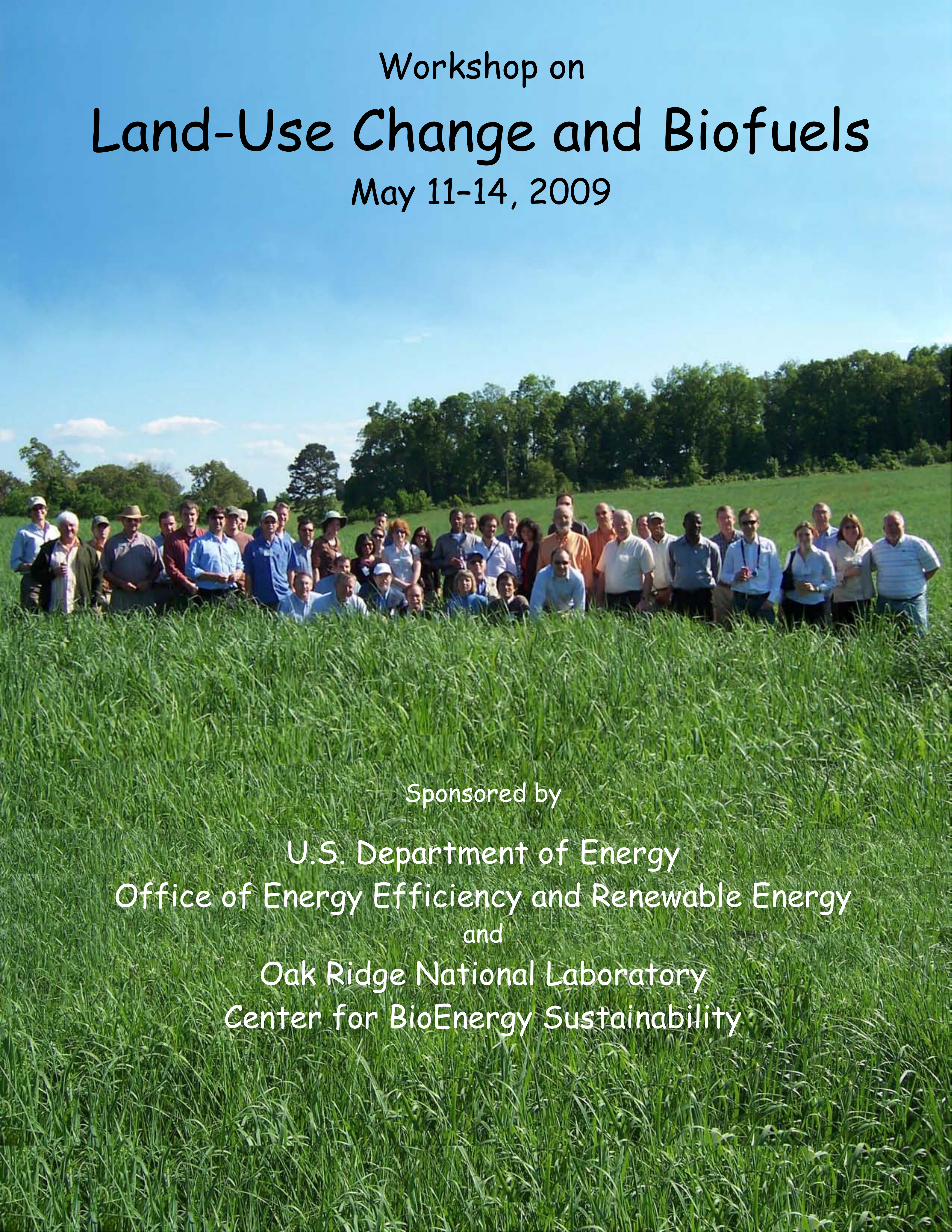
Workshop on

Land-Use Change and Biofuels

May 11–14, 2009



Sponsored by

U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
and
Oak Ridge National Laboratory
Center for BioEnergy Sustainability

Land-Use Change and Bioenergy: Report from the 2009 Workshop

May 11–14, 2009
Vonore, Tennessee

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Information about the workshop and all plenary presentations can be found at the web site for Oak Ridge National Laboratory's Center for BioEnergy Sustainability
http://www.ornl.gov/sci/besd/cbes.shtml

Suggested citation for this report: CBES (Center for BioEnergy Sustainability, Oak Ridge National Laboratory). 2009. Land-Use Change and Bioenergy: Report from the 2009 workshop, ORNL/CBES-001, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy and Oak Ridge National Laboratory, Center for Bioenergy Sustainability (**http://www.ornl.gov/sci/besd/cbes.shtml**).

October 2009

This workshop was supported by the U.S. Department of Energy (DOE) under the Office of the Biomass Program. Oak Ridge National Laboratory is managed by the UT-Battelle, LLC, for DOE under contract DE-AC05-00OR22725. The views in this report do not necessarily represent those of ORNL, DOE, or any other agency.

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EXECUTIVE SUMMARY

The U.S. Department of Energy Biomass Program sponsored the Land-Use Change and Bioenergy workshop in Vonore, Tennessee, from May 11 to May 14, 2009. More than 50 experts from around the world gathered to review the state of the science, identify opportunities for collaboration, and prioritize next steps for the research and data needed to address key issues regarding the land-use effects of bioenergy policies. A key outcome of the workshop was the identification of research areas that may improve our understanding of land-use change in a bioenergy context.

The agenda integrated plenary talks, short presentations, and group discussions, which led workshop participants toward the development of research plans to improve the scientific basis for estimating the land-use-change effects of biofuels. Workshop participants reviewed the state of global data, models, approaches that are currently being used to estimate effects of bioenergy use on land-use change, as well as pertinent regulations and policies (Section 2 of this report). The limitations and uncertainties of these data and models were discussed (Section 3), and the steps needed to address these issues were identified (Section 4). Finally, solutions were proposed that included enhanced collaboration and specific research plans (Section 5).

The workshop focused on the interface between land-use changes and global economic models, represented by the shaded area in the center of Figure ES-1. A recurring theme emerged around the need to improve the current generation of land-use-change models. Current modeling efforts are limited by the availability of appropriate data sets and knowledge of driving factors of land-use change. These models could be improved with long-term, fine-scale, multi-dimensional data sets that reflect the social and political factors that dictate land use and enable an understanding of the causal factors of land use change. As reflected in Figure ES-1, predominant factors driving initial land-use change may often be distinct from those driving subsequent land-use decisions. Unfortunately, historical data on actual land uses (rather than land cover) are often nonexistent or available only at coarse scales or for a single point in time, especially in developing countries. Land-use and land-cover data originate from different sources and inventory techniques. The utility of land-cover data is also limited due to the use of different sensors over time, the use of varying classification schemes between years, and the use of alternative definitions of land-cover classes among regions and data products. Each source of land-use and land-cover data, whether from remotely sensed images or ground-based surveys, has its own domain of applicability and quality standards. Nevertheless, data are often used for modeling without explicitly considering the suitability of the data for the specific application, the potential bias that originates from data inventory and editing, and the effects that data have on model results.

Limitations inherent in the models used for estimating land-use change and land-use-change effects of bioenergy were key topics of discussion. Most models currently available focus on certain aspects of land systems and their dynamics, such as agriculture, forestry, urbanization, or economic trade phenomena, while representing other sectors as external drivers or treating them in a simplified manner. These models are not capable of representing the social, economic, and environmental effects of biofuels on global land-use with certainty. Constructive dialogue on how to handle uncertainty and the research needed to characterize, quantify and reduce uncertainty in land-use change modeling, were recurring themes throughout the workshop.

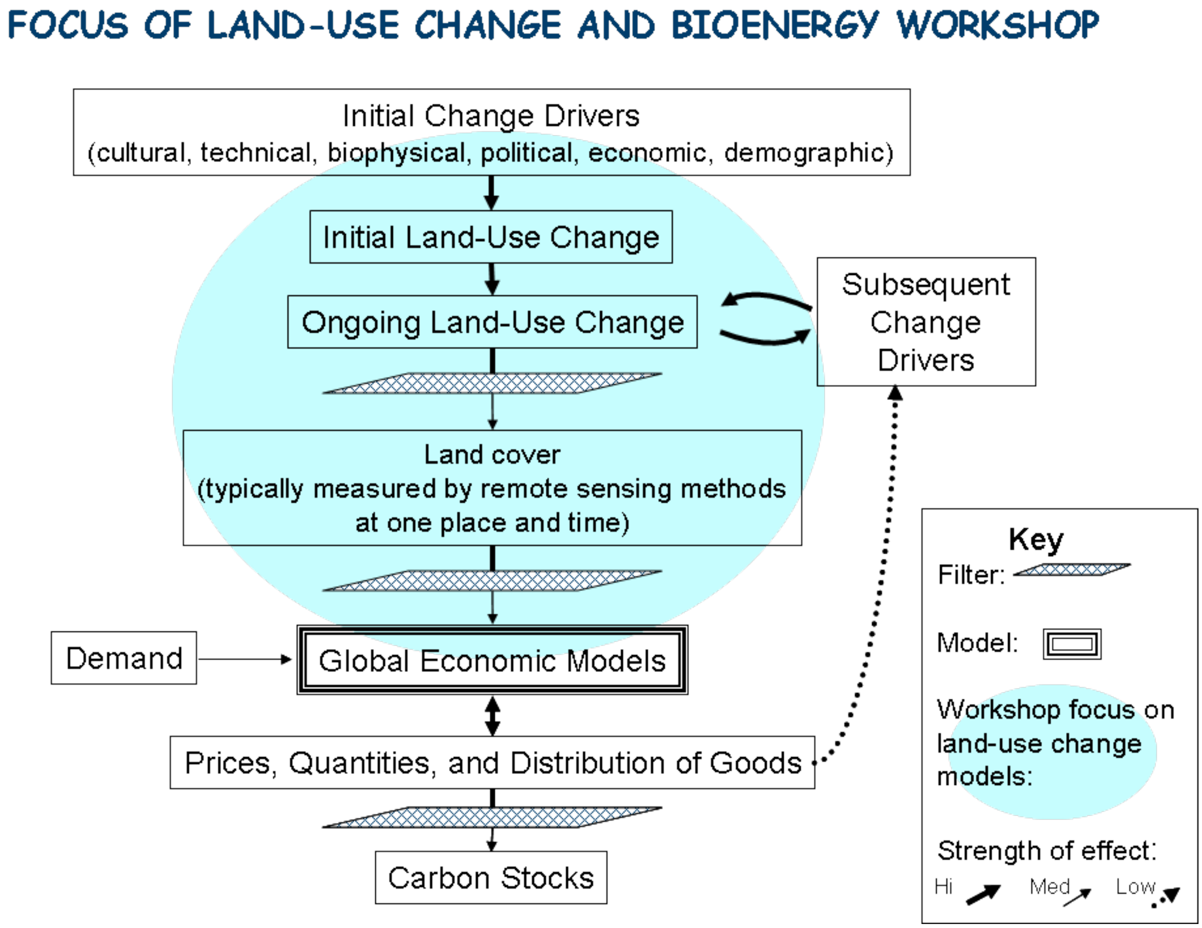

Figure ES-1. Overview of the workshop framework, with a focus on the interface between land use/land cover and global economic models[1]

The current models offer many challenging opportunities for improvement to represent bioenergy-driven land-use change, such as:

- Capturing interactions and feedbacks both within and between the social, the environmental, and other model components
- Reducing uncertainties associated with design assumptions, scenarios, and the results of sub-models
- Developing adequate reference cases and potential future scenarios relevant to biofuel production
- Integrating equilibrium models with sub-models representing the more regional drivers of land-use changes
- Validating and calibrating models for land-use change effects.

