual demands in the most efficient or effective ways);
- provide public goods (where private markets do not provide incentives to meet collective societal demands in the most efficient or effective ways);

- correct for policy failures (where there are undesirable spillovers from one set of policies); or
- to alter outcomes deemed undesirable by society, even when markets are working smoothly and public goods are adequately provided (for example, where the distribution of income or wealth is not acceptable, or ethical values are not respected).

In many OECD countries, the historical need of agriculture was perceived as 'providing more food and fibre for the population', which with abundant supplies and long-term falling real prices for commodities then became translated as a concern in some countries to maintain a level and pattern of farming, farmers and farm incomes. Most countries adopted policies targeted at maintaining or increasing domestic output (quantity oriented). In recent decades, the need is perceived as providing enough food and fibre for the population but producing it with more respect for the environment. Thus policies increasingly target environmental performance (quality oriented) rather than commodity output. In fact, in some countries, the need seems to be perceived as providing less food with more respect to the environment and taking into account ethical and health issues. Policies targeted to animal welfare, fairness (both within and across countries globally and throughout the agri-food chain) and nutritional status are becoming more significant.

With respect to agri-environmental linkages, four propositions relevant to policy may be made:

- Policies that directly target or change farmer behaviour and agricultural production parameters (commodity production incentives or disincentives) will indirectly affect the environment – the environmental outcomes will be 'non-intended' consequences.
- Policies that directly target or change environmental parameters (environmental regulations or payments for provision of ecosystem services) will indirectly affect agricultural production – the production outcomes will be 'non-intended' consequences.
- Policies that target or change both agricultural and environmental parameters (cross-compliance or conditionality measures) will lead to a lower level of agricultural production and a smaller environmental outcome than would be the case with respectively unconstrained production or environmental policies.
- While the greater the degree of decoupling of agricultural policies from farm production decisions will mean that there is a greater influence of market parameters on commodity production, to the extent that environmental outcomes (whether beneficial or harmful) are jointly generated with commodity production, there is rarely a unique combination of optimal (efficient) agricultural and environmental outputs.

Agricultural policy developments

Agriculture is a highly supported sector, although there has been a slow and not very significant downward trend in support since the mid-1980s. The OECD annually measures the support to the agricultural sector due to policies (OECD, 2004a), with further detailed explanation of the definitions, methodology and interpretation of the OECD's support estimates available on the OECD website and publications (OECD, 2003a; OECD, 2004b). The overall transfers from agricultural policies to farmers individually, the sector as a whole (general services), and net consumer food subsidies, financed both by taxpayers (budgetary payments) and consumers (maintaining domestic market prices above those on world markets), as measured by the Total Support Estimate (TSE) was estimated at US$324 billion (€330 billion) on average in 2001-03 compared to US$304 billion (€276 billion) on average in 1986-88. This represented, respectively, 2.3% and 1.2% of OECD GDP.

Of the TSE, the support going to farmers – the Producer Support Estimate (PSE) – was estimated at US$238 billion (€243 billion) on average in 2001-03 compared with US$241 billion (€219 billion) on average in 1986-88. This represented, respectively, 31% and 37% of gross farm receipts from commodity production in the OECD area.

The PSE includes the whole range of policy measures – from those very closely linked to specific commodity production, to those for which agricultural production is not a requirement. As shown in Figure 15.1, those policies deemed to be most production and trade distorting (market price support plus payments based on output and inputs) accounted for 77% of support on average in 2001-03, down from 90% on average in 1986-88, as measured by the percentage PSE. Comparing the US and EU for the period 2001-03, with the OECD for reference, Figure 15.2 shows that while the share of the most distorting policies accounts for roughly the same share of the percentage PSE (around two-thirds), in the EU area and livestock payments are significant, while payments based on historical entitlements are important in the US. However, under the reforms of the EU's Common Agricultural Policy (CAP), a significant further step towards decoupling support from production decisions was agreed in 2003 whereby support will generally be linked to historical entitlements and will therefore remain largely linked to farm size.

A number of key messages emerge from a review of the recent data on support to agriculture. Firstly, while there has been a slight reduction in the level of support as measured by the %PSE, the reduction has not continued in the most recent years. However, the biggest change has been in the shift towards less production and trade distorting policies. For example, in 1986-88 average domestic prices paid by consumers of farm products at the farm gate were 63% above those in the world market, while in 2001-03 that ratio had fallen to 37%. There are also wide year-on-year variations in support that mainly mirror the non-transmission of world price movements to domestic markets. Secondly, there has been and continues to be a wide variation in the levels of support across OECD countries (ranging from a %PSE of under 5% in Australia and New Zealand to

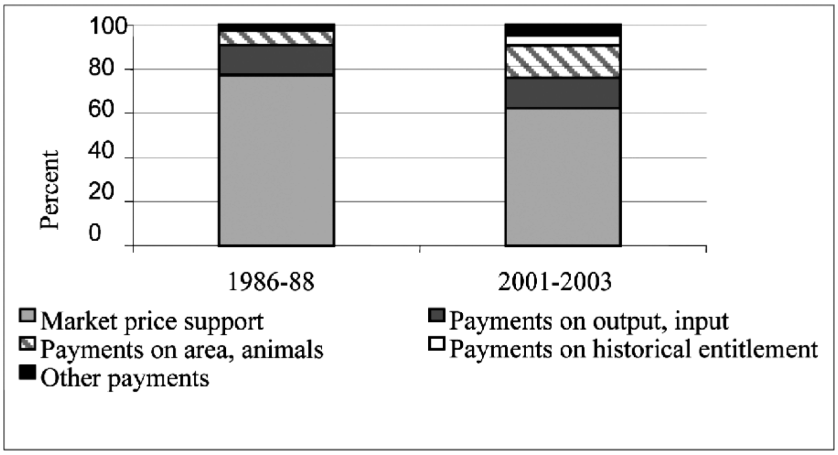


Figure 15.1 Share of agricultural support from different policy measures in the OECD (1986-88 and 2001-03)
Source: OECD, PSE/CSE database.

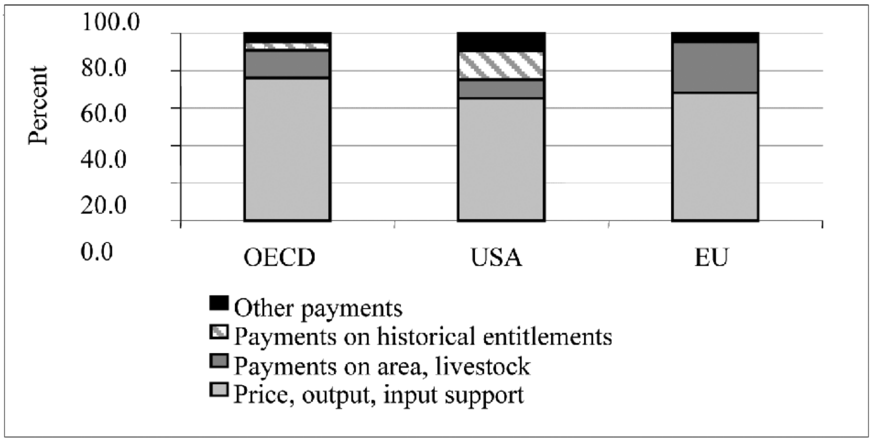


Figure 15.2 Share of agricultural support from different policy measures in the OECD, USA and EU (2001-03)
Source: OECD, PSE/CSE database.

over 55% in Iceland, Japan, Korea, Norway and Switzerland, with the EU at 35% and the US at 20% on average in 2001-03) and commodities (ranging from under 10% for wool and eggs to over 45% for rice, sugar and milk, with wheat at 37% and beef and veal at 33%). Thirdly, there is a wide and increasing use of forms of supply controls, cross-compliance measures and agri-environmental measures within the suite of policy measures affecting agriculture.

How do these general agricultural policy developments relate to land use and climate change? Firstly, research in the OECD has demonstrated that production-linked policies have the effect of expanding the extensive margin, keeping land in production, and of raising the value of land, which in turn has increased incentives to increase the intensity of its use (OECD, 2001b). Secondly, many policies in place in OECD countries - including commodity price guarantees, disaster and emergency payments, and safety nets - reduce the risk to farmers of producing in vulnerable conditions (such as in flood or drought prone areas). This can dampen the incentive to farmers to take into account climate change risks in their decision-making (OECD, 2000a; OECD, 2003b).

Agri-environmental policy measures

It is difficult to accurately quantify the net transfers to agriculture arising from agri-environmental measures, and to evaluate the efficiency and effectiveness of policies addressing the environment in agriculture, although the OECD has undertaken a preliminary comparative assessment for OECD countries (OECD, 2003c; OECD, 2003d; OECD, 2004c). Some caution is necessary here. Firstly, many policy measures (such as supply controls, cross-compliance, payments per head of livestock and area) are intended to achieve a number of objectives, both in terms of production and the environment. Secondly, many of the measures take the form of regulations or cost-sharing agreements between farmers and the government, which involve a mix of costs imposed on farmers and support payments. Thirdly, many of the general services provided to agriculture (such as research, development, education and information) include elements related to improving environmental performance, but it is not easy to factor them out of the total expenditures. Figure 15.3 shows the generally increasing trend in expenditure on explicit, budgetary-financed agri-environmental payments to farmers over the last decade in selected OECD countries.

LAND USE, CLIMATE CHANGE AND BIOMASS

Agriculture accounts for around 40% of the land area in OECD countries on average. Although land used for agriculture has been falling in most OECD countries, it is being used more intensively, often due to the effects of agricultural policies. Moreover, environmental pressure on land (and water) will rise because of the need to globally supply enough food to feed up to an estimated 50% more people each consuming around 14% more calories on average by 2050. A significant effort has been undertaken over the last decade to measure the effects of agriculture on the environment through agri-environmental indicators (OECD, 2001c). Figure 15.4 shows the changes in land used for agriculture between the mid-1980s and 1990s. This shows that in the majority of countries, land has been moving out of agriculture over the recent period.