Twenty-four strategic research topics were proposed to help address the needs and issues identified above. The merits of research questions were debated, and research topics were organized into the following eight categories:

- Improvement of the conceptual framework of the driving forces for land-use change
- Scenario development for sustainable bioenergy systems (including additional field study of land use change processes in different countries)

[1] See Dale V "Plenary presentation" on workshop web site: **http://www.ornl.gov/sci/besd/cbes.shtml**

- Inventory of best available global data and requirements for bioenergy land-use change modeling
- Examination of historical land-use changes with a goal to linking them to real-world drivers
- Inquiry into the interface between land use and economic models
- Quantification and reduction of uncertainty in indirect land-use change models
- Characterization of underutilized lands for biofuels
- Attribution of biofuels, agriculture, and petroleum products to climate forcing (that is, changes in factors that affect the atmospheric concentration of greenhouse gases and thus influence global climate)
- Examination of the role of science in biofuel policy implementation and approaches to manage uncertainty

For each of the categories, a working group was assembled and charged with developing a preliminary research plan that is actionable in the short term, improves the scientific basis for understanding and describing land-use change, fosters collaborative efforts, and focuses on biofuels. The results of those working groups are presented in Section 5 of the report.

Participants also identified specific activities that could be launched in the near term to build on the relationships formed at the workshop and catalyze plans for improving the scientific underpinning of the role of land use in expanding the global bioenergy economy. For example, the organizing committee agreed to prepare and distribute this workshop report – developed with substantial contributions from many participants – in order to share the workshop findings in a timely manner. The U.S. Department of Energy (DOE) agreed to assess workshop results to identify research priorities relevant to DOE's biofuel mandate that could be considered in planning future work with the national laboratories and other partners. Other next steps that were proposed by workshop participants included the development of a policy-relevant paper, collaborations on other topic-specific white papers, and fostering opportunities to continue the dialogue in subsequent meetings and conferences.

Workshop participants recognized both the importance of biofuels in a sustainable energy future and the need to develop a comprehensive land-use change framework to understand the impact of bioenergy policy on land-use decisions. Many participants identified opportunities for collaborations that will help address research challenges and improve our abilities to model land-use changes related to bioenergy within the broader context of environmental effects inherent under future energy scenarios. The importance of quantifying and reducing uncertainties surrounding output from current models to project land-use change effects was emphasized. Integrating approaches is no small task, but improvements are vital now because biofuel policy, private investments, and public opinions are moving forward rapidly.

Participants at the Workshop on Land-Use Change and Bioenergy**

McKinley Addy, California
Harry Baumes, U.S. Department of Agriculture
Budhendra Bhaduri, Oak Ridge National Laboratory
Eddie Bright, Oak Ridge National Laboratory
J. Elliott Campbell, University of California, Merced
Bruce Dale, Michigan State University
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Jill Davidson, Archer Daniels Midland Company
Stuart Davies, Harvard University
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Paul Gallagher, Iowa State University
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Nathanael Greene, Natural Resources Defense Council
Angelo Gurgel, Institute for International Trade Negotiations
Zia Haq, U.S. Department of Energy
Nancy Harris, Winrock International
John Houghton, U.S. Department of Energy
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Siwa Msangi, International Food Policy Research Institute
Michael O'Hare, University of California, Berkeley
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Nagendra Singh, Oak Ridge National Laboratory
Jerry Tagestad, Pacific Northwest National Laboratory
Raju Vatsavai, Oak Ridge National Laboratory

Peter Verburg, Wageningen University and Research Centre, Netherlands
Tris West, Oak Ridge National Laboratory

** In addition, some of the workshop's plenary sessions were accessed live via an internet link by as many as 22 individuals and groups around the world.

Staff for Workshop

Daniel Fishman, BCS, Inc.
Bob Fleming, Oak Ridge National Laboratory
Gary Forbes, Facilitator
Lana McDonald, Oak Ridge National Laboratory
Fred O'Hara, Consultant in Technical Communication
Seema Patel, BCS, Inc.
Becky Rumbaugh, Information by Design
Phyllis Young, Oak Ridge National Laboratory

ACKNOWLEDGEMENTS

All workshop participants contributed to the ideas and discussions, and many also contributed to the writing of this report. Their collaborative spirit and willingness to share their experiences, insights, and past work is greatly appreciated.

This report reflects the best efforts of the organizers to consolidate and faithfully present many diverse contributions. The views expressed do not necessarily represent those of any single participant nor the institutions with which participants are affiliated.

The hard-working staff were supportive in allowing the meeting to run smoothly. Becky Rumbaugh made sure that all the pieces of the workshop fell into place – from having information posted on the external web site to having the hospitality room stocked with supplies. Phyllis Young provided essential support throughout the planning and implementation of the workshop by establishing the key vendors, helping prepare background material, and managing the attendee list. Seema Patel set up the internal website for the workshop, communicated to participants about the workshop, and provided technical information for many aspects of the discussions. Daniel Fishman provided technical background on regulations related to land-use change. Fred O'Hara helped develop and write this report. All of these staff helped with the breakout group reporting. In addition, Lana McDonald oversaw the travel arrangements and needs of key workshop participants

The excellent facilitator, Gary Forbes, ensured that the workshop goals were achieved while allowing each person a chance to express their ideas. Bob Fleming and Bruce Johnston allowed the workshop to be broadcast via Live Meeting so that as many as 22 audiences around the world could listen and see the plenary sessions of the workshop as they occurred.

The workshop participants enjoyed a field trip on the first afternoon to a nearby switchgrass field. Sam Jackson and his colleagues from the University of Tennessee Institute of Agriculture gave an interesting overview of the work that is being conducted on the agricultural, economic, social and environmental aspects of their large-scale switchgrass demonstration project occurring under the Southeastern SunGrant Center (see **www.utbioenergy.org**). The cover photograph of this report shows the workshop participants standing in the field.

Others who provided assistance for the workshop include Connie Arnwine, Latha Baskaran, Tammy Beaty, Budhendra Bhaduri, Norma Cardwell, Laura Marie Chavez-Becker, Helena Chum, Douglas N. Collins, Jean Eubanks, Robin Graham, Gary Jacobs, Joshua Kirby, Debo Oladosu, Michael S. Pung, Eli Ripoll, Angelia Smiddy, Ed Stanford and Stan Wullschleger. Arielle Notte and Chad Covert deserve special thanks for helping to incorporate extensive review comments on drafts of this report.

FOREWORD

Excerpts from letter of March 11, 2009 in support of workshop

United States Department of Energy
Washington, D.C. 20585

The Energy Independence and Security Act (EISA, December 2007) set guidelines for a new U.S. Renewable Fuels Standard including the requirement for analysis of lifecycle impacts of energy to include "aggregate quantity of greenhouse gas emissions (including direct emissions and significant indirect emissions such as significant emissions from land use changes), as determined by the Administrator, related to the full fuel lifecycle..."

The DOE led the development of a National Biofuels Action Plan (published and publicized in October 2008 through the Biomass Research and Development Interagency Board, BRDI). The National Biofuels Action Plan prioritized cooperation around the "key goal... to maximize the environmental and economic benefits of biofuels by advancing sustainable practices." This document discusses the importance of improving science to determine what is sustainable and to better understand land-use change impacts. The recommendations in the document include: "Planning a series of workshops with internal and external stakeholders. Internal workshops will inventory key research efforts in the area of sustainability; identify relevant models, and identify strengths and weaknesses of existing models and gaps. External workshops will involve discussions of analytical and modeling efforts to address pressing issues/challenges, and also inform R&D priorities through dialogues between decision makers and scientists."

In response to the EISA legislation and the National Biofuels Action Plan, DOE has a mandate to determine land-use change impacts associated with biofuels. To help DOE set its research agenda and to forge international cooperation on the topic, DOE is providing funding to Oak Ridge National Laboratory to co-chair with DOE an invitation-only workshop on Land-Use Change and Bioenergy. The workshop will assemble leaders in global land-use change modeling and experts in the land cover and land-use datasets upon which the models rely. The workshop participants will review the state of the art, identify opportunities for collaboration, and prioritize next steps for the research needed to address key issues regarding the ability to estimate direct and indirect effects of bioenergy. The output of this workshop will be a report that will guide DOE/OBP's strategic planning for the coming years in determining the direct and indirect effects of land-use change on bioenergy.

Thank you.

Alison Goss Eng
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1. INTRODUCTION

The Land-Use Change and Bioenergy workshop was designed to help identify a path forward for research by the U.S. Department of Energy (DOE) and. Leaders in global land-use-change modeling and experts in the land-cover and land-use data sets were assembled and encouraged to identify short- and medium-term research, data, and modeling needs in order to improve estimates of direct and indirect land-use effects of bioenergy. Oak Ridge National Laboratory (ORNL) and the Office of the Biomass Program (OBP) of the Energy, Efficiency and Renewable Energy (EERE) of DOE hosted the invitation-only workshop at Vonore, Tennessee, on May 11-14, 2009. This report is a direct product from the collaboration and discussions at the workshop.

This report presents background information on the issues related to land-use change estimation related to bioenergy, the regulatory environment, and the data and models that are being used to address effects of bioenergy use on the land (Section 2). Major science issues are presented in Section 3. Section 4 outlines the steps required to address these science issues, and several immediate research needs are described. The conclusion section (Section 5) highlights the major findings and benefits of the workshop. The appendices contain definitions pertinent to land use and bioenergy and a list of acronyms.

1.1 Workshop Objectives

The ultimate goal of the Land-Use Change and Bioenergy Workshop was to make scientific progress in addressing key issues regarding the estimation of direct and indirect land-use effects of bioenergy so that policy could be better informed. The overarching issue guiding the workshop discussion was that land-use change and bioenergy are key components of new policies and regulations, but the science to address these concerns must be improved with integrated research efforts.

Participants of the workshop were tasked with reviewing the state of the science, identifying opportunities for collaboration, and prioritizing next steps for the research needed to address key issues. Specific objectives set forth prior to the workshop covered eight areas:

- Identifying the key requirements, characteristics, and mechanisms for more effective modeling of the interactions among energy, agriculture, land use, and economics at regional, national, and global scales
- Developing a strategy to improve modeling tools for understanding the energy/agriculture/land-use nexus and for enabling simulations of the interaction between bioenergy choices and land-use changes
- Discussing the process and structure that would lead to the development of a benchmark data set that could be used for determining bioenergy land-use impacts
- Developing an understanding of the level of certainty associated with data and modeling outputs currently used to support policy decisions and steps that can be taken in the near and medium terms to reduce uncertainty
- Identifying opportunities to improve the quality and consistency of research and monitoring of the land-use impacts of bioenergy programs and policies, such as
    - collaborations to measure and analyze land-use and land-cover changes around the world and

    - comparing and linking data sets and models to understand the bioenergy-related driving forces behind those changes
- Developing plans for enhanced information sharing, networking, and collaboration to embrace the opportunities identified and to provide more reliable information in support of decisions and policies related to bioenergy
- Clarifying "best practices" for presenting land-use change research and modeling results that enhance transparency regarding assumptions, data sources, uncertainty, and limitations
- Beginning to develop a strategic research plan for DOE/OBP (and DOE laboratories) to fill key gaps and to develop improved science-based approaches for measuring the impacts of U.S. biofuel policies and programs on land use and related emissions.

The workshop focused on the data and models associated with understanding land-use change as reflected in the shaded circular area in the center of Figure ES-1. This figure illustrates that the predominant drivers of *initial* land-use change (e.g., deforestation driven by government policies and customary land claiming) often differ from the primary causes of *subsequent, ongoing* changes. Workshop participants considered gaps in current knowledge of the driving forces for land-use change and some of the evidence for potentially attributing these changes to bioenergy.

1.2 Workshop Structure

The workshop was designed to facilitate formal and informal exchanges among researchers in different disciplines and to improve understanding of what is known and not known about the land-use implications of biofuel choices. The workshop emphasized small-group discussions. Time was allotted for participants to identify and discuss intersecting research ideas and plans. Plenary sessions presented the background behind the workshop, reviewed key modeling and data issues, and allowed for discussion of breakout-group products to include strategies and plans for coordinated research agendas. The workshop was highly participatory and involved a team-building approach led by a professional facilitator. About 75 percent of the time focused on participation; the participants were involved via rotating roles and were mixed into various small groups. A rapid pace in structured sessions was meshed with extended working breaks to promote creative and energetic discussions. The structure of the workshop also allowed participants to introduce themselves and share brief descriptions of their relevant work. Innovations of the workshop included online communications before, during, and after the workshop; integrated participatory report writing; a focus on workshop goals and formation of task-oriented work groups from the beginning; invited short "3-in-5" presentations (presenting three slides in a maximum of five minutes); and web broadcast of plenary sessions for off-site observers.

1.3 Attendees

The workshop assembled leaders in global land-use-change modeling and experts in the land-cover and land-use data sets upon which the models rely. Their experience covers land-use changes from around the world in both developed and developing countries. In addition, some plenary sessions of the workshop were available via web cast. Among those who reported following workshop discussions via the internet connection were groups or individuals at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria; Argonne

National Laboratory, Lehrstuhl für Technische Thermodynamik; University of Maine; United States Department of Agriculture (USDA) Forest Service; University of Nebraska-Lincoln; Dupont Corporation; and Air Improvement Resource.

2. BACKGROUND

2.1 Perspective of the U.S. DOE on the Role of Biofuels in Land-Use Change[2]

The workshop was sponsored by DOE based on its strong commitment to sustainability. Progress toward DOE's goal of "diverse, domestic and sustainable energy resources" is being supported in part via the life-cycle impact assessment of a major scale-up in biofuels production, from feedstocks to vehicles. As a part of this assessment, DOE is committed to addressing issues related to land use, soil health, water use, air and water quality, and effects on greenhouse-gas emissions. DOE is also seeking ways to develop improved methods for assessing, monitoring, and measuring environmental effects of bioenergy options.

DOE's perspective on bioenergy is based on the Energy Independence and Security Act (EISA, December 2007)[3] that sets guidelines for a new U.S. Renewable Fuels Standard, including the requirement for analysis of lifecycle impacts of energy to include "aggregate quantity of greenhouse gas emissions (including direct emissions and significant indirect emissions such as significant emissions from land-use changes), as determined by the Environmental Protection Agency (EPA) Administrator, related to the full fuel lifecycle." The EISA Target of 36 billion gallons of biofuels by 2022 has implications for land use and for land-use change. To investigate those implications, DOE has contributed to an Interagency Report that compares pre-EISA USDA baseline crop production and land-use projections to EISA scenarios.[4] The scenarios modeled assumed no net loss in USDA Conservation Reserve Program lands. One of many interesting findings from this analysis was that the EISA biofuel production goals can be met with relatively small shifts among the cropland-pasture and pasture land categories and without significant changes in total cropland area.[5] Most scenarios illustrated how the mandates could be met through a combination of sources while using slightly less cropland than was projected in the pre-EISA reference case.

Accurately quantifying land-use change is critical in the U.S., California, and European regulatory arenas (as is discussed later in this report). It is also important to understand the implications of increasing use of biofuels in the broader context of strategies for climate change, energy security, and economic growth.

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[2] See Haq Z "Plenary presentation" on workshop web site: **http://www.ornl.gov/sci/besd/cbes.shtml**
[3] U.S. Public Law 110-140
[4] Biomass Research and Development Board. Increasing Feedstock Production for Biofuels. http://www.brdisolutions.com/default.aspx
[5] http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf and http://www.brdisolutions.com/Site%20Docs/Increasing%20Feedstock_revised.pdf

2.2 Indirect Land-Use-Change Debate

Efforts to quantify indirect land-use changes resulting from bioenergy are based on a set of assumptions and data inputs that simplify global supply, demand, and trade in order to model their relationships. Many existing models treat land use for biofuel production as directly removed from other land-using economic activities, because it is assumed that all existing lands are already committed. The implied shock to the land market causes prices to rise. These simplifications do not adequately account for the complex realities of land-use change resulting from the intricate relationships that exist among agriculture, forest use and deforestation, local and global economies, and land-tenure policies. It is important to quantify indirect land-use change as a precursor to estimating and managing greenhouse gas emissions as part of a full life-cycle assessment of bioenergy and other fuels.

However, the life-cycle analysis (LCA) studies mandated by EISA have their own set of technical requirements (eg the ISO 14040 Series) that are challenging to implement in the context of indirect land use change. For example, technical LCA requirements dealing with data quality, allocation, system boundaries and sensitivity analysis can profoundly shape the conclusions of land use change analysis. Many research challenges need to be resolved to adequately address these technical LCA requirements when conducting studies to estimate indirect land-use change.

Underlying the indirect land-use-change debate are differing opinions (and a lack of definitive evidence) about the relative importance and effects of drivers of land-use change, such as agriculture (broadly defined), land tenure, urbanization, and energy production. Because land-use change is often the result of a government's policy (or lack thereof) on developmental issues, both domestic and international, the way in which bioenergy policies interact with other drivers of proximate and distal (e.g., overseas) land-use change is not fully understood.

The greenhouse gas benefits of bioenergy have recently been questioned partly on the basis of economic modeling of indirect land-use changes. The actual emissions due to both direct and indirect land-use change depend heavily on where and how agriculture expands or intensifies. For example, the conversion of tropical forests, peatlands, and savannas to agricultural land releases large amounts of carbon to the atmosphere. If, as some theorize, biofuels are the direct cause of this conversion, a large "carbon debt" is created that could take decades or centuries to offset with the carbon benefits associated with biofuels use. If the initial conversion of land is fully and directly attributed to biofuels, and if the lands are assumed to be pristine prior to conversion, anywhere from 17 to 420 times more carbon dioxide could be released than the annual greenhouse gas reductions that are anticipated from the displacement of fossil fuels.[6] Global equilibrium economic models have estimated that indirect land-use change associated with an increased use of corn-based ethanol could potentially double greenhouse gas emissions associated with that fuel pathway in the next 30 years.[7] Both of these arguments are supported by model projections which suggest that, in any given future year, biofuels would cause farmers to convert forests and grasslands to new agricultural lands *that would otherwise be conserved*.

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[6] J. Fargione et al. 2008. ***Science*** 319:1235-1238.
[7] T. Searchinger et al. 2008. ***Science*** 319:1238.

However, the uncertainties in these model projections have not been fully assessed, and research to validate these indirect effects of biofuels is ongoing.

Other research has pointed out that most previously cleared land is underutilized, and assigning cause for new deforestation is not a simple task.[8] Moreover, estimating the location and area of abandoned agricultural land is not simple.[9] Land transformation and use are dynamic processes, influenced by social, economic, technological, biophysical, political and demographic forces.[10] Therefore it is challenging to estimate the incremental land-use change effect and carbon benefit of increased biofuel production.