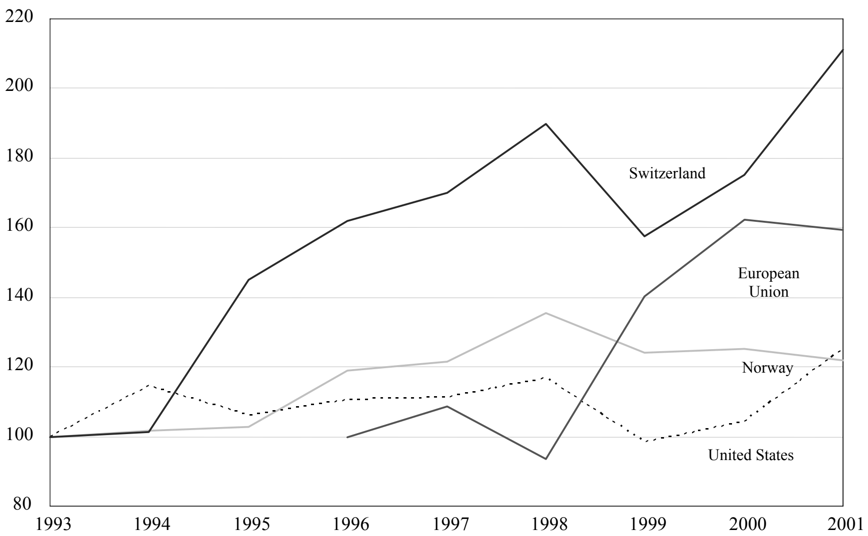


Figure 15.3 Trends in agri-environmental payments in selected countries, 1993-2001 (1993=100, national currencies)
Source: OECD, PSE/CSE database.

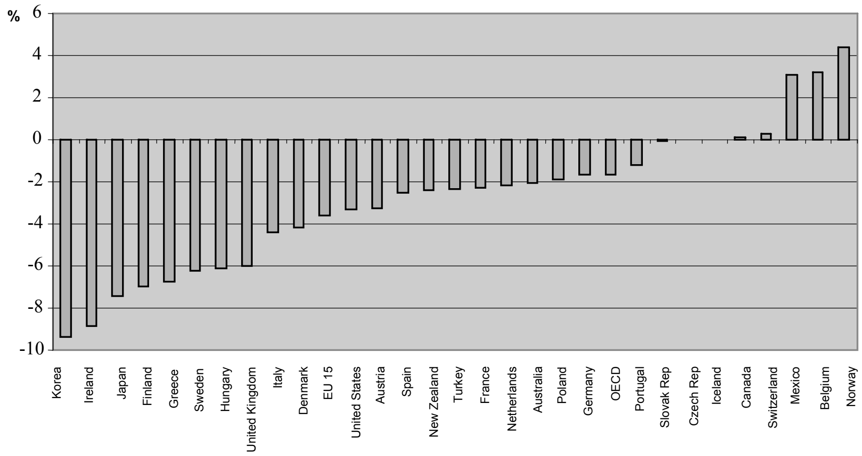


Figure 15.4 Change in agricultural land area 1990-92 to 1991-2001
Source: FAO database.

Where did the retired agricultural land go? Figure 15.5 shows the uses to which it was put in selected OECD countries. Forests, wetlands and built-land accounted for major uses of converted agricultural land, but the shares vary considerably among the OECD countries shown.

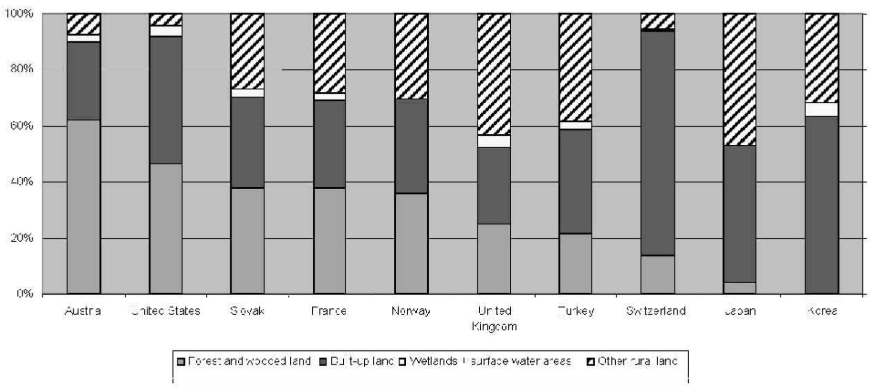


Figure 15.5 Use of land converted from agriculture from the mid-1980s to mid-1990s (as % of total agricultural land converted)
Source: OECD, Agri-Environmental Indicator database.

With regard to greenhouse gas (GHG) emissions and climate change, agriculture accounts for only a small share of emissions, but there are wide country variations. On average, in OECD countries, agriculture accounts for only around 7% of total GHGs, but in New Zealand, in particular, the share is around one-quarter. Overall, there has been a very small increase in the collective OECD country agricultural emissions over time as a whole, but with a wide disparity across countries (Figure 15.6).

Perhaps more important for policy is the fact that agriculture contributes to carbon sequestration, which offsets to some extent the GHGs emitted. Croplands contain less than 2% of the world's vegetative carbon but account for about 10% of soil carbon. Thus all lands subject to agricultural management account for a notable share of soil carbon (Smith, 2002). In some OECD countries policies, in particular carbon-trading, are being implemented or developed to meet the commitments under the Kyoto Protocol to reflect the different balances between emissions and sequestration across and within sectors. Agriculture can earn carbon credits, which enhances income sources for farmers, but policy has not yet been well worked out in this respect.

Climate change and weather variability are likely to affect the pattern and location of agriculture, a phenomenon already beginning to be observed in many countries, which are experiencing severe weather events. However, some agricultural policies can encourage farming in areas where there are high risks of climate-related events (flooding or drought) through providing forms of income compensation or underwriting of insurance risks. On the other hand, other policies that encourage the conservation of water through agriculture can mitigate the adverse effects of climate change on agriculture. In the first case policies can hinder adjustment to climate change risks in agriculture, while in the second case they can help adjustment.

Figure 15.6 Gross emissions of greenhouse gases from agriculture from 1990-92 to 1999-2001 (% changes)
Source: OECD, UNFCCC and EUROSTAT databases.

A series of commodity sector studies (on pigs, dairy and arable crops) in the OECD has explored the effects of agricultural policy reform agricultural trade liberalisation on the agri-environment and the effects of environmental regulations on competitiveness and trade. Among the results, the studies show that reform and trade liberalisation is associated with changing land use patterns, which lead to shifts in the location and type of production, and different patterns of GHGs and carbon sequestration. In broad terms, moving from areas with higher levels of support and protection, characterised by more intensive production systems to areas with lower levels of support and protection, characterised by less intensive production systems provide net global reductions on GHGs (OECD, 2000b; OECD, 2004e; OECD, 2005 forthcoming).

With regard to biomass, there is increasing interest in OECD countries to find alternative, sustainable forms of energy as well as alternative and diverse sources of income for farmers. Projections to 2030 (by the Paris-based International Energy Agency) show that growth rates in bioenergy and materials from agriculture have been higher than for fossil fuel products, albeit from a low base. The overall market share of biomass from agriculture (in terms of its contribution to energy and material needs, and in relation to production for food) is likely to remain small in the near term, although with considerable variation across countries. At present, at current relative prices for food and energy, biomass is not generally a financially viable activity. However, taking into account the net environmental effects that are not currently factored into prices and values, an economic case can be made to support the conversion of some agricultural land to biomass. The economic case becomes stronger with the development of technology, lowering the relative costs of biomass from agriculture. It should be noted that large increases in land producing biomass could adversely impact food prices (by reducing the production of food crops). Associated environmental effects (on soils, biodiversity and landscapes) depend on which crops are planted. The land requirement for biomass will mainly depend on improvements in biomass crop yields, the price of land (competition for other uses) and markets for by-products.

At present, in OECD countries, financial incentives are the main policy instruments employed to encourage biomass: production support, tax credits, investment subsidies, and ‘feed-in tariffs’. Good practice guidelines and research and development programmes are being developed, while some governments are starting to establish carbon markets with credits to biomass producers for fossil fuel displacement and GHG sinks. An OECD workshop looked at the environmental, economic and social aspects of biomass from agriculture at a workshop in 2003 (OECD, 2004e).

CONCLUSIONS

There appears to have been an overall improvement in environmental performance in agriculture. However severe local and regional problems exist and future pressures on land and water resources are likely to be significant. The substantial body of recent work in the OECD - and elsewhere - on the linkages between agriculture and the environment has laid the foundations for drawing some policy conclusions. The overall architectural framework of analysis and many of the building blocks have been established - such as identifying the characteristics of (and support arising from) policies in place and developing indicators of the effects of agriculture on the environment. But explaining the environmental effects of different policies or policy mixes, identifying policy drivers from other factors influencing the environment, and tracking the effects of changes in policies on management practices and environmental outcomes, in order to allow cross-country comparisons for the evaluation of policies, are at an early stage. The analysis of the cause-effect linkages between policy measures and environmental outcomes is complex and too little is yet known to make strong recommendations on appropriate mixes of policy measures and market actions or to make definitive judgments about 'good policy practice'.

The environmental improvement has involved costs that would have been lower in the absence of output and input linked support measures. In other words, the policies may have been effective, but there have been trade-offs and in some cases, inefficiencies. It is unlikely that for all countries there is a unique or optimal mix of market and policy solutions to achieve the most efficient environmental outcomes due to different agro-ecological conditions, farm structural parameters, societal preferences and histories across the OECD.

A few general policy requirements can be made: phasing out production distorting agricultural policies and get the prices right so that policy incentives work in harness with the market; assessing and quantifying the public's demand for the environment (for ecosystem services, pollution and resource use); targeting policies to environmental outcomes as directly as possible; ensuring coherence between agricultural, environmental, land use and territorial policies; and facilitating research and development, education and information that keeps future agriculture on the path of sustainable agriculture. Agricultural policies alone will not deliver an optimal allocation of land use to maximise net environmental benefits consistent with producing economically efficient agricultural production.

In conclusion, the overarching aim is to appeal to the self-interest of farmers, governments and the public. The challenge is not only to better adapt markets to achieve desired economic, social and environmental outcomes; or to design and implement appropriate complementary policies, while phasing out harmful subsidy policies and avoiding unintended and undesired spillovers. It is also to tap into the often-latent reserves of goodwill and co-operation that exist among farmers and other stakeholders to ensure that farmers fulfil their role as good stewards of the environment.

REFERENCES

Legg, W. (2003) Presidential address - agricultural subsidies: measurement and use in policy evaluation. *Journal of Agricultural Economics*, Vol. 54 (2), pp.175-201.

OECD (1995) *Sustainable Agriculture – Concepts, Issues and Policies in* OECD Countries. Paris, France.

OECD (2000a) *Income Risk management in Agriculture*. Paris, France.

OECD (2000b) *Production Effects of Agri-Environmental Policy Measures: Reconciling Trade and Environment Objectives*. Paris, France.

OECD (2001a) 'Agriculture'. In *Sustainable Development – Critical Issues.* Paris, France, pp. 397-425.

OECD (2001b) *Market Effects of Crop Support Measures*. Paris, France.

OECD (2001c) *Environmental Indicators for Agriculture Volume 3: Methods and Results*. Paris, France.

OECD (2003a) *Methodology for the Measurement of Support and Use in Policy Evaluation* on OECD website at www.oecd.org/agr/support.