Several assumptions and data inputs used to calculate the magnitude of potential land-use change associated with biofuels have been questioned recently.[11] It has been argued that the relationships between biofuels, commodity prices, trade and land-cover changes that are assumed by current modeling approaches (e.g. Searchinger et al., GTAP-CARB, and others) are not consistent with historic data for initial land conversion and expansion. For example, trade and land-use data for the U.S. and Brazil over the past six years of biofuel expansion show that while biofuels expanded, exports were maintained and deforestation diminished, contrary to model estimates. Approaches used to estimate a "carbon debt" from indirect land-use change assume that biofuels, rather than other policies and circumstances, are a direct causal factor for new land clearing. These approaches and models have not thus far considered how biofuels fit into larger, land-conversion dynamics that include ongoing deforestation, incremental degradation, fires, and mismanagement. In such circumstances, it is hypothesized that new biofuel markets can increase land-use efficiency and can help stabilize the agricultural frontier.[12] Data on the interactions among land degradation, fire, commodity markets and climate change, and their corresponding effects, are not readily available for use in modeling.

Measuring what really changes as a result of bioenergy policies and crops compared to what is expected to occur in their absence is an important challenge that must be addressed to improve land-use accounting.[13] To protect ecosystems and improve livelihoods through more sustainable land-use practices, the forces that actually drive deforestation should be better understood.[14] The scientific communities working with land-cover and land-use data sets, and those modeling

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[8] E. Lambin *et al*., *Annu. Rev. Env. Res*. **28**, 205 (2003); H. J. Geist and E. Lambin, *BioScience* **52**, 143 (2002) ; P. E. Kauppi *et al*., *Proc. Nat. Acad. Sci. U.S.A.* **103**, 17574 (2006); K. Kline and V. Dale 2008. ***Science*** 321:199.

[9] Campbell et al. 2008. *Environmental Science and Technology* 42:5791-5794.

[10] K. Kline and V. Dale 2008. ***Science*** 321:199.

[11] Goldemberg and Guardabassi. 2009. *Energy Policy* 37:10-14; Mathews J.A. and H. Tan. 2009. Biofuels, Bioproducts and Biorefining 3:305-317; R Keeney and TW Hertel.2009. Amer J Agric Econ 91:895-909; Liska AJ and RK Perrin. 2009. Biofuels Bioprod. Bioref. 3:318-328; Waasenaar T and S Kay. 2008. Science 321:20 ; Wang M and Haq Z 2008 http://www.sciencemag.org/cgi/eletters/319/5867/1238>http://www.scienc >emag.org/cgi/eletters/319/5867/1238; Holmes S 2008 http://www.sciencemag.org/cgi/eletters/319/5867/1238>http://www.scienc >emag.org/cgi/eletters/319/5867/1238

[12] Kline, et al. 2009. *Issues in Science and Technology* 25:75-84.

[13] Yuan et al. 2008 *Trends in Plant Science* 13:421-429; Negra et al. 2008. *Journal of Environmental Quality* 37:1376-1382; Kim et al. 2009. *Environmental Science and Technology* 43:961-967; Antizar-Ladislao and Turrion-Gomez 2008. *Biofuels, Bioproducts and Biorefining* 2:455-469.

[14] Robertson et al. 2008. *Science* 322:49-50.

biofuel impacts, play an important role both in improving our understanding and in communicating the findings to policymakers.[15]

2.3 Regulations and Policies Related to Bioenergy and Land-Use Change

2.3.1 U.S. Environmental Protection Agency

The United States Congress enacted the Energy Independence and Security Act (EISA) that calls for direct and indirect emissions from land-use change to be taken into account when calculating the climate performance of biofuels. EISA directs the EPA to promulgate a rule mandating that biofuels improve upon the greenhouse-gas emission profile of petroleum-based fuels based on a full life-cycle assessment of biofuel production and use. In May of 2009, the proposed rule was released for public comment.

In the life-cycle assessment of biofuels conducted for the proposed rule, greenhouse gas emissions from land conversion caused by international land-use changes (the so-called "carbon debt") were identified as ranging from 0% to more than 75% of the greenhouse-gas profile of biofuels.[16] EPA's economic modeling indicated that diversion of grain to meet EISA mandates would lead to (1) increased grain commodity prices and (2) decreased U.S. grain exports, thus resulting in global crop expansion and international land-use change.[17] The EPA accounted for increases in crop yields by looking at historic domestic and international trends and, for example, projected annual increases in corn yield up to 2022 of 1.6% in the United States and 1.1% in Brazil.[18]

EPA proposed a theoretical framework in which predicted global crop expansions can be distributed among a global supply of grasslands, savanna, forests, and shrublands on the basis of historical trends in land-cover change derived from remotely sensed images. To quantify these trends, 2001 and 2004 Moderate Resolution Imaging Spectroradiometer (MODIS) land-cover data at 1-km resolution were compared in ten countries including Brazil. For each country it was assumed that the proportion of land converted to cropland between 2001 and 2004 would be representative of future expansions of cropland due to biofuel policies. Changes in acreage from forested and other nonagricultural land to cropland were calculated. These changes were combined with Forest and Agricultural Sector Optimization Model (FASOM) and Food and Agricultural Policy Research Institute (FAPRI) model output to predict biofuel-driven, expanded global crop acreages (e.g., for corn ethanol, an increase of 0.13 domestic acres and 1.68 international acres per 1000 gallons of corn ethanol produced[19]). This expanded area of biofuel crops was used to estimate the amount of land conversion that would result from various biofuel policy scenarios. These acreages were then used with land-conversion greenhouse-gas-emission factors to calculate the greenhouse-gas emissions for different biofuel scenarios. The FASOM land-use-change results in the U.S. for the different fuel scenarios considered are shown in Table 1, and the FAPRI foreign land-use-change results for the different fuel scenarios are in Table 2.

[15] Tyner. BioScience 58:646-653.
[16] Technical Highlights: EPA Lifecycle Analysis of Greenhouse Gas Emissions from Renewable Fuels
[17] Ibid
[18] Ibid, p. 353.
[19] Ibid, table 2.6-22&23, p 354-356.

EPA's proposed rule discussed areas of uncertainty in its analysis and illustrated the importance of key issues with sensitivity analysis. Furthermore, EPA sought comment on a wide range of issues related to the estimation of indirect land-use-change impacts.

Table 1. Domestic Crop Expansion by Scenario, 2022 [from pages 354-356]
http://www.epa.gov/OMSWWW/renewablefuels/420d09001.pdf

Scenario	Total Cropland Increase (million acres)	Normalized Cropland Increase (acres per thousand ethanol equivalent gallons)
Corn Ethanol	0.3	0.13
Soybean Biodiesel	0.2	0.34
Corn Stover Ethanol	0.0	0
Switchgrass Ethanol	1.3	0.28

Table 2. Foreign Cropland Increase by Scenario, 2022 based on the FAPRI land-use-change results for the different fuel scenarios [from pages 354-356]
http://www.epa.gov/OMSWWW/renewablefuels/420d09001.pdf

Scenario	Total Cropland Increase (million harvested acres)	Normalized Cropland Increase (acre per thousand ethanol equivalent gallons)
Corn Ethanol	4.4	1.68
Soybean Biodiesel	0.9	1.87
Switchgrass Ethanol	1.3	0.41
Brazilian Sugarcane Ethanol	3.7	1.48

2.3.2 California Air Resources Board[20]

In contrast to the national approach being developed by EPA for the U.S., the State of California adopted a Low Carbon Fuel Standard (LCFS) and a corresponding proposed regulation. The regulation, which was subject to comment at the time of the workshop, requires life-cycle analysis for greenhouse-gas emissions including estimation of direct and indirect land-use change. Until the LCFS becomes final, stakeholders have the option to estimate life-cycle greenhouse-gas emissions with a wide range of fuel pathways by using official reports such as the August 2007 *California Energy Commission/Air Resources Board (CEC/ARB) Full Fuel Cycle Analysis*. The August 2007 *CEC/ARB Full Fuel Cycle Analysis* report is the foundation of the LCFS. The LCFS proposed regulation updated 14 common fuel pathways from the August 2007 CEC/ARB report with Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, version 1.8b. The regulation thereby designated default values for emissions that incorporate direct and indirect land-use change effects for several biofuel pathways.

[20] See McKinley Addy "3x5 presentation" on workshop web site: http://www.ornl.gov/sci/besd/cbes.shtml

2.3.3 European Union Policy

Still another approach to dealing with land-use change and bioenergy is being pursued in Europe. According to the European Commission, "land should not be converted for the production of biofuels if its carbon stock loss upon conversion could not, within a reasonable period, taking into account the urgency of tackling climate change, be compensated by the greenhouse gas savings resulting from the production of biofuels. This would prevent unnecessarily burdensome research by economic operators and the conversion of high carbon stock land that would prove to be ineligible for producing raw materials for biofuels."[21]

The European Commission hypothesizes that biofuels made from feedstocks produced on cropland will result in a net increase in cropland acreage. This pressure to convert could affect high-carbon-stock land, such as forests, including both deforestation and slowed afforestation, which would result in further carbon-stock losses. According to the European Commission, it is appropriate to promote measures to encourage increased rates of productivity on land already used for crops, the use of degraded land, and the adoption of sustainability requirements to help avoid expansion of global cropland into high-carbon-stock lands.[21]

The European Parliament and the Council of the European Union proposed that the Commission should develop a concrete methodology to minimize greenhouse-gas emissions caused by indirect land-use change by December 2010. In developing this methodology, the Commission will try to address the potential indirect land-use change resulting from biofuels produced from nonfood cellulosic material and from lignocellulosic material.[21]

Additionally, the Commission was directed to develop a methodology to calculate the indirect impacts of different biofuel crops and production pathways by the end of 2011. If an appropriate methodology is not developed, a default value of 40 g CO_2eq/MJ will be used in the life-cycle analysis of biofuels grown on agricultural land.[22] European Union member states are directed to report on the promotion and use of energy from renewable sources by June 30, 2011. These reports should include commodity price and land-use changes within the state associated with its increased use of biomass and other forms of energy from renewable sources. Furthermore, the Commission will monitor the origin of biofuels and other bioliquids consumed in the European Union and will track the impacts of their production on land use in Europe and in other primary countries of supply.[23]

Meanwhile, countries like the United Kingdom (UK) are pushing forward with their own policies and studies. A recent study from the UK on the effects of indirect land-use change from biofuels concluded that the sustainable biofuels industry has a future, but significant risks of consequential indirect land-use change are present.[24]

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[21] http://register.consilium.europa.eu/pdf/en/08/st03/st03740-re01.en08.pdf
[22] http://www.foeeurope.org/agrofuels/documents/
[23] http://ec.europa.eu/energy/climate_actions/doc/2008_res_directive_en.pdf
[24] Renewable Fuels Agency (2008b) The Gallagher Review of the indirect effects of biofuels production. Renewable Fuels Agency, UK.