OECD (2003b) *Agricultural Policies in OECD Countries – Monitoring and Evaluation 2003*. Paris, France.

OECD (2003c) *Environmentally Harmful Subsidies: Policy Issues and Challenges*. Paris, France.

OECD (2003d) Agri-environmental policies in OECD countries. In *Agricultural Policies in OECD Countries – Monitoring and Evaluation 2003*. Paris, France.

OECD (2004a) *Agricultural Policies in OECD Countries: At a Glance - 2004 Edition.* Paris, France.

OECD (2004b) Agricultural support: how is it measured and what does it man? *OECD Policy Brief*. Paris, France.

OECD (2004c) *Lessons Learned from OECD Work on Agriculture and the Environment.* Paris, France.

OECD (2004d) *Agriculture, Trade and the Environment: the Dairy Sector*. Paris, France.

OECD (2004e) *Biomass and Agriculture: the Vienna Workshop*. Paris, France.

OECD (2005 forthcoming) *Agriculture, Trade and the Environment: the Arable Crop Sector*. Paris, France.

Smith, C.A.S. (ed.) (2002) *Soil Organic Carbon and Agriculture: Developing Indicators for Policy Analyses*. Proceedings of an OECD expert meeting, Ottawa, Canada October 2002, Agriculture and Agri-Food Canada, Ottawa, Canada and OECD, Paris, France.

Institutional and Organizational Change: Biosphere Greenhouse Gas Management in Canadian Northern Great Plains Agriculture

16

Murray Fulton, Patricia L. Farnese, Bob MacGregor, Marie Boehm and Alfons Weersink

INTRODUCTION

There appears to be a consensus that the climate of the future will be warmer (IPCC, 2001), although it is also recognized that there is a great deal of uncertainty about what will occur 20 to 50 to 100 years from now. For the northern Great Plains of North America, the pressures of climate change are likely to have a major effect on the agriculture of the region. For agriculture on the Northern Great Plains of Canada, greenhouse gas mitigation efforts and climate change responses will result in significant changes to the physical landscape (e.g., major shifts in land use) and to production practices (e.g., new technologies and crops) (see Chapter 14). The changes that agriculture will undergo are not limited to land use, however. The organizational structure of agriculture can be expected to change, as well as the underlying economic and legal foundations of society and the economy in Canada.

The purpose of this chapter is to examine the changes in the organizational structure of agriculture and in the institutions governing agriculture that are likely to occur over the next 50 to 75 years. These changes will take a number of different forms, including changes in society values, new regulations and policies, and new organizational structures. Particular attention is paid to the changes required to encourage successful adaptation (e.g., incentives to encourage experimentation and risk taking) to changes in the physical and policy environments. Changes in organizations and institutions are often ignored when considering climate change. However, as will be argued in this chapter, failure to consider these changes will not allow a full understanding of how climate change will affect agriculture and land use patterns. Over the short term, for instance, when institutions are largely fixed, the policies available to deal with climate change will often be limited. Over the medium to long term, however, changes in society values will allow for a much broader range of policy options.

As is the case in the overall book, this chapter is based on the presumption that major transformations will occur in agriculture. The chapter contributes to

F. Brouwer and B.A. McCarl (eds.), Agriculture and Climate Beyond 2015, 279-289.

the book by focusing on the broad institutional and industry specific structural changes that will need to be made to allow this transformation to occur. These changes will not happen in the next five years, but will really begin to take effect after 2015.

The chapter is structured as follows. The next section of the chapter outlines the climate changes and resulting land use changes that form the basis for the subsequent analysis and discussion. The chapter then examines some of the institutional changes that are likely to occur, first in the short term and second in the medium to long term. This exploration is followed by an examination of the structural changes in agriculture and of whether the agricultural production system will be able to maintain large stocks of carbon and nitrogen if it is required to close the cycles for these elements. The chapter concludes with a discussion of the appropriate public response to the pressures and issues that can be expected to emerge.

BACKGROUND - LAND USE IMPACT OF CLIMATE CHANGE

Given the tremendous uncertainty that exists about future climatic conditions that will exist globally and on the great northern plains of North America, it is necessary to stress that the analysis in this chapter is predicated on a particular set of beliefs about what the future will look like. Specifically, it is assumed that temperature and the rate of evapo-transpiration on the northern Great Plains will increase over the next 50 years. The result will be a higher probability of drought, a northward migration of grasslands and forests, and a risk of a loss of water flow in the major rivers that flow from the Rocky Mountains.

As is outlined in Chapter 14, these changes will cause a significant change in land use on the northern Great Plains. In the short term (e.g., next 10 years), the major impact will be a greater sequestration of carbon in soils as farmers more fully adopt zero-till and other similar agronomic practices. The pressure for this change will come largely from economic pressures to conserve water and soil organic matter and thereby increase yields and economic returns, rather than as a response to directly reduce greenhouse gas emissions.

In the medium term (e.g., the next 20 - 30 years), crop production can be expected to shift from the southern portion of the northern Great Plains (the brown soil zone) where it will be replaced by pasture and forage. Crop production can be expected to continue in the dark brown and black soil zones, with a wide range of pulses and oilseeds produced alongside cereals. Hog production will increase and will become more integrated with crop production. Along the northern edge of the northern Great Plains (the gray soil zone), land use can be expected to shift from crops to tree production. These general trends can be expected to continue over the long term (e.g., the next 50 - 75 years). Depending on relative prices and advances in technology, a portion of the land may be used for the production of crops that go into energy production rather than food/feed for human and animal consumption (see Chapter 14). Also, the trend towards greater integration of crop and livestock production can be expected to continue as pressures increase on agriculture to close the N and C cycles (i.e., making agriculture neither a net supplier nor user of nitrogen and carbon).

These long-term land use changes will be associated with significant changes in the concerns people have about greenhouse gas (GHG) emissions and climate change, which in turn will alter some of the major institutions in the economy and may dramatically affect the organization of agricultural production. The next section examines these changes.

INSTITUTIONAL AND ORGANIZATIONAL IMPACT OF CLIMATE CHANGE

As Uphoff (1993) indicates, institutions are 'complexes of norms and behaviors that persist over time by serving collectively valued purposes'(p. 64). Examples of institutions include the rules of civil and criminal law. Institutions will be affected by climate change and climate change mitigation, in large part because these developments affect the collectively valued purposes of society (i.e., the things that society values). In the short run, institutional change is typically small – as will be argued below, climate change is no different. Over the medium to long term, however, the nature of climate change can be expected to have some fairly significant institutional and organizational impacts. The most immediate driver of institutional change in Canada is the Kyoto Protocol (KP), which Canada ratified in December 2002. To meet its KP requirements, Canada is looking at agriculture, as well as other sectors such as forestry, as a possible source of GHG emission reductions through the sequestration of carbon in the soil. Direct efforts, however, to reduce GHGs in agriculture over and above a 'business-as-usual' case are likely to be limited over the short and perhaps even the medium term due to the lack of incentives for farmers to enter into a carbon market (Fulton et al., 2005). The subsequent lack of reduction in GHGs over and above what could be expected in the absence of the KP is a direct consequence of the likely lack of any significant change in Canada's underlying legal and economic institutions over the short term. In the medium to long term, however, these institutions can be expected to change, which in turn will lead to additional reductions in agricultural GHG emissions. Over both the short and the long term, farmers and others in agriculture will have to adapt. The nature of this adaptation will be critical to future reductions of GHGs.

Short term institutional changes

In the short term, the most important institutional changes in Canada connected to climate change are the ratification of the KP and the introduction of a carbon offset market as part of this ratification. Briefly put, a carbon offset market is a market in which firms and organizations that wish to emit more carbon than they are permitted can purchase additional permits, and in which firms and organizations that have permits in excess of what they emit can sell their permits (for information on how a carbon offset market in Canada might function, see Government of Canada, 2003a).

The ratification of the KP represents an institutional change because it alters the importance that Canadian society places on GHGs and climate change. As will be argued below, this change is very small in the short term. The introduction of a carbon market represents an institutional change because it changes the importance that society attaches to GHGs by creating property rights for GHG permits, and it changes the rules and mechanisms by which GHGs are managed and controlled.

The magnitude of both these institutional changes are likely rather modest, at least in the short run. Carbon offset markets are one of the mechanisms by which Canada plans to meet its KP commitments. As Böhringer and Vogt, (2003) and Grubb et al. (2003) argue, the KP is unlikely to impose substantial compliance costs on the ratifying countries, including Canada. The low compliance costs are a direct result of the U.S. not being a signatory to the KP and of the large amount of so-called hot air that is available from the Eastern European economies,[1] both of which result in a low expected price of carbon in the short term. The result is that while the signing of the KP and the introduction of a carbon market represent a change in values towards GHG mitigation, the magnitude of this change, at least for the time being, is small. It is only when significant increases in carbon prices arise and adjustments occur can the KP and the carbon market that it has fostered be said to be a major institutional change.

For agriculture, if carbon offset prices are as low as is expected, most farmers are unlikely to find it economically advantageous to sign carbon contracts to sequester carbon, since the direct cost of this sequestration is likely to exceed the carbon price (Fulton et al., 2005). In addition, the economics of a farmer entering into a carbon offset contract are not straightforward. Even if a farmer believes her costs of sequestering carbon are less than the price of carbon offsets, this does not mean that she will sign a contract to sequester carbon. Because of uncertainty over what might happen in the future and the difficulties of getting out of a carbon contract, farmers may decide, by not signing a carbon contract, to keep their options open until further information is available. The only way a farmer may be willing to give up this option is if the returns from the carbon contract are significantly greater than the costs of sequestering carbon. At the current time, however, the demand for carbon offsets is likely to be insufficient to cause the price increases necessary to entice farmers (and others, such as those who might plant trees) to enter the carbon offset market (see Vercammen, (2003) for additional details).

Although farmers may not sign offset contracts, they are likely to nevertheless sequester carbon. Specifically, farmers are likely to find it economical to continue to adopt practices such as zero-till, and in doing so sequester carbon, regardless of whether a carbon offset market exists or not. Zero-till provides substantial economic benefits to farmers, as the adoption numbers indicate. The Soil Conservation Council of Canada estimates that roughly 50% of the cultivated acres on the Canadian Prairies and Peace River area are currently

[1] Hot air refers to the reduction in emissions that took place in these economies since 1990. This decline in emissions was due to the decline in economic activity that these economies experienced as they moved from a centrally planned economy to a market-based economy. These emission reductions can be sold to countries and firms wishing to purchase carbon offsets.

under zero-till. The 2001 Census of Agriculture reports that 31% of seeded acreage was seeded using zero-till, while another 31% was seeded using low-tillage techniques (Statistics Canada. 2003).

The use of zero- and low-till, along with new varieties of oilseed and pulse crops, has enabled farmers in the Northern Great Plains to grow a wider range of crops, to expand their total aggregate crop production and to maintain viable farming operations. Continued price-cost pressures and a growing realization by farmers that traditional tillage practices are not as profitable (see Lafond (2003) for evidence on this point) will likely lead to continued adoption of this technology.

Medium to long term institutional changes

Over the medium and long term, and as was the case in the short term, the most important factor in reducing GHG emissions is likely to be technological change. In agriculture, the key incentives for developing and investing in GHG reducing technologies will be higher prices for carbon, regulations on GHG emissions, and the push by farmers for technologies that lower their cost of production or increase their yields. The effectiveness of these first two incentives in reducing GHGs is closed linked to institutional change.

Before examining these first two incentives, consider the incentive that farmers have for technologies that lower their cost of production or increase their yield. As was the case with zero-till in the past, a number of the technologies that increase returns will also reduce GHG emissions. GHG emissions are reduced when carbon is more efficiently managed (e.g., soil organic matter is increased, with the resulting increase in yield potential), which in turn leads to higher returns. Thus, even without increases in carbon prices and/or the imposition of regulations around GHG emissions, farmers can be expected to reduce GHG emissions in the normal process of striving for greater efficiency and profitability. In addition, farmers may have an incentive to indirectly sequester carbon as a result of agricultural policies directed at improving environmental management or land conservation.

An incentive also exists to develop new GHG reduction technologies if there is an expectation that carbon offset prices are likely to rise in the future and/or that regulations around GHG emissions are likely to become more stringent. Currently, however, the GHG related regulations in place provide limited incentives to develop GHG reducing technologies. As was pointed out in the previous section, the price of carbon is expected to be low over the short term. In addition, the Canadian government has indicated that it will not allow the price of carbon to rise above \$15 per tonne CO_2. While the Government of Canada has indicated that it may use covenants to get large emitters to reduce their GHG emissions and that subsidies may be provided to some groups to achieve this end (Government of Canada, 2003b), these steps fall short of the actions that could be undertaken to reduce GHGs. For instance, the idea of a carbon tax has largely been put aside and there is currently no legislation in place that requires firms or industries to meet stringent GHG targets.

Price increases and more stringent regulations will only materialize if the legal system supports such changes. The legal system, however, typically reacts to and reflects the changing needs and values of society, rather than acting as an architect of these values. Since the policies and regulations in place fall short of what is possible, the conclusion is that, at least at the current time, the Canadian public is not ready to push for a large-scale reduction in GHGs, unless of course it could be done fairly costlessly.

There are many reasons why public sentiment and values are not supportive of a more direct and aggressive GHG emission reduction and attention to climate change issues. One reason is that a high degree of uncertainty exists regarding what the future might look like with respect to GHG emissions and climate change, and thus no consensus exists as to what precisely should be done to address the problems that may arise. For instance, as outlined above, while there is some consensus that the climate of the future on the northern Great Plains will be warmer and drier, this view is not universally shared. Nor is there consensus on the climatic impact of reducing GHG emissions.

Secondly, in Canadian law there is no formalized recognition of a public right to be free from the negative effects of climate change. Put somewhat differently, the right to pollute – currently an unchallenged component of the bundle of rights contained in private property – is in no way limited by a public right to be free from its harmful effects, unless individuals can show personal damage. Thus, the primacy that Canadians afford to private property makes problematic the introduction of regulations addressing GHG emissions. Third, other issues, such as health care, are much more immediate and thus have become the focus of people's attentions.

In order for public values to change significantly to support much more direct and aggressive GHG regulation, the impacts of GHG and climate change will have to be become more definitive and will have to more directly affect the lives and well being of Canadian citizens. Put another way, only when Canadian citizens believe that a problem exists that affects them significantly and that well understood strategies exist that can be used to address the problem will the legal system change in such a way so as to support a more assertive approach to GHG management. When the legal change occurs, the outcome can be expected to be higher prices for carbon and more stringent policies for the management of GHGs. It is only when such impacts really start to take effect that farmers and others involved in agriculture will actively explore new ways of reducing net GHG emissions. Otherwise, the reductions will result from the adoption of practices to increase farm profits or to satisfy government programs that encourage land conservation and improved environmental management, practices that have the side benefit of reducing GHGs and/or providing other environmental benefits.

Structural changes in agriculture

Climate change will not only affect the institutions that govern agriculture and the rest of the economy; it will also have an impact on the manner in which agriculture is organized. The impact from climate change will be in addition to the significant structural changes that will otherwise occur. For instance, the decrease in the number of farms and the increasing scale of what might be called the commercial farms that has occurred in the northern Great Plains over the last 100 years is likely to continue. In addition, the relationship of the farm operator with the rest of the agriculture and food system is likely to continue to evolve. In particular, farm operators are likely to become less and less independent and more and more integrated with the rest of the system. This greater integration will likely continue to occur through the use of contracts and in some cases outright vertical integration (Boehlje, 1996; Hobbs and Young, 2001).

These structural changes are likely to be magnified by climate change, and by the legal and market changes that climate change is likely to induce at some point in time. Assuming the northern Great Plains do become warmer and drier, the price–cost margins in crop production are likely to be further squeezed.[2] The result will be even greater pressure on farm operators to raise yields and to increase their scale of operations. For farmers unable to move to a larger scale, the price–cost squeeze will make off-farm income increasingly attractive. The result is a continuing movement of farm size to a bi-modal distribution. Although small farms will continue to exist, overall farms will become larger and the number of farms will continue to fall.

Accompanying this fall in farm numbers will be a continued reduction in the rural population. This decrease in the farm and rural population is likely to be particularly significant in the brown soil zone. Given the low farm and rural population currently in this area, further reductions may result in a virtual abandonment of this area in 50 - 75 years. The dark brown and black soil zones are likely able to support a larger (at least relative to the brown soil zone) farm and rural population, in part because of the greater integration of hog and crop production systems that is predicted.

If the impact of climate change over the next 30 - 50 years is significant enough that that it engenders changes in the legal system that support more aggressive reduction strategies, it is expected that the structure of agriculture will be altered even further. For instance, suppose the pressures to control GHGs mount to the point where industries are legally required to close their N and C cycles. This requirement might arise as a way of ensuring that GHG emissions are significantly reduced so that GHG concentration can be stabilized (as the IPCC (2001) notes, GHG concentrations will continue to rise when GHG emissions are positive). To address this requirement, production in agriculture is likely to become even more specialized and integrated than it would be otherwise.

The most likely way of closing (or even partially closing) the N and C cycles within agriculture is to closely integrate crop and livestock systems. With this integration, manure from the livestock systems would be used as nutrients for the crops, which in turn would produce the feed used by the livestock. The manure

[2] As a consequence of technological adoption and high rates of productivity growth in primary agriculture in most countries, the long-term price trend of almost all agricultural commodities is downward. The implicit assumption behind the analysis of this chapter is that this long-term price decline will continue as a result of continued yield increases and reductions in the cost of production. For farmers on the Great Northern Plains, the result of this continued price decline will be a further cost-price squeeze.

could also be used to produce methane, which could be used to power livestock facilities and potentially even machinery used in crop production.

Assuming the economic and legal incentives are large enough, agri-business firms will begin to organize the production of crops and livestock in such a way that N and C are used in the most efficient manner possible. Doing so will require further structural transformations in agriculture. In addition to the increased vertical integration and coordination that will continue to occur, agricultural firms will be increasingly integrated horizontally across the crop and livestock systems. At the same time, the need for size economies in production will mean a continued specialization in large-scale production units.

Thus, under the scenario sketched out above, it is expected that agriculture will increasingly be dominated by large integrative organizations (these organizations could be corporations or co-operatives) that coordinate the production of crops and livestock in such a way that N and C are efficiently managed. This coordination may occur through contractual arrangements with the crop and livestock operators, or it may occur through outright ownership of both the crop and livestock units. Regardless of the precise organizational structure used to ensure coordination, the operators of the crop and livestock units will likely be given little leeway to make their own production and technology decisions. Instead, these decisions will be made at a central point so as to balance the recycling of N and C with the need to earn a profit on the operations.

It is very unclear what the impact of these changes will be on the overall stock of C and N in the agricultural sector. Even if the analysis is correct in assuming that social, economic and legal pressures will build to close the N and C cycles in agriculture (as well as in all other sectors), the question still remains as to what stock levels of N and C can be supported when the systems are closed. This question is important because the current technology (i.e., zero-till) used to sequester carbon – and the one most likely to be used over the short to medium term – involves the input of N from outside sources (e.g., chemical fertilizers). If N cannot be added from the outside, but must be supplied from within the agricultural system, the question arises as to whether sufficient N can be made available to support a high carbon stock. Clearly a great deal of coordination between livestock operations and cropping operations (including the use of pulse crops and forages) will be required to make the best use of the available N. However, even with this coordination, the overall level of carbon stocks may have to fall in order to meet the objective of closing the N and C cycles.

If this is the case, then agriculture may emerge as a net contributor of carbon in the future. If this outcome were to be likely, the question needs to be asked as to whether it is desirable from a policy perspective to encourage the sequestering of carbon over the short to medium term if it is going to be released subsequently over the longer term.

ADAPTATION AND PUBLIC POLICY – WHAT TO DO TODAY?

This chapter has explored some of the changes in the organizational structure of agriculture and in the institutions governing agriculture that are likely to occur over the next 50 to 75 years. This exploration has been based on a number of assumptions regarding the nature of climate change and the values and beliefs of Canadian society. As the chapter has highlighted, a great deal of uncertainty – and even ignorance – exists around the future of agriculture in the northern Great Plains.

Given this uncertainty, is very difficult to plan for the future and to implement policies based on climate change. For instance, as was discussed in the last section, is it desirable to encourage the sequestration of carbon today if this stock cannot be maintained well into the future? Is enough known about the manner in which nitrogen moves in physical systems to be confident that efforts taken today will actually result in reduced N_2O emissions. Even when the appropriate policies might be known, many of them cannot be implemented until society's values change in such a way that these policies are acceptable to the Canadian public. How and when will the values of society change? Will other issues arise that will override those surrounding GHGs and climate change?

Given this uncertainty and ignorance, perhaps the only appropriate policy is one that encourages adaptation. Adaptation is of the utmost importance in a world of change.

As was discussed earlier in the chapter, the technology (i.e., zero-till) that is most likely to be used to address GHG mitigation over the short to medium term is one that was developed 25 – 30 years ago. It is highly likely that the situation 25 – 30 years hence may be similar, where the technologies used then will be ones that are developed within the next five to 10 years.