2.3.4 Priority Issues for Science to Address Land-Use-Change Policy Concerns

There will always be uncertainty around the magnitude of greenhouse gas emissions resulting from indirect land-use change related to biofuel production, but a priority issue for science is to quantify and reduce this uncertainty to the extent possible. One reason for the current debate about indirect land-use change is that the output from scientific analyses can sometimes focus on different metrics from those needed to directly measure land-use change impacts. Therefore, workshop participants made important contributions toward resolving these issues with a set research questions related to indirect emissions from land-use change around which the scientific community can convene and build consensus.

Policy decisions with respect to biofuels will continue to be made. When scientific expertise is sought, scientists' responses often contain words such as "draft," "preliminary," "until better data become available," or "limited resources." This partly reflects the general cautiousness of scientists to jump to conclusions, but also reflects the true uncertainty that surrounds the science of emissions from indirect land-use change. A first priority for the scientific community is therefore to increase the level of collaboration and thus build consensus. For example, the goal could be for experts to come to an agreement on a conceptual framework of the factors that drive land-use change and particularly the causal factors behind *initial* conversion. A second priority would be the acquisition of reliable global land-use inventories. A third priority could be to develop a land-use-change model that addresses the issue at hand – estimating the effects of biofuels – based on a land-change model rather than adapting other models developed for different purposes (e.g., Global Trade Analysis Project (GTAP), Food and Agricultural Policy Research Institute (FAPRI), and others that include land area used for agricultural production but lack inventory data and validated mechanisms to attribute causes of initial land-use changes within a context of constantly shifting production areas). Since the underlying objective of such work in the United States is to produce data for life cycle analysis as directed by EISA, the technical requirements of LCA as noted above must be an integral part of the science.

2.4 Existing Global Datasets for Estimating Indirect Land-Use Change

Most common land-use or land-cover data are derived from remote-sensing images and survey or census data, with census or survey data focused largely on high value segments of the agricultural sector.

The data currently available for estimating the magnitude of the effects of indirect land-use change vary by scale, so it is important to discuss the data in a scale-specific way. At the local scale, rigorous studies of forest cover change (with measurements of forest cover at a minimum of two points in time using high resolution remote sensing) appear in journals every year. Since 2000, approximately 70 such studies have appeared in peer-reviewed journals. At the national scale, the quality of land-cover and land-use data varies considerably, with some countries such as Brazil and India collecting very high quality (remotely sensed) data and other countries, such as Indonesia and many African nations (e.g., Democratic Republic of the Congo and Gabon), collecting lower quality data or no data at all.[25] At the global scale, recent remotely sensed data, collected through a combination of MODIS and Landsat technologies, provide high quality estimates of changes in the extent of some land-cover types (such as large scale conversion from forest to cropland) but do a poorer job with providing accurate estimates of changes among land-cover types with more variable canopy cover such as shrubland, savanna and grasslands. MODIS and other global land-cover products also fail to produce accurate assessments of the extent of underutilized lands that are suitable for biofuel production, as the features of regrowth in landscapes are too subtle to capture with coarse resolution data.

Food and Agriculture Organization of the United Nations (FAO) estimates of national forest cover have long been used as the default global data set because no equivalent alternative was available. However, recent research, discussed below, has brought into question their suitability for use in high quality scientific analysis. Cropland data, available after 1960 in a time series format from FAO (Food and Agriculture Organization Statistics (FAOSTAT)), also vary in quality from country to country. Approximately one third of all countries in the database provide no information about the ways in which their data were collected.

Land-cover data sets are only one component of estimating indirect land-use change. While *land cover* represents the ecological condition of an area, *land use* incorporates the management practices that occur on the land. To build upon available land-cover data sets, many land-use models incorporate economic data to predict shifts in demand for agricultural products, assumed to affect the way people use land. Economic data are generally derived from country-level statistics, and a key uncertainty in using these data is the problem of downscaling country-level data (e.g., Gross Domestic Product (GDP), price elasticities of yield, trade patterns, etc.) to the subnational scale. Furthermore, economic and management data such as yield trends and agronomic practices in the less developed world are not well understood, yet these are critical to model projections. Therefore, even if very detailed land-cover data are available, the final output of a given land-use-change model will be degraded by a lack of similar detail in the economic and management data sets.

2.5 Combining Different Data Sources to Establish New Land-Use and Land-Cover Databases

The acknowledgment of differences in data sets and the possible complementarities between different data sets has provided the incentive to various institutions to prepare harmonized data sets, i.e., data sets that are spatially co-registered so that they can be overlain easily in a geographic information system. Table 3 provides a partial overview of a number of such data sets prepared at the global level. Many of the data sets combine (sub) national census data with remote-sensing information. Ramankutty et al. (2008) use satellite data to spatially disaggregate historical agricultural inventory data within each administrative unit. This way, the strength of the ground observations used to generate the inventory data is combined with the high spatial detail of data from remote-sensing platforms. However, given that crop and pastureland inventories were obtained from various government and other entities and were conducted at

[25] Hardcastle, P.D., D. Baird, V. Harden, P.G. Abbot, P. O'Hara, J.R. Palmer, A. Roby, T. Hausler, V. Ambia, A. Branthomme, M. Wilkie, E. Arends and C. Gonzalez. 2008. Capability and cost assessment of the major forest nations to measure and monitor their forest carbon. LTS International, 136 pp.

different scales, there is a risk of inconsistent definitions of agricultural and especially grassland or pastureland classes among countries (see discussion in Section 4.1.1), leading to a globally inconsistent map. Remote-sensing products often use a consistent interpretation globally. However, estimates of land-cover and land-use areas derived from remote sensing data tend to deviate strongly, due to uncertainties in the interpretation of the spectral signatures.
Similar techniques to integrate field observations with remotely sensed data have been used for individual countries or continents [e.g., Hurtt et al. (2001) integrated land-use statistics and remote-sensing data to generate a land-use map for the U.S., while Cardille and Foley (2003) combined remote-sensing and census data to estimate past agricultural land-use change in the Brazilian Amazon]. Historic data are more difficult to get than recent, country-level data sets. Therefore several attempts have been made to reconstruct historic land use based on sparse data on human population, potential vegetation and numerous model assumptions.[26]

Table 3. Overview of the Main Characteristics of a Number of Harmonized, Global Data Sets for Land Cover Based on the Combination of Different Individual Land-Cover Products.

Method	Reference	Thematic coverage	Spatial resolution	Time period
Remote sensing and (sub)national inventory data	(Ramankutty and Foley, 1998)	croplands	5 min	1992
Remote sensing and (sub)national inventory data	(Monfreda et al., 2008; Ramankutty et al., 2008)	Croplands, grasslands, 175 crop types	5 min	Circa 2000
National level census data and available thematic spatial data sets	(Erb et al., 2007)	Cropland, grazing, forestry, urban, transportation	5 min	2000
IGBP DIScover, Global Land Cover 2000 (GLC2000)	(Goldewijk et al., 2007)	Cropland and grasslands	5 min	1990-2000
Satellite imagery, ecological modeling, country surveys, existing maps of potential land cover and layers of the major anthropogenic land covers	(Sterling and Ducharne, 2008)	Cropland, built-up land, grazing land, wetlands, irrigated land, inundated land	5 min	1990-2000

[26] Examples of global land-cover reconstructions include (Klein Goldewijk, 2001Estimating Global Land Use Change Over the Past 300 Years: the HYDE Database, GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 15, NO. 2, PAGES 417–433, 2001; Pongratz et al., 2008. A Global Land Cover Reconstruction AD 800 to 1992- Technical Description - Reports on Earth System Science Berichte zur Erdsystemforschung 51 2008 51 2008; Ramankutty and Foley, 1999, Estimating Historical Changes in Global Land Cover: Croplands from 1700 to 1992 Global Biogeochemical Cycles, Vol. 13, No. 4, Pages 997–1027, 1999; Wang et al., 2006. A second generation human haplotype map of over 3.1 million SNPs, *Nature* **449**, 851-861 (18 October 2007)).

2.6 Existing Models for Estimating Indirect Land-Use Change Effects of Biofuel Production[27]

Several approaches exist to model land-use change dynamics[28] and biofuels demand[29]. The motivation for several recent efforts was apparently the increasing interest in biofuels impacts on food supply and also on greenhouse gas emissions. Modeling land-use change is a complicated task, since it requires the representation of a large number of important drivers at different scales. Important drivers include governance capacity, population growth, land tenure regimes, macroeconomic and trade policy, environmental policy, infrastructure, land suitability, domestic and international agricultural and energy markets, climate conditions, and many others. It is a huge challenge for any single model to represent even the most important of those forces within limited boundaries of time and space. As a consequence, there are several alternative approaches to assess land-use changes, none of them considered completely appropriate for all applications, but each one designed to consider some of the drivers. And, as with the data sets (Section 2.5), scale is a critical factor in considering the information provided by a model. Here we describe some of these alternative approaches and reference some of the most important models in each.

Figure 2 gives a general overview of modeling approaches dealing with land-use change induced by biofuels demand. The list of models in Figure 2 is not exhaustive but focuses on some better known examples. Some models in Figure 2 may fit more than one category. For example, some partial and general equilibrium models are also optimization models.