In this vein, the management techniques and technologies that will be used in the future are likely to be ones that will be developed to address long-term physical and economic constraints associated with growing crops on the Northern Great Plains. To generate these new management techniques and technologies, it is necessary to promote research and experimentation. This research and experimentation must be undertaken at the macro level by government and agri-business firms along with efforts at the micro level by farmers. As the case of zero-till indicates (zero-till was initially explored and adopted by farmers), farmers may be in the best position to recognize the problems that need to be addressed, as well as the solutions to these problems.

While the current organizational structure of agriculture still provides incentives for farmers to innovate and adapt, this situation may change as the structure of agriculture changes. In particular, the more vertically integrated is primary agriculture with the other parts of the food system, the less ability farmers may have to experiment on their own with such things as new tillage methods. As well, greater horizontal integration – as crop and livestock systems are managed to make the most efficient use of N and C – may restrict a farmer's incentive and ability to innovate.

Recognizing that experimentation is required requires recognizing that failure is going to occur. Many of the experiments that will be tried are unlikely to be successful. Yet these failures must be allowed to take place. Given the large uncertainty that exists in what might happen 20 or 50 years from now, it is impossible to know ahead of time which results and which research paths should be taken and which ones should not be taken. Thus, a strategy that encourages adaptation is one that must allow failure. In a similar vein, flexibility is required.

Given the large uncertainty that exists over the future course of Great Plains agriculture, it is imperative that the agricultural system not be locked into only one or two ways of operating.

Finally, the promotion of adaptation and innovation means that attention must be paid to existing policies to ensure that they do not penalize the early adopters. Thus, programs such as crop insurance need to be constantly examined to make sure that experimentation is fostered, not discouraged.

To conclude, the agricultural economy of the Northern Great Plains, like that in almost all parts of the world, has been dramatically transformed over the last one hundred years, a transformation that continues today. As this book argues, climate change, and the resulting land use changes that will result from it, can be expected to further transform agriculture. This chapter has focused on the broad institutional and industry specific structural changes that will need to be made to both allow and to encourage this transformation to occur. The ability of the sector to respond to the new environment in which it finds itself will depend on the new technologies that are developed, the institutional structures that are in place, and the manner in which the sector is organized. Over the short term, the sector will have to rely largely on existing technologies to adapt to climate change. Over the medium term and long term, the response of the sector will be determined by new technologies that are developed. To ensure a choice from a variety of technologies, considerable experimentation and flexibility is required, since it is virtually impossible to predict today what will be required for the sector over the long term.

REFERENCES

Boehlje, M. (1996) Industrialization of agriculture: what are the implications? *Choices*, Fourth Quarter (4), pp. 30-33.

Böhringer, C. and C. Vogt (2003) Economic and environmental impacts of the Kyoto Protocol. *Canadian Journal of Economics*, Vol. 36 (2), pp. 475-94.

Fulton, M.E., M. Cule and A. Weersink (2005) Greenhouse gas policy and Canadian agriculture. *Current Agriculture, Food and Resource Issues*, Vol. 6, pp. 1-11. Website: www.cafri.org.

Government of Canada (2003a) Offset System Discussion Paper. http://climatechange.gc.ca/english/publications/offsets/cover.html.

Government of Canada (2003b). *Climate Change Plan for Canada*. http://www.climatechange.gc.ca/plan_for_canada/plan/index.html

Grubb, M., T. Brewer, B. Müller, J. Drexhage, K. Hamilton, T. Sugiyama and T. Aiba, (2003) *A Strategic Assessment of the Kyoto-Marrakech System: Synthesis Report*. The Royal Institute of International Affairs, Sustainable Development Program, Briefing Paper No. 6, London. June. Website: www.riia.org.

Hobbs, J.E. and L.M. Young (2001) *Vertical Linkages in Agri-Food Supply Chains in Canada and the United States*. Agriculture and Agri-Food Canada. Ottawa Ontario.

IPCC (2001) *Third Assessment Report. Climate Change 2001: Working Group 1: The Scientific Basis*. Website: www.ipcc.ch.

Lafond G. (2003) Long-term direct seeding effects: can we measure them and are they economically important? *The Protector*. Soil Conservation Council of Canada Newsletter, Winter, pp. 6-7.

Statistics Canada (2003) *2001 Census of Agriculture*. Ottawa, Ontario.

Uphoff, N. (1993) Grassroots organizations and NGOs in rural development: opportunities with diminishing states and vanishing markets. *World Development*, Vol. 21 (4), pp. 607-22.

U.S. Department of Agriculture (USDA) (2002) Remarks by Deputy Secretary Jim Moseley, Climate Change Workshop, Department of Energy, Washington, DC, November 18. Release No. 0482.02, Washington, DC, November 21. Available at http://www.usda.gov/news/releases/2002/11/0482.htm.

Vercammen, J. (2003) *Dynamic Economic Modeling of Soil Carbon*. Technical Report # 1-02. Agriculture and Agri-Food Canada. Strategic Policy Branch Contract #01B04-0-C047. Ottawa Ontario, March.

Performance Standards and the Farmer: Design and Application in Greenhouse Gas Mitigation

17

Patricia L. Farnese

INTRODUCTION

Agriculture's impact on the global climate is increasingly becoming understood. Much remains unknown, but from what is known, agriculture can both aid and prevent the release of greenhouse gases (GHG), depending on the land-use pattern adopted. The majority of this volume is devoted to identifying the interactions between agriculture, climate change, and land-use patterns. This chapter moves the discussion to the implementation of policies aimed at the mitigation of on-farm activities that have a negative impact on the climate. At some point in the near future, farmers will be asked or forced to adopt specific land-use practices and a system will be established that evaluates a farmer's performance in this regard. This chapter argues that the form in which the standard used to evaluate the farmer will influence a policy's success.

Without a specific understanding of what farmers will be asked to do under a GHG mitigation scheme, it may appear premature to discuss performance standards. Such a view is short-sighted. The successful use of agricultural land as a carbon sink or the reduction of fossil fuels used in production, for example, will depend on farmer support for the endeavour. Without this support, compliance will be an issue in a mandatory system. It will also impact the level of farmer participation in a voluntary system. This is because performance standards are intrinsically linked with risk. Farmers may not be willing to fully participate in a GHG mitigation scheme if they feel that their participation has a real potential of attracting liability.

Consider the relationship between agricultural lands and GHG sequestration. These lands are known to function as a carbon sink. If this role becomes formally recognized in a greenhouse gas mitigation scheme, it will be the responsibility of farmers to manage land for this purpose. Farmer participation can be voluntary, as in a carbon credit system or a payment-by-result program, or mandated by state legislation. In either system, farmers will be required to undertake land management practices that are designed to mitigate GHG emissions. The integrity

F. Brouwer and B.A. McCarl (eds.), Agriculture and Climate Beyond 2015, 291-304.

of the GHG mitigation scheme will depend on assurances that farmers are meeting an acceptable standard of performance in these GHG management activities.

The source of environmental performance standards applicable to agriculture in law are threefold:

- contracts;
- the common law; or
- government statutes and regulations.

This chapter reviews the different performance standards currently being used in each of these areas to evaluate a farmer's impact on the environment. Examples from Canadian law are provided although the conclusions reached have broad application. The chapter concludes with an evaluation of their appropriateness for GHG mitigation in agriculture. It is hoped that policy-makers will find this chapter informative as they attempt to identify and design effective means to encourage the adoption of appropriate land-use patterns in agriculture.

CONTRACTUAL STANDARDS

Performance standards may pose a number of risks to farmers. The failure to perform under a contract will usually attract damages. The meaning of performance under any contract must be determined on a case by case basis. What constitutes performance will depend on the intent of the parties as evidenced by the words contained in the contract itself and the parties' conduct as it relates to the contract (Waddams, 1999). Failure to perform under a contract can occur as a result of issues arising from the timing and quality of performance. This is in addition to failures that result as a consequence of one party omitting to carry out the contractual obligation all together.

Because each farmer will be evaluated by a performance standard unique to the specific contract in question, it is difficult to make generalized comments about what the content of the standard will entail. Instead, the discussion that follows emphasizes the importance of ensuring that the contractual parties have a clear understanding of the contract's purpose as well as the standard that will be used to measure contractual performance.

Depending on the mitigation scheme in place, a GHG emitter who contracts with a farmer to offset its emissions may face significant penalties if the farmer does not satisfy her contractual obligations. These penalties will likely become a component of the damages an emitter seeks from a farmer in an action for non-performance. Therefore, in the event of non-performance an emitter may be able to shift the responsibility for its GHG emissions to the farmer.

This shift of responsibility to the farmer may seem to be a reasonable result in the event of a farmer's complete failure to undertake the land management practices she has contracted with an emitter to perform. The reasonableness of this result, however, becomes questionable if there is a misunderstanding between the parties as to the performance standards the farmer must satisfy. In this way, the overall goal of the contract becomes important. Is the farmer contracting to undertake a specific set of land management practices or is the farmer contracting to offset an emitter's GHG emissions? It may appear that the farmer's obligations under the contract remain the same regardless of the understanding of the contract's purpose. In fact, a difference in this understanding may fundamentally alter the ultimate performance standard a farmer may be held to in the event of a dispute.

An example may assist in outlining why a clear understanding of the purpose of a contract is important. Consider a situation where a farmer enters into a contract with an emitter. Under the contract, the farmer agrees to maintain permanent cover on a segment of her land by planting a specified perennial forage crop. After planting the field, through no fault of the farmer, the seeds fail to germinate as a consequence of lack of moisture or a sudden drop in temperature. To avoid an action for breach of contract or to mitigate the damages the plaintiff will suffer, the farmer replants the field with seeds of a different perennial forage crop. Unknown to the farmer, the original crop is better at preventing the release of GHGs from the soil.

Under these facts, the courts may find that the emitter essentially received the full benefit of the contractual bargain and, therefore, rule that the farmer was not in breach. Or, the court could decide that the farmer is in breach of the contract, but the damages suffered by the emitter are negligible. Either of these results are possible if the court determines that the purpose of the contract is merely to maintain permanent cover over a specific piece of land and that the specification of the crop to be planted is not an essential component of the contract.

On the other hand, if the courts determine that the purpose of the contract was to facilitate the capture of GHGs through a specified land management practice, the opposite result will likely occur. In that instance, planting a specific crop may be an essential component of contractual performance. Not only will the farmer be in breach, she may face significant damages if the emitter becomes subject to financial penalties as a result of not satisfying its own mitigation commitments. Not surprisingly, the same problem arises in a mandatory, legislated GHG management system in agriculture. In order for the system to have 'teeth', the legislation will likely include significant penalty provisions for non-compliance. Farmers will face an unknown risk of liability if the legislation is not explicit as to the standard that will be used to evaluate a farmer's performance.