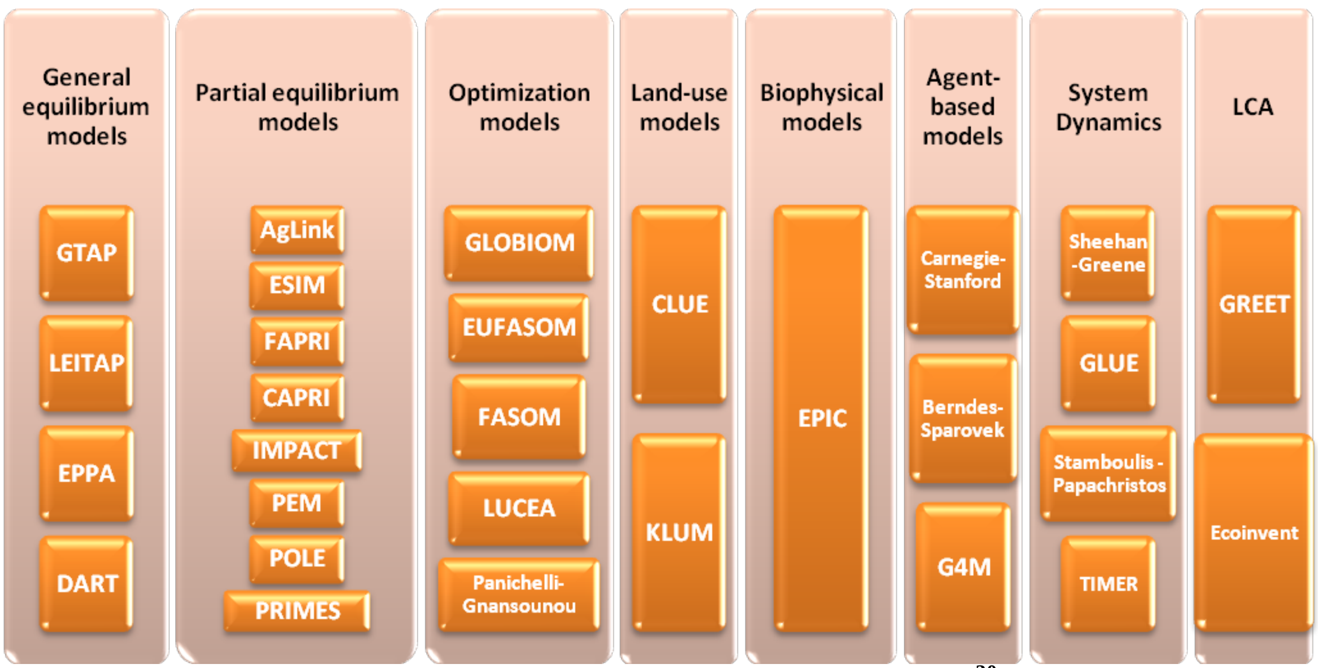

Figure 2. Overview of selected modeling approaches.[30]

[27] See Panichelli L "Plenary presentation" on workshop site: http://www.ornl.gov/sci/besd/cbes.shtml
[28] Heistermann M., C. Müller, K. Ronneberger, 2006. Land in sight?: Achievements, deficits and potentials of continental to global scale land-use modeling, Agriculture, Ecosystems & Environment, 114 (2-4) 141-158
[29] ftp://ftp.jrc.es/pub/EURdoc/JRC42597.pdf
[30] See Panichelli L "Plenary presentation" on workshop site: http://www.ornl.gov/sci/besd/cbes.shtml

General equilibrium models represent the whole economy and the main interactions between economic sectors of a single region or multiple regions. Many of the models in this class are now being applied to estimate the impact of European and U.S. biofuels mandates on global land-use demand, although they were originally developed for other purposes. Considerable improvements have been made in some of these models to include the biofuels sector and land allocation as a primary production factor. The main examples are represented by the GTAP,[31] Agricultural Economics Research Institute Trade Analysis Project (LEITAP),[32] Emissions Predictions and Policy Analysis (EPPA),[33,34] Dynamic Applied Regional Trade (DART)[35], and Future Agricultural Resources Models (FARM) (Figure 2).

Partial equilibrium models give a detailed description of a specific economic sector. Most of the models dealing with biofuels and land-use change are agricultural models, namely FAPRI[36,] FASOM[37] (and their global and European versions, GLOBIOM[38] and EUFASOM[39] respectively), IMPACT[40], AgLink[41], CAPRI[42], ESIM[43], PEM, and the energy sector models, such as POLE[44] and PRIMES[45] among others (Figure 2).

POLYSYS is a modular economic simulation modeling system of the U.S. agriculture sector in which planning decisions are made at the Agricultural Statistics District level and crop demands and market prices are solved at the national level. The integrated livestock sector is also solved at the national level. POLYSYS simulations are anchored to a baseline of projections such as those estimated by FAPRI, the U.S. Department of Agriculture, or the Congressional Budget Office.[46] POLYSYS has supported analyses for the Biomass Research and Development Board (BRDI Board) by examining land-use and emissions implications for meeting the EISA targets.

Optimization models aim to allocate resources by maximizing or minimizing an objective function, generally an economic objective function of profit or utility. The Land Use Change Energy and Agriculture Model (LUCEA[47]), the GLOBIOM, FASOM and EUFASOM models are currently being applied to estimate bioenergy demand and land-use change impacts. LUCEA is a dynamic non-linear programming model (economic optimization model) that was used to

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[31] https://www.gtap.agecon.purdue.edu/databases/v7/

[32] http://www.mnp.nl/en/themasites/image/model_details/agricultural_economy/Demandforfoodanimalsandcropsproducts.html

[33] http://www.lei.wur.nl/UK/newsagenda/Dossiers/Biobased_economy.htm

[34] http://globalchange.mit.edu/igsm/eppa.html

[35] http://www.ifw-members.ifw-kiel.de/publications/integrating-biofuels-into-the-dart-model/KWP%201472.pdf

[36] http://www.fapri.iastate.edu/models/

[37] http://www.fs.fed.us/pnw/pubs/pnw_rp495.pdf

[38] http://cgse.epfl.ch/webdav/site/cgse/shared/Biofuels/Regional%20Outreaches%20&%20Meetings/LUC%20Workshop%20Sao%20Paulo/Presentations%20day%202/Havlik.pdf

[39] http://www.fnu.zmaw.de/fileadmin/fnu-files/publication/working-papers/wp156_eufasom.pdf

[40] http://www.ifpri.org/themes/impact/impactresearch.asp

[41] http://ageconsearch.umn.edu/bitstream/14808/1/ospawp08.pdf

[42] http://www.ec4macs.eu/home/capri-news.html

[43] http://wwwuser.gwdg.de/~mbanse/publikationen/dokumentation-esim.pdf

[44] http://www.enerdata.fr/enerdatauk/tools/Model_POLES.html

[45] http://www.e3mlab.ntua.gr/manuals/PRIMsd.pdf

[46] http://www.agpolicy.org/polysys.html

[47] Johansson D., Azar C., 2007. A scenario based analysis of land competition between food and bioenergy production in the U.S., *Climatic Change* 82.

analyze land-use competition for food and bioenergy in the U.S. GLOBIOM, FASOM and EUBIOM are partial equilibrium optimization models currently adapted to estimate changes in prices, produced quantities and allocation of land and primary resources for biofuels. REAP is a comparative-static, regional, mathematical programming model of U.S. agriculture that seeks to determine the set of prices and quantities that establish equilibrium in several related markets by maximizing net social benefit.[48]

Panichelli and Gnansounou[49] developed a constrained non-linear optimization model to perform carbon pay-back time scenarios in biofuels production. The model calculates GHG emissions from direct and indirect land-use changes based on a set of assumptions about the feedstock production and the potential displacements.

Spatially explicit land-use models focus on the spatial allocation of land, based on land suitability, productivity, and available infrastructure and transport costs. The CLUE[50] model has been applied to estimate land allocation for bioenergy crops to fulfill European mandates for biofuels. KLUM[51] is a land-use model that employs the Lund-Potsdam-Jena (LPJ) dynamic global vegetation model to simulate biofuel feedstocks and other crops.[52]

Biomass production depends not only on economic drivers but on biophysical characteristics of the site where the biofuel feedstock is produced. *Biophysical models* such as EPIC[53] attempt to incorporate biophysical, site-specific issues.

The Integrated Model to Assess the Global Environment (IMAGE[54]) integrates and links many models including models dealing with biophysical issues. IMAGE is an ecological-environmental framework that simulates the environmental consequences of human activities worldwide. It represents interactions between society, the biosphere and the climate system to assess sustainability issues like climate change, biodiversity and human well-being.

In modeling land-use changes at the local/regional level, actors' behaviors, preferences and heterogeneity are main factors in explaining the type and location of the land-use change. *Agent-based models* (ABM) focus on the simulation of actors' decisions. Some ABM models are being developed to simulate sugarcane expansion dynamics in the Brazilian agricultural frontier (e.g., a model developed by the Carnegie Institution for Science and Stanford University[55] and an agent-based approach under development by G. Berndes of Chalmers University, Sweden, and G. Sparovek, University of São Paulo, Brazil).

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[48] http://www.ers.usda.gov/Publications/TB1916/

[49] Panichelli, L., Gnansounou, E. 2008. Estimating greenhouse gas emissions from indirect land-use change in biofuels production: concepts and exploratory analysis for soybean-based biodiesel production; J. of Scientific & Industrial Research, 67, 1017-1030

[50] http://www.cluemodel.nl/index.htm

[51] http://www.uni-hamburg.de/Wiss/FB/15/Sustainability/KLUM_WP.pdf

[52] http://www.earthsystemschool.de/fileadmin/user_upload/Documents/Theses/

[53] http://www.brc.tamus.edu/simulation-models/epicapex.aspx

[54] http://www.mnp.nl/en/themasites/image/index.html

[55] http://cgse.epfl.ch/webdav/site/cgse/shared/Biofuels/Regional%20Outreaches%20&%20Meetings/LUC%20Workshop%20Sao%20Paulo/Presentations%20day%202/Fernandez.pdf

System dynamics models that are being applied to land-use issues have the capability to simulate time-dependent phenomena such as land-use change and account for feedbacks in the system. Some system dynamics models are being used to simulate the biofuel production chain in the U.S. accounting for land in the feedstock-production phase[56] and the greenhouse-gas emissions from indirect land-use changes (e.g., Systems Thinking Experimental Learning Laboratory with Animation (STELLA)[57]). The Targets IMAGE Energy Regional (TIMER[58]) model is a sub-model of the Integrated Model to Assess the Global Environment. It is a system dynamics model of the global energy system used to perform long-term analysis of energy conservation and the transition to non-fossil fuels.

EISA 2007 (current U.S. renewable fuels law) requires estimating greenhouse-gas emissions from land-use changes induced by biofuels.[59] *Life cycle assessment (LCA) models* quantify and sum the emissions associated with the life cycle of a given biofuel pathway. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET[60]) tool examines a large set of U.S. transportation fuels and vehicle systems. The Ecoinvent[61]database is another tool that uses a similar approach. GHGenius is another LCA model for the transportation sector, which is maintained by Natural Resources Canada. GHGenius[62] is a spreadsheet model that calculates the amount of greenhouse gases generated from the time a fuel is extracted or grown to the time that it is converted in a motive energy vehicle to produce power. GHGenius identifies the amount of greenhouse gases generated by a wide variety of fuels and technologies, the amount of energy used and provided, and the cost-effectiveness of the entire life cycle. To date, these LCA tools have considered direct land-use change and associated greenhouse gas emissions but require integration with other modeling systems or expansion of the existing models to capture indirect land-use changes.

The purpose of LCA is to document the economic and environmental effects of a given production of service, in this case for biofuels and for petroleum fuels. Therefore, significant indirect effects (not just possible land-use effects) of both of these fuels should be estimated, a process that has not yet begun in earnest. One model cannot tackle all issues and model integration is needed to account for feedbacks and interactions between the agricultural and the energy sectors. Different model integration approaches have been attempted. Examples of integrating or linking frameworks include: economic-biophysical models (LEITAP-IMAGE[63], GTAP-KLUM59), general equilibrium and partial equilibrium models (GTAP-FAPRI, GTAP-IMPACT, GTAP-PEM[64]), economic-forestry models (GLOBIOM-G4M[65]), economic-energy

[56] Bantz S.G., M.L. Deaton, 2006. Understanding U.S. Biodiesel Industry Growth using System Dynamics Modeling, Proceedings of the 2006 Systems and Information Engineering Design Symposium, Michael D. DeVore, ed., http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=04055130
[57] http://www.bio.org/letters/CARB_LCFS_Sheehan_200904.pdf
[58] http://www.rivm.nl/bibliotheek/rapporten/461502024.pdf
[59] This provision of the law may change. The U.S. House of Representatives passed a measure that allows five years to improve the science before applying indirect land-use change factors to biofuel LCA. The Senate is considering similar language to delay or eliminate the application of indirect land-use changes in LCA of renewable fuels.
[60] http://www.transportation.anl.gov/software/GREET/
[61] http://www.ecoinvent.ch/
[62] http://www.ghgenius.ca/
[63] http://www.lei.wur.nl/NR/rdonlyres/1E914875-C76F-4C90-A9C0-39087151C5BD/57425/25_Scenar2020.pdf
[59] https://www.gtap.agecon.purdue.edu/resources/download/3681.pdf
[64] http://www.oecd.org/document/6/0,3343,en_2649_33777_36642246_1_1_1_1,00.html

models (LEITAP-TIMER[66]), economic-agricultural models (AgLink-SAPIM, IFPSIM-EPIC, GTAP-CAPRI-FSSIM), economic–land-use models (GTAP-CLUE)[67], and economic-environmental models (GTAP-FAPRI- FASOM-GREET-Winrock-BESS-CENTURY-ASPEN-MOVES-NEMS, GTAP-CA-GREET).

3. SCIENTIFIC, TECHNICAL AND METHODOLOGICAL ISSUES FOR ESTIMATING INDIRECT LAND-USE CHANGE

3.1 Model Limitations and Uncertainties[68]

3.1.1 Uncertainties in Current Land-Use Models

Some of the uncertainties in land-use model results related to bioenergy derive from model structure and assumptions that reflect gaps in data or historic knowledge, as well as the common need to simplify models. Most models currently used to estimate global land-use change effects of biofuels were developed for other purposes; many therefore omit factors and land classifications that are relevant for estimating land-use change. Compromises between spatial and temporal resolution, conceptual frameworks, combinations of model components and computer power can also lead to increasing or compounding uncertainties. The uncertainties in model structure can lead to varying results from different models. For example, Priess's presentation comparing results from two land-use-change models for assumed biofuel production volumes showed widely varying land-supply requirements.[69] In addition, some of the large uncertainties in land-use-change projections reflect uncertainties in model parameters (i.e., data inputs as described in Section 3.2.1).

The global equilibrium models used to simulate land-use change and bioenergy choices do not consider all the major drivers of this change. The basic assumption of these equilibrium economic models is that global economic forces drive land-use changes. The models do not include environmental, technological, political, cultural and demographic forces or address issues that have been documented to affect local or regional land change, especially first-time land conversion[70]. Moreover, this information is not generally known for many regions of the

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[65] http://www.occ.gov.uk/activities/eliasch/Gusti_IIASA_model_cluster.pdf
[66] http://www.mnp.nl/en/themasites/image/model_details/energy_supply_demand/index.html
[67]http://cgse.epfl.ch/webdav/site/cgse/shared/Biofuels/Regional%20Outreaches%20&%20Meetings/LUC%20Workshop%20Sao%20Paulo/Presentations%20day%202/Fernandez.pdf
[68] Based on: Verburg, Rounsevell, Veldkamp, 2006. Agriculture, Ecosystems and Environment 114. and Schaldach, R.; Priess, J.A. (2008). Integrated Models of the Land System: A review of modeling approaches on the regional to global scale. Living Reviews on Landscape Research 1, 1-37.
[69] See Priess J "3X5" on workshop web site: http://www.ornl.gov/sci/besd/cbes.shtml and Lapola D.; Bondeau A., Priess J.A. (2009). Modeling the land requirements and potential productivity of biofuel crops in Brazil and India. Biomass & Bioenergy, doi:10.1016/j.biombioe.2009.04.005 http://dx.doi.org/10.1016/j.biombioe.2009.04.005>
[70] Veldkamp A, Lambin EF. 2001. *Agriculture, Ecosystems & Environment* 85:1-6; E. Lambin *et al., Annu. Rev. Env. Res.* 28, 205 (2003) ; H. J. Geist, E. F. Lambin, *BioScience* 52, 143 (2002) ; P. E. Kauppi *et al., Proc. Natl. Acad. Sci. U.S.A.* 103, 17574 (2006);Heistermann M, C Müller, K Ronneberger. 2006. Land in sight? Achievements, defecits and potentials of continental to global scale land-use modeling. Agriculture, Ecosystems & Environment 114:141-158; K. Kline and V. Dale 2008. *Science* 321:199.

world. Assessing indirect impacts of bioenergy policy on first-time conversion using such models is speculative, and resulting levels of uncertainty in model outputs are unknown.

Some models used to estimate effects of bioenergy on the land were designed for analyzing trade. Adapting them to predict changes in land use requires data on land-use parameters; however that information varies across locations and is uncertain at a global scale. Some land categories, such as abandoned, secondary growth (under long rotations) and wilderness land, have no market presence and thus have no effective presence in some of the models that are oriented to economic exchange; yet these land categories are large and could be important for estimating land-use change. The lack of inclusion of land categories appropriate for biofuel feedstocks is an important deficiency in some models that needs to be addressed in future model development.

Moreover, the global economic models for bioenergy assessment depend on land-cover data that do not capture the intricacies of land-use practices and their effects on the environment. These practices have a strong effect on above-and below-ground carbon storage as well as runoff of sediment and nutrients from croplands and potential future use of the land. Yet only land-cover data as observed by satellites are available for much of the world.

Few models (so far) properly represent dynamic responses to initial shocks over time. Computable general equilibrium models, for example, are instantaneous adjustment models used to measure effects of a perturbance to their baseline conditions.

Potential future scenarios are often not considered in current models, such as technological changes in biofuel systems. For example, double cropping can increase agricultural output with no new land required. If demand for agricultural feedstocks rises as a result of biofuel demand, history suggests that technological changes will drive increased land-use efficiency. However, land-use models and scenarios currently do not address these potential effects that go beyond simple price-induced yield changes. Another example of a neglected scenario is climate change. Few models incorporate climate change as a driver for land-use change, and models do not appear to reflect land-use consequences of future scenarios that depend less on fossil fuels and more on other alternative sources of energy.

General-equilibrium economic models are built on databases that aggregate price and elasticity data derived from multiple sources of varied reliability. The databases are often out of date (i.e. more than 5 years old) and severely limited by the necessity to use average values. Necessarily, land-use models have finite resolution. Model resolution is often coarse, and data aggregation limits the ability to model important interactions at finer scales. For example, the GTAP model aggregates corn into a category of “coarse grains” with sorghum, oats and other coarse grains. This combination eliminates the ability of the model to reflect shifts in land-use among these similar crops even though empirical data show that such shifts occur. Indeed, shifts from sorghum to corn help explain how corn-ethanol production in the U.S. roughly tripled between 2001 and 2006 while the area actually dedicated to “coarse grains” shrank, despite all modeling results to the contrary.[71] Yield was another important factor accounting for this increase.

[71] Kline KL, Dale VH, Oladosu GA; 2009. Feedstock & Bioenergy Sustainability: Land-Use Change Modeling for Bioenergy. Presentation for the April 9, 2009, DOE Feedstock Platform Peer Review, Washington, D.C.

In general, land-use change is attributed to a fuel on a unit basis. If the system response is not linear with the size of the fuel volume increment, model outputs may misrepresent the land-use change for a marginal unit or for the total fuel production, unless the model is able to properly represent this nonlinear response.

Land-use change for biofuels is currently estimated by the process summarized in the first three boxes in Figure 3. Each stage contributes cascading uncertainties to the estimates of carbon, other emissions, and economic effects.