In addition to the content of performance, its duration may also dissuade participation. Ideally, once a mitigating land-use pattern is adopted, it is hoped that the land-use pattern will not revert to one which is known to have a negative impact on climate change. The tendency may, therefore, be to enter into long-term contracts with farmers to avoid this from occurring. It is unclear that farmers will be willing to restrict their land-use options for many years into the future. In addition, such restrictions will not be desirable as new understandings of the linkages between agriculture, land-use, and climate change emerge. Long-term contracts reduce flexibility and may prevent the adoption of innovative practices that emerge over time.

The uncertainty associated with contractual standards may also increase when parties are contracting across political boundaries. In the event of a dispute, the question of what law is applicable will arise. Not only does the content of law vary between nations, there can be some variance between provinces within a single country. A farmer may be certain of his expectations and obligations under the law in her home jurisdiction, but if the contract is interpreted by a court in another jurisdiction, she may be held to a different standard. Luckily, this uncertainty is easily avoided by specifying what law will apply in the event of a dispute.

Although not strictly a performance standard issue, contracts across political boundaries may also discourage participation in contracts to mitigate GHGs if it is not clear that the contracts can be enforced. Enforcement will specifically become an issue in contracts that cross national political boundaries. A farmer who has entered into a GHG mitigation contract with an emitter in another needs assurances that he will be able to enforce that contract if the emitter fails to meet his contractual obligations (and vice versa). It is possible that the emitter will have no assets in the farmer's jurisdiction available for seizure in the event of the emitter's failure to pay the farmer for executing the contract. In those circumstances, once the farmer has obtained a judgment in the farmer's jurisdiction against the emitter for breach of contract, the farmer will need to be able to enforce that judgment in the emitter's home jurisdiction. Enforcement across national boundaries is not automatic, but relies on an agreement between nations to do so.

COMMON LAW STANDARDS

The common law generally serves to address areas of law that have not been specifically contemplated by the legislature. The law of nuisance, negligence, and trespass have emerged to tackle, among other things, many environmental disputes. From these actions, two important standards have emerged. They are reasonableness and strict liability. To date, these standards have not been applied in the context of a GHG mitigation scheme. The content of each standard is therefore discussed in the context of other environmental disputes with the view of gaining an appreciation of the suitability of their use in evaluating a farmer's performance under a GHG mitigation scheme.

Reasonableness

Reasonableness is a common standard used to evaluate a farmer's actions and to attach liability for on-farm, environmental injury. Historically, actions in nuisance and negligence have provided a remedy to parties injured, either physically or in law, as a consequence of some aspect of an agriculture operation. To prevent an unending chain of liability, the common law has limited what injuries are compensable through the use of a reasonableness standard. Due to its inherent fluid nature, this standard eludes precise definition. An understanding, however, of the many permutations of the reasonableness standard can be gained through an analysis of its application in the torts of nuisance and negligence. Agricultural operations have historically faced numerous actions in nuisance and negligence.

Nuisance

Prior to zoning laws, nuisance 'served as an all-purpose tool of landuse regulation' (Halper, 1998). Under the common law, a person is generally entitled to quiet use and enjoyment of her land. If this use is interfered with unreasonably, an action in private nuisance will arise. Unreasonableness is determined in light of the circumstances and considers such factors as: duration, character of the neighbourhood, type and severity of harm, sensitivity of the plaintiff, and the utility of the activity causing the nuisance (Lindon, 1997). Because nuisance is used to remedy situations where the full enjoyment of one's property is impeded by another's use of her property, an action in nuisance can address physical injury to property or person as well as less obvious interferences such odours and noise. In this way, nuisance attempts to balance the rights of competing property-holders.

In light of the fact that private nuisance involves the rights of competing property-holders, it is not surprising that agricultural operations have been the target of numerous nuisance charges over the years. A number of these cases have involved odour and the corresponding attraction of flies from hog barn and associated manure lagoon. Others have involved dust and noise originating from agricultural operations. In each of these cases, a farmer's actions were evaluated using a standard of reasonableness.

It is important to note that an action for public nuisance also exists in Canada. It usually involves the unreasonable interference with a common public right like navigation, access to public roads, or public health and safety (e.g. tower on farmer's property that interferes with commercial flights thus placing the public in danger). In addition, the widespread interference with private property rights can collectively constitute a public nuisance. Unlike a private nuisance, a public nuisance action must be brought to court by the Attorney-General acting on behalf of the effected public (Lindon, 1997). Like a private nuisance, liability is based on a reasonableness analysis. Only those actions that 'materially affect the reasonable comfort and convenience of life' of substantial number of the public are actionable (Lindon, 1997).

The reasonableness standard employed in a nuisance action does not focus on the reasonableness of the defendant's action. Rather, the courts primarily look at the reasonableness of the interference from the plaintiff's perspective. Therefore, a farmer can become liable to another in nuisance as a consequence of a reasonable farming practice like composting manure. The focus only shifts, somewhat, to the defendant when the court analyzes the utility of the activity interfering with the plaintiff's right. Notwithstanding this shift, the focus remains on the nature of the activity rather than the care or diligence exercised by the defendant.

Negligence

A reasonableness standard is similarly used in an action for negligence. An action in negligence has the compensation of losses suffered by a plaintiff because of a defendant's conduct as a primary goal (Dobbs, 2000). A person will be found negligent if she does not take reasonable care to avoid injuring those she ought reasonably be able to foresee as likely to be affected by her conduct. Not all losses, however, are recoverable. Each element of a cause of action for negligence must be analyzed to determine when a loss is recoverable. These elements are best understood as a series of questions addressing a specific aspect of a cause of action in negligence (modified from Prosser, 1971):

- Has the plaintiff suffered loss or damage?
- Is there a duty, recognized in law, that required the defendant to take care to avoid subjecting others to unreasonable risks?
- Has the defendant breached her duty owed to the plaintiff by acting unreasonably in the circumstances?
- Is the defendant's conduct the cause of the plaintiff's loss or damage?
  Was it foreseeable that the defendant's breach of the standard of care would result in the plaintiff's loss or damage?
  Are there any reasons in law or has the plaintiff contributed in anyway to the loss thereby barring recovery or reducing the damages awarded?

As shown, the courts must determine if the defendant's conduct was unreasonable in the circumstances.

In negligence, the reasonableness standard necessarily involves an objective evaluation of the surrounding circumstances. This is specifically called 'the reasonable person test.' The fundamental question that must be determined is 'who is the reasonable person?' The reasonable person, as understood in Canadian law, is best described in Arland v. Taylor (1955):

> [The reasonable person is] a mythical creature of the law whose conduct is the standard by which the Courts measure the conduct of all other persons and find it to be proper or improper in particular circumstances as they may exist from time to time. He is not an extraordinary or unusual creature; he is not superhuman; he is not required to display the highest skill of which anyone is capable; his is not a genius who can perform uncommon feats, nor is he possessed of unusual powers of foresight. He is a person of normal intelligence who makes prudence a guide to his conduct. He does nothing that a prudent man would not do and does not omit to do anything that a prudent man would do. His conduct is guided by considerations which ordinarily regulate the conduct of human affairs. His conduct is the standard 'adopted in the community by persons of ordinary intelligence and prudence'.

Assuming an average defendant, this standard gives little attention to the actual circumstances of the defendant. Rather, the focus is on an artificial analysis of what a reasonable person would have done in the circumstances.

The application of the standard of reasonableness may do little to encourage farmers to voluntarily participate in GHG mitigation efforts. The standard fails to consider the actual circumstances of the defendant. Instead, it determines liability based on an analysis of what the average person would do in the circumstances.

In this way, the reasonable person test discourages innovation and rewards the status quo. A farmer who tries a new farm practice for the purpose of mitigating GHGs may not be acting 'reasonably' for the purpose of determining nuisance or negligence. This may be the case even if the farmer acted diligently to avoid any harm.

The imprecision of the reasonableness standard may also be problematic even though a certain amount of flexibility in determining liability may generally be desirable. Without a precise definition of what conduct will attract liability, farmers can never be entirely certain as to the level of risk they are facing when they undertake a new GHG mitigation activity. Farmers who are more risk averse may chose to avoid these activities altogether. In the alternative, farmers who otherwise would be willing to undertake these activities may choose not to if faced with competing demands for the adoption of new on-farm practices. The additional risk associated with an innovative GHG mitigation practice may be the determining factor in a farmer's choice to invest her energy into better management of food safety risks rather than GHGs. This will be particularly true if the recent estimates of the limited economic returns likely to accrue to farmer as a result of investment into GHG management, are accurate.

Strict liability

Another standard employed in the common law to redress injury is strict liability. Under a traditional strict liability standard, a defendant will be liable once the prohibited conduct is proven to have occurred notwithstanding that the defendant acted reasonably or with due diligence. The key distinguishing feature of the strict liability standard is the fact that wrongful conduct is not a consideration in the application of the standard (Osborne, 2000).

Trespass exemplifies the use of a strict liability standard in the common law. Below is a discussion of these two actions. The discussion of the application of a strict liability standard in a GHG mitigation context will be saved, however, until the next section because of its common use in regulatory offences.

Trespass

A person will liable in trespass for any direct intrusions onto another's property (Osborne, 2000). Trespass is actionable *per se*. That is, one is liable for all unauthorized intrusions onto another's property even if no damage was caused. Furthermore, the trespass need not be intentional to result in liability. A plaintiff in an action for trespass only needs to establish that the trespass occurred in order to be successful. This standard is known as strict liability.

Rule in Rylands v. Fletcher

The rule in 'Rylands v. Fletcher' also promotes a strict liability standard. Under this rule, a defendant will be liable for any damage that results as a consequence bringing something onto her land that is likely to cause mischief if it escapes (Osborne, 2000). The application of this rule, however, is limited to damages that result from the defendant's non-natural uses of land. This standard differs from trespass because it is not limited to direct intrusions on another's property. It contemplates actions that may otherwise be considered a nuisance. Unlike nuisance, the plaintiff is not required to establish the unreasonableness of the interference. The rule in 'Rylands v. Fletcher' is also actionable *per se*.

REGULATORY STANDARDS

In designing a policy regime aimed at mitigating climate change, governments can choose to use mandatory regulatory standards in addition to or instead of efforts to encourage the voluntary adoption of desirable land-use patterns. In addition to enforcement, how the regulatory standard is designed will influence whether or not the public chooses to comply with it. It is therefore important to consider regulatory design if the goal of minimizing agriculture's impact on climate change is to be realised.

In Canada, the legislature has an almost unrestricted right to design environmental standards as it sees fit provided that the laws do not violated the Canadian Constitution and Charter of Rights and Freedom by being arbitrary, overly vague, or outside their constitutional authority. Canada may also choose to limit this authority by participating in international agreements like those governing international trade.

Currently, there are numerous environmental regulatory offences of general application in Canada that have an impact on farmers. In addition, there are certain regulatory offences that are specifically targeted at agriculture. Generally, all of these offences take one of the following forms:

- specifically mandated or prohibited conduct;
- zero-tolerance; and
- prescribed limits.

Either a strict liability standard or an absolute liability standard is used to determine when someone will be held accountable in law for the commission of a regulatory, environmental offence. In addition, many jurisdictions have taken legislative action to respond to the particular susceptibility of agricultural operations to nuisance actions. They have passed laws that prohibit nuisance claims where a farmer employed "normally acceptable agricultural practices" thereby creating a new standard only applicable to agriculture.

Each of these regulatory standards is discussed below. Strict liability, absolute liability, and the defence of due diligence will be discussed first. This will be followed by an analysis of how the form of the offence as well as the standard used to determine liability can inform the debate on the appropriate standards to be used in GHG mitigation in agriculture. The chapter will then discuss the unique 'normally acceptable agricultural practices' standard.

Strict liability, absolute liability and the defence of due diligence

The discussion of the use of the standard of strict liability in the common law outlined that strict liability offences are actionable *per se* without proof of intention or wrongful conduct. The same is true of absolute liability offences, however, an important distinction must be made between the standards of strict and absolute liability. Strict liability offences are subject to various defences. That is, one can escape liability if they have an acceptable defence to the action. The defences vary according to the offence and include acts of God, necessity, self-defence, and in some instances, due diligence. Absolute liability offences do not permit these defences.

The distinction between absolute and strict liability offences was not made in the above section for two reasons. First, there are no true, absolute liability environmental offences in the common law. And second, common law strict liability offences are rarely subject to a due diligence defence. This last factor is a key distinction between the regulatory and common law strict liability standards.

Due diligence emerges as a defence to a strict liability offence once it has been established that the defendant committed the offence in question. The defendant will be liable unless she can establish that she used due diligence. Essentially, the onus shifts to the defendant to establish that she used reasonable care in the circumstances. An analysis of due diligence may include a consideration of the following factors (Fuller and Buckingham, 1999):

- acceptable standards in the industry and whether they were followed;
- the nature and gravity of the environmental harm;
- the foreseeability of the harm, including atypical sensitivity;
- available alternative solutions;
- legislative and regulatory compliance;
- character of the neighbourhood;
- the efforts made to address the problem and matters beyond control;
- the expected skill level of the defendant;
- preventative practices;
- economics; and
- any action taken by officials.

These factors are reminiscent of those considered under the common law reasonableness standard.

The due diligence defence is often incorporated into environmental legislation. It serves the dual purposes of reducing the burden of proof a plaintiff must meet, while accommodating those offenders whose actions were reasonable in the circumstances. Its usefulness in the context of GHG mitigation in agriculture will largely depend on the form the offence takes.

Specifically mandated or prohibited conduct

It is common for environmental legislation to require or prohibit specific conduct. Often prohibitions and mandated conduct are used in conjunction to achieve the overall goal of the legislation. For instance, Saskatchewan's 'Environmental Management and Protection Act, 2002' provides that:

Subject to subsections (2) to (4), without holding a valid permit that authorizes the person to do so, no person shall: cause or allow the discharge of any substance that may cause or is causing an adverse effect to the quality of any water.

Furthermore, the EMPA holds that in the event of an accidental discharge, the person responsible is required to report the discharge to the appropriate government authority. With the inclusion of definitions for what is considered pollution and what constitutes a discharge, EMPA provides relatively clear notice of what conduct is expected of the public – do not discharge a pollutant without a permit and if you do, report it. Therefore, the only issue that remains is whether non-compliance with either of these sections is an absolute or strict liability offence.

In designing a regulatory standard aimed at climate change mitigation, strict liability will always be the preferred standard from a farmer's perspective because it provides an opportunity to for the farmer defend non-compliance. On the other hand, if legislatures are serious about mitigating GHGs it may be undesirable to excuse non-compliance under any circumstances. An absolute liability offence may be justified where the standard of conduct expected of producers is unambiguous. If absolute liability is rejected in these circumstances, the burden to establish due diligence should be set quite high so as not to undermine the standard's effectiveness.

As will become clear as the other forms of offences are discussed, GHG mitigation schemes that specifically mandate or prohibit conduct may be in the best position to balance the goal of reducing the risk to producers of non-compliance with the goal of mitigating GHGs. One of the principal reasons for this is the fact that producers will have an incentive to innovate as traditional land management practices become unacceptable through a prohibition. Such a prohibition is not unlikely with respect to summer fallowing on the Canadian prairie.

A regulation that specifically mandates conduct will also promote innovation if it directs an outcome rather than a process. For instance, a regulation could state that producer must employ land management practices that maintain a constant level of organic matter in the soil. A regulation in this form will allow producers to innovate within their own operations and employ practices that best suit their situation.

Zero tolerance

Environmental legislation may outline zero-tolerance of certain substances that are deemed hazardous to the environment in all amounts. EMPA states that "[n]o person shall manufacture, offer for sale, sell, use or consume any product containing a halocarbon that acts as a propellant.” Zero-tolerances are closely related to the prohibition of conduct in environmental legislation. The distinction being obvious – zero-tolerance prohibits actual substances in specific forms instead of prohibiting conduct. The use of zero-tolerance presumes that there are means to test for the presence of the prohibited substance.

The use of zero-tolerance may pose an additional risk to producers in a GHG mitigation scheme. Unlike prohibited conduct, the meaning of zero-tolerance may change as the means used to detect the presence of a prohibited substance improve. For example, if a GHG mitigation scheme establishes zero-tolerance for methane emissions from confined livestock operations, producers may be faced with having to satisfy a changing standard, at a considerable expense to their operation, each time the tools of measurements become more precise.

In this circumstance, whether the scheme employs a strict or absolute standard of liability is of great importance. The added uncertainty as to what will attract liability under a scheme that establishes zero-tolerances argues for a strict liability standard. As mentioned above, however, the reduced risk to farmers under a strict liability standard is achieved by sacrificing the environmental objectives the standard is ultimately trying to promote.

It should be noted that the changing standard does create an incentive for continual innovation in order to establish better GHG mitigation practices on the farm. Unfortunately, this incentive is achieved as a result of an increased risk to producers.

Prescribed limits

Environmental legislation also may permit an activity up to a certain prescribed level of acceptance. For example, the ‘Canadian Environmental Protection Act’ (CEPA) (1999) provides that:

> No person shall manufacture for use or sale in Canada or import a cleaning product or water conditioner that contains a prescribed nutrient in a concentration greater than the permissible concentration prescribed for that product.

CEPA provides the maximum acceptable nutrient concentration in its regulations. This leaves no ambiguity as to what is expected of a person in these circumstances because the statute outlines a clear standard of conduct. Therefore, there is no added risk of non-compliance due to a misunderstanding as to the standard that will be used to evaluate conduct.

This form of standard may be attractive in the context of GHG mitigation because it is less restrictive than a straight prohibition of offending conduct. It will allow activities to occur up to an acceptable threshold. This may be desirable if GHG mitigation will require a fundamental shift in land management activities. The threshold can be lowered overtime to allow for the gradual adoption of new activities by producers. It must be noted, however, that once the initial threshold is established there is a risk that the subsequent legislative amendments may not occur.

Prescribed limits may also be a means to target those producers who can have the largest impact on GHG emissions without burdening small players with the costs associated with change. The prescribed limit can be set at a level above what would be expected from small producers.

Unfortunately, the use of prescribed limits does not always produce a clear standard of conduct. EMPA also uses prescribed limits to control activities that may be harmful to the environment. Below is an example of such:

> No person shall discharge or allow the discharge of a substance into the environment in an amount, concentration or level or at a rate of release that may cause or is causing an adverse effect unless otherwise expressly authorized to do so.

This section of EMPA leaves a lot of room for interpretation. Although adverse effect is defined elsewhere in EMPA, the inclusion of that definition provides little assistance in outlining the expected standard of conduct. The section is designed in an overly broad and imprecise fashion thereby introducing ambiguities and enhancing the risk of non-compliance as a consequence of a misunderstanding.

Even when the standard is clear, however, the use of prescribed limits may be unattractive. The mere imposition of a prescribed limit alters the focus of compliance to meeting the limit. The overall objective of mitigating GHG in agriculture gets lost. Prescribed limits do not provide an incentive for on-going innovation to develop best practices once the threshold has been met. In addition, establishing the prescribed limit in itself may prove problematic. At some point, this process involves the creation of an arbitrary threshold.

Normally accepted agricultural practices

The normally accepted agricultural practices standard emerged in response to an increase in nuisance actions directed at agricultural operations. It is a unique example of the creation of a new standard designed to protect a specific industry. This standard has been adopted by numerous jurisdictions across North America. For example, the 'Agricultural Operations Act' of Saskatchewan provides:

> The owner or operator of an agricultural operation is not liable to any person in nuisance with respect to the carrying on of the agricultural operation, and may not be prevented by injunction or other order of any court from carrying on the agricultural operation on the grounds of nuisance where the owner or operator uses normally accepted agricultural practices with respect to the agricultural operation.

It goes on to define a normally accepted agricultural practice as one that, among other things:

> is conducted in a prudent and proper manner that is consistent with accepted customs and standards followed by similar agricultural operations under similar circumstances including the use of innovative technology or advanced management practices in appropriate circumstances.

Therefore, a producer will be immune from liability for any nuisance her operation is causing provided that she is using management practices that are custom in her industry.

This standard has not been employed in any other area besides nuisance. Special preference given to the property rights of one segment of society at the expense of another segment is rarely justified. It is highly unlikely that this standard will be employed in a GHG mitigation scheme and its use in this context should not be encouraged. The protection afforded to operations that employ customary practices preserves the status quo and has the potential to penalize innovation.

CONCLUSIONS

In a voluntary scheme, standards of concern to farmers will likely be a component of contracts they have entered into with large-scale emitters. As a result, it is impossible to generalize about which performance standards would be most appropriate in a contract because that will likely be negotiated among the parties on contract by contract basis. Instead, it must be stressed that the standard used to evaluate performance will be influenced by the overall purpose of the contract. It is important that time be spent when first drafting a contract to clearly outline the expected standard of performance and the contractual purpose. Any ambiguity may influence the allocation of risk under the contract.

Likewise, consideration must be paid to the appropriate duration of the contract. A balance must be struck between the goal of maintaining gains achieved through the contract at the same time as allowing room for innovation as new understandings of the relationship between agriculture, climate change, and land-use emerge.

In a mandatory scheme, legislatures have a choice of standards in which to employ in order to evaluate a farmer's performance. A legislated standard that clearly mandates or prohibits conduct is most desirable, regardless of whether it is a strict or absolute liability offence. This is because these standards are in the best position to balance the goal of reducing the risk to producers of non-compliance with the goal of mitigating GHGs. Such a standard leaves little room for ambiguity as to what will constitute a violation. As a result, producer compliance is facilitated by clear expectations. In addition, these standards promote innovation by prohibiting traditional land management practices that do not encourage GHG mitigation thereby forcing farmers to look for alternative methods. Farmers are free to innovate without running the risk that a new practice may in fact fail. This luxury is not afforded to an innovator where there is a prescribed limit or a zero-tolerance level.

Where no standard is discernible, the option to rely on the common law standard of reasonableness remains. As outlined, this standard is less than desirable as it fails to consider the specific circumstances of the farmer when evaluating performance and leaves enough ambiguity to discourage a farmer from participating in an activity that may attract liability.

From the foregoing, two things become clear. First, the form a performance standard takes may influence its ability to foster the land-use pattern it aims to encourage. This is because risk is intrinsically linked to performance standards. If the standards are unknown or those known are ambiguous, farmers are less able to determine the standard of conduct required of them to avoid liability. In a voluntary GHG mitigation system, this may discourage participation. In a mandatory system, compliance may become an issue. The integrity of the GHG mitigation scheme, however, will depend on assurances that farmers are meeting an acceptable standard of performance.

Second, all standards have benefits and drawbacks. No one policy will encourage all farmers to effectively adopt the desired land-use pattern. It is therefore desirable to adopt a range of policies aimed at bringing about the same outcome to ensure that farmers fully understand the performance standard they must satisfy in order to avoid liability.

REFERENCES

Arland v. Taylor (1955) *Ontario Reports*, 131, 142.

Dobbs, Dan B. (2000) *The Law of Torts*. St. Paul, Minn., West Group.

Fuller, Robert S. and Donald E. Buckingham (1999) *Agricultural Law in Canada*. Toronto, Butterworths.

Halper, L.A. (1998) Untangling the nuisance knot. *Boston College Environmental. Affairs Law Review*, Vol. 26, p. 89.

Lindon, Allen M. (1997) *Canadian Tort Law*. Sixth Ed. Toronto, Butterworths.

Osborne, Philip H. (2000) *The Law of Torts*. Toronto, Irwin Law.

Prosser, William L. (1971) *Handbook of the Law of Torts*. Fourth Ed. St. Paul, Minn., West Pub. Co.

Waddams, S.M. (1999) *The Law of Contracts*. Fourth Edition. Toronto, Canada Law Book Inc.

Index

ENVIRONMENT & POLICY

1. Dutch Committee for Long-Term Environmental Policy: *The Environment: Towards a Sustainable Future*. 1994 ISBN 0-7923-2655-5; Pb 0-7923-2656-3
2. O. Kuik, P. Peters and N. Schrijver (eds.): *Joint Implementation to Curb Climate Change.* Legal and Economic Aspects. 1994 ISBN 0-7923-2825-6
3. C.J. Jepma (ed.): *The Feasibility of Joint Implementation*. 1995 ISBN 0-7923-3426-4
4. F.J. Dietz, H.R.J. Vollebergh and J.L. de Vries (eds.): *Environment, Incentives and the Common Market.* 1995 ISBN 0-7923-3602-X
5. J.F.Th. Schoute, P.A. Finke, F.R. Veeneklaas and H.P. Wolfert (eds.): *Scenario Studies for the Rural Environment*. 1995 ISBN 0-7923-3748-4
6. R.E. Munn, J.W.M. la Rivière and N. van Lookeren Campagne: *Policy Making in an Era of Global Environmental Change.* 1996 ISBN 0-7923-3872-3
7. F. Oosterhuis, F. Rubik and G. Scholl: *Product Policy in Europe: New Environmental Perspectives.* 1996 ISBN 0-7923-4078-7
8. J. Gupta: *The Climate Change Convention and Developing Countries: From Conflict to Consensus?* 1997 ISBN 0-7923-4577-0
9. M. Rolén, H. Sjöberg and U. Svedin (eds.): *International Governance on Environmental Issues.* 1997 ISBN 0-7923-4701-3
10. M.A. Ridley: *Lowering the Cost of Emission Reduction: Joint Implementation in the Framework Convention on Climate Change*. 1998 ISBN 0-7923-4914-8
11. G.J.I. Schrama (ed.): *Drinking Water Supply and Agricultural Pollution.* Preventive Action by the Water Supply Sector in the European Union and the United States. 1998 ISBN 0-7923-5104-5
12. P. Glasbergen: *Co-operative Environmental Governance: Public-Private Agreements as a Policy Strategy*. 1998 ISBN 0-7923-5148-7; Pb 0-7923-5149-5
13. P. Vellinga, F. Berkhout and J. Gupta (eds.): *Managing a Material World*. Perspectives in Industrial Ecology. 1998 ISBN 0-7923-5153-3; Pb 0-7923-5206-8
14. F.H.J.M. Coenen, D. Huitema and L.J. O'Toole, Jr. (eds.): *Participation and the Quality of Environmental Decision Making.* 1998 ISBN 0-7923-5264-5
15. D.M. Pugh and J.V. Tarazona (eds.): *Regulation for Chemical Safety in Europe: Analysis, Comment and Criticism.* 1998 ISBN 0-7923-5269-6
16. W. Østreng (ed.): *National Security and International Environmental Cooperation in the Arctic – the Case of the Northern Sea Route*. 1999 ISBN 0-7923-5528-8
17. S.V. Meijerink: *Conflict and Cooperation on the Scheldt River Basin*. A Case Study of Decision Making on International Scheldt Issues between 1967 and 1997. 1999 ISBN 0-7923-5650-0
18. M.A. Mohamed Salih: *Environmental Politics and Liberation in Contemporary Africa*. 1999 ISBN 0-7923-5650-0
19. C.J. Jepma and W. van der Gaast (eds.): *On the Compatibility of Flexible Instruments*. 1999 ISBN 0-7923-5728-0
20. M. Andersson: *Change and Continuity in Poland's Environmental Policy.* 1999 ISBN 0-7923-6051-6

ENVIRONMENT & POLICY

21. W. Kägi: *Economics of Climate Change: The Contribution of Forestry Projects*. 2000 ISBN 0-7923-6103-2
22. E. van der Voet, J.B. Guinée and H.A.U. de Haes (eds.): *Heavy Metals: A Problem Solved?* Methods and Models to Evaluate Policy Strategies for Heavy Metals. 2000 ISBN 0-7923-6192-X
23. G. Hønneland: *Coercive and Discursive Compliance Mechanisms in the Management of Natural Resourses.* A Case Study from the Barents Sea Fisheries. 2000 ISBN 0-7923-6243-8
24. J. van Tatenhove, B. Arts and P. Leroy (eds.): *Political Modernisation and the Environments.* The Renewal of Environmental Policy Arrangements. 2000 ISBN 0-7923-6312-4
25. G.K. Rosendal: *The Convention on Biological Diversity and Developing Countries.* 2000 ISBN 0-7923-6375-2
26. G.H. Vonkeman (ed.): *Sustainable Development of European Cities and Regions*. 2000 ISBN 0-7923-6423-6
27. J. Gupta and M. Grubb (eds.): *Climate Change and European Leadership*. A Sustainable Role for Europe? 2000 ISBN 0-7923-6466-X
28. D. Vidas (ed.): *Implementing the Environmental Protection Regime for the Antarctic*. 2000 ISBN 0-7923-6609-3; Pb 0-7923-6610-7
29. K. Eder and M. Kousis (eds.): *Environmental Politics in Southern Europe: Actors, Institutions and Discourses in a Europeanizing Society*. 2000 ISBN 0-7923-6753-7
30. R. Schwarze: *Law and Economics of International Climate Change Policy.* 2001 ISBN 0-7923-6800-2
31. M.J. Scoullos, G.H. Vonkeman, I. Thornton, and Z. Makuch: *Mercury - Cadmium-Lead: Handbook for Sustainable Heavy Metals Policy and Regulation.* 2001 ISBN 1-4020-0224-6
32. G. Sundqvist: *The Bedrock of Opinion*. Science, Technology and Society in the Siting of High-Level Nuclear Waste. 2002 ISBN 1-4020-0477-X
33. P.P.J. Driessen and P. Glasbergen (eds.): *Greening Society*. The Paradigm Shift in Dutch Environmental Politics. 2002 ISBN 1-4020-0652-7
34. D. Huitema: *Hazardous Decisions.* Hazardous Waste Siting in the UK, The Netherlands and Canada. Institutions and Discourses. 2002 ISBN 1-4020-0969-0
35. D. A. Fuchs: *An Institutional Basis for Environmental Stewardship: The Structure and Quality of Property Rights.* 2003 ISBN 1-4020-1002-8
36. B. Chaytor and K.R. Gray (eds.): *International Environmental Law and Policy in Africa.* 2003 ISBN 1-4020-1287-X
37. F.M. Brouwer, I. Heinz and T. Zabel (eds.): *Governance of Water-Related Conflicts in Agriculture*. New Directions in Agri-Environmental and Water Policies in the EU. 2003 ISBN 1-4020-1553-4

ENVIRONMENT & POLICY

38. G.J.I. Schrama and S. Sedlacek (eds.): *Environmental and Technology Policy in Europe. Technological Innovation and Policy Integration*. 2003 ISBN 1-4020-1583-6
39. A.J. Dietz, R. Ruben and A. Verhagen (eds.): *The Impact of Climate Change on Drylands*. With a focus on West Africa. 2004 ISBN 1-4020-1952-1
40. I. Kissling-Näf and S. Kuks (eds.): *The Evolution of National Water Regimes in Europe*. Transitions in Water Rights and Water Policies. 2004 ISBN 1-4020-2483-5
41. H. Bressers and S. Kuks (eds.): *Integrated Governance and Water Basin Management*. Conditions for Regime Change and Sustainability. 2004 ISBN 1-4020-2481-9
42. *To be published*.
43. E. Croci (ed.): *The Handbook of Environmental Voluntary Agreements*. Design, Implementation and Evaluation Issues. 2005 ISBN 1-4020-3355-9
44. X. Olsthoorn and A.J. Wieczorek (eds.): *Sciences for Industrial Transformation: Views from Different Disciplines*. 2006 ISBN 1-4020-3755-4
45. H. Aiking, J. de Boer and J. Vereijken (eds.): *Sustainable Protein Production and Consumption: Pigs or Peas?* 2006 ISBN 1-4020-4062-8
46. F. Brouwer and B.A. McCarl (eds.): *Agriculture and Climate Beyond 2015*. A New Perspective on Future Land Use Patterns. 2006 ISBN 1-4020-4063-6