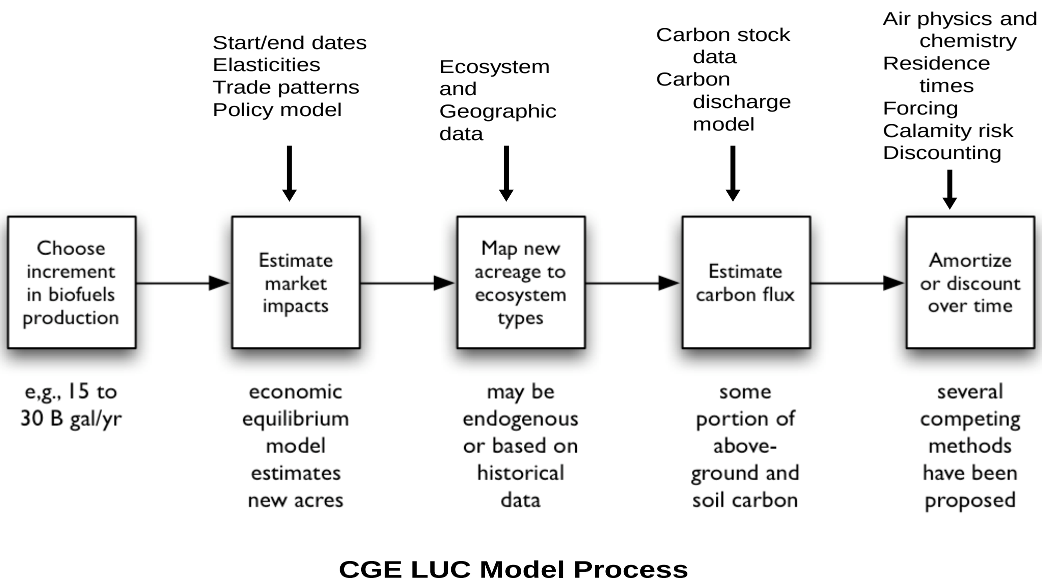

Figure 3. A process for modeling effects of bioenergy. (CGE is computable general equilibrium; LUC is land-use change.)

As individual models "feed" into each other, the uncertainties multiply through the "propagation of errors" effect. For example, integrated (i.e., coupled) modeling approaches employ two or more component models to represent sub-systems or processes such as plant growth or various environmental impacts. In some parts of the world, models are used to generate land-use data at local and sub-national levels and for national reporting. The overall uncertainty from a set of linked models is always larger than the uncertainty from any individual model in the set. However, the uncertainties associated with the results of submodels (and the resulting products of uncertainty propagation), are rarely communicated to users, are ignored, or most often, are unknown.

Life-cycle analysis models have the distinct challenge of setting spatial and temporal bounds of analysis, which clearly affect results. Robust models used in LCA studies must consider the process of transitions that occurred prior to the land being used for biofuels, what productive uses were made of standing biomass prior to or during land conversion processes, how the land was being managed or used immediately prior to use for biofuels, and how it would most likely

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http://www.bcsmain.com/mlists/files/biomass/obpreview2009/feedstocks/documents//Feedstock_Sustainability_Kline_1.1.1.6b_v3.pdf be used in the future in the absence of biofuels, as these factors can have profound impacts on life-cycle greenhouse gas emissions. Also, models need to include the likely patterns of land management post-conversion to biofuels or another use, as these management strategies will also impact greenhouse gas emissions. For example, using conservation tillage and cover crops has been shown to significantly reduce greenhouse gas emissions for both grassland and temperate forest conversion,[72] and in many parts of the world, long-term rotations among agriculture, grasslands, and forests are the norm and include extensive and repeated use of fire. The inclusion of bioenergy crops in such a rotation system could either (a) be perceived as causing significant emissions if only two points in time are considered or (b) be perceived as generating large net savings in GHG emissions under a more comprehensive analytical comparison of land management practices and emissions over time.

3.1.2 Uncertainty in Model Feedback Loops[73]

Land-use change related to bioenergy choices may be dependent on initial conditions, and small, essentially random events may lead to very different outcomes, making prediction problematic, especially at the local level. Changes in land use and land cover often have nonlinear feedbacks, and thresholds often play an important role.[74] For example, certain trajectories of land-use change may be the result of "lock in" that comes from systems that exhibit autocatalytic behavior. In these cases, dynamic modeling and the subdivision of the simulation period into time-steps becomes essential. Only then can land-use-change analysis account for the path-dependency of system evolution, the possibility of multiple stable states, and multiple trajectories. Land-use change cannot be explained simply as the equilibrium result of the present set of driving forces. Yet, many biofuel assessments rely on partial equilibrium models to calculate future states of land use.

Many current land-use models treat interactions and feedbacks within and between the social and the environmental components in a simplified manner. In many approaches, competition among different land uses is simulated explicitly, while the level of aggregation of land-use or land-cover types is related to the model's purpose (e.g., comparing wheat versus corn or food crops versus biofuel crops versus urban land). However, most models focus on certain aspects of land systems and their dynamics, such as agriculture, forestry, and urbanization, and represent other sectors as external drivers or treat them in a simplified manner.

In most deforestation and urbanization models, a one-way conversion from one land-use category to another is assumed because of the focus on a single land-use conversion.[75] However,

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[72] Kim H, S Kim and B Dale, 2009. Biofuels, Land Use Change, and Greenhouse Gas Emissions: Some Unexplored Variables. Environmental Science &Technology 43Z: 961-967.
[73] Based on: Verburg PH (2006) Simulating feedbacks in land use and land cover change models. Landsc Ecol 21:1171-1183 and Verburg PH, Schot P, Dijst M, Veldkamp A (2004) Land use change modeling: current practice and research priorities. Geojournal 61:309-324.
[74] Turner II 1997. "The Sustainability Principle in Global Agendas: Justifications for Understanding Land Use/Cover Change". *Geographical Journal* 163: 133-140. ; Turner II et al. 2003. *Integrated Land Change Science and Tropical Deforestation in Southern Yucatan: Final Frontiers*. (Oxford: Clarendon Press of Oxford University Press), forthcoming; Steffen et al. 2004 *Global change and the Earth system: a planet under pressure*. Berlin:Springer.

in agricultural and semi-natural landscapes, changes in land use are often reversible or cyclical. In the Amazon, for example, recent research suggests that a third of forest area initially cleared "for pasture" had been abandoned by the early 1990s.[76] While the land-use history of a location can help estimate feedbacks and future use in that location, it may not be applicable to other seemingly similar locations. Thus, land-use change processes are often location and path-dependent. This complexity arises from particular chains of events and sequences of causes and effects that lead to specific land-use changes.[77]

Land-use-change decisions are made at different time scales; some decisions are based on short-term dynamics (such as daily weather fluctuations); others are based on long-term dynamics (such as climate change). Most land-use-change models use annual time steps in the calculations, implying that short-term dynamics are often ignored or aggregated to annual changes. However, this temporal aggregation can hamper linkages to decisions made over shorter time scales.[78] Temporal complexity and feedback mechanisms still pose a major challenge to land-use/cover change modelers. Overcoming this challenge would involve developing well balanced approaches for adequately dealing with this complexity and appropriate tools to validate predictions of path-dependent systems.

The combination of temporal and spatial dynamics of land-use change often causes complex, non-linear behavior in these models. However, many land-use models are based on an extrapolation of the trend in land-use change through the use of a regression on this change.[79] These types of models are less suitable for long-term scenario analyses because they are valid only within a certain temporal range of land-use change, usually one or two decades. The validity of historical relationships may also be violated if competitive conditions exist between land-use choices. This critique does not apply to all empirical models. 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 modeling of competition between land-use types, they may have a much wider range of applications.

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[75] Clarke, K. C., and L. J. Gaydos, Loose-coupling a cellular automaton model and GIS: long-term urban growth prediction for San Francisco and Washington/Baltimore, *International Journal of Geographical Information Science*, 12**,** 699–714, 1998. Pontius, R. G., and P. Pacheco, Calibration and validation of a model of forest disturbance in the Western Ghats, India 1920–1990, *Geojournal*,
in press, 2004.

[76] Rodrigues ASL, Ewers RM, Parry L, Souza C et al. 2009. Boom-and-Bust Development Patterns Across the Amazon Deforestation Frontier. *Science*, 324 (5933): 1435-1437.

[77] Lambin and Geist 2003. Dynamics of Land-Use and Land-Cover Change in Tropical Regions. Annual Review of the Environment and Resources 28: 205-241.

[78] Laney, R.M., 2004. A process-led approach to modeling land change in agricultural landscapes: a case study from Madagascar. Agric. Ecosyst. Environ. 101, 135–153.

[79] Mertens, B., Lambin, E.F., 2000. Land-cover trajectories in southern Cameroon. Ann. Assoc. Am. Geogr. 90 (3), 467–494; Geoghegan, J., Villar, S.V., Klepeis, P., Mendoza, P.M., Ogneva-Himmelberger, Y., Chowdhury, R.R., Turner II, B.L., Vance, C., 2001. Modeling tropical deforestation in the southern Yucatán peninsular region: comparing survey and satellite data. Agric. Ecosyst. Environ. 85, 25–46.; Schneider, L.C., Pontius Jr, R.G., 2001. Modeling land-use change in the Ipswich watershed, Massachusetts USA. Agric. Ecosyst. Environ. 85, 83–94.; Serneels, S., Lambin, E.F., 2001. Proximate causes of land use change in Narok district Kenya: a spatial statistical model. Agric. Ecosyst. Environ. 85, 65–81.

3.1.3 Challenges for Model Validation

It is important to distinguish between the uncertainty of model inputs (parameter values) and model errors, i.e., the poor representation of a land-use-change process. The latter type of error can be assessed through model validation, coupled with studies of the drivers of land-use change. Although techniques for the validation of spatially explicit land-use models are available, consistent historic databases on land use must also be available to allow a proper comparison.[80] In most cases, the uncertainty in the land-use databases themselves is tremendous. For example, differences between baseline measures for the same time and place in different databases may be larger than the observed changes.[81] Therefore, the quality of input data to scenario studies is an issue of considerable importance, because it could have a potentially large effect on the scenario outcomes. To complicate the situation further, some data sets necessary for validation are available only at high cost, some are not publicly available, and the most useful information, such as causal factors of deforestation, simply has not been collected. Differences in modeling results may reflect differences in input databases, and agreement between outputs from different models may simply reflect a common set of questionable input data rather than an indication of the validity of the results. Validation should, therefore, be based on observed land-use data.

3.1.4 Key Questions for Model Improvement

Current models of the evolution of land use are not capable of fully representing the social, economic, and environmental effects of land-use change as related to bioenergy choices. Ongoing work to improve those models would be facilitated with some agreement on key questions:

- Which areas of the world where bioenergy-driven land-use change may occur should be the first to be added to economic models in more detail?
- Which drivers of land-use change should be added to models?
- Which land categories should be added to models?
- Which future scenarios should be simulated or considered?
- What land-use and land-cover data are needed to support the models?
- At what resolution and precision should those data be collected?
- How should the measurements and data be structured?
- How should data from disparate sources be managed and distributed?
- How much would it cost to acquire the data?
- Who should invest in this data-collection activity?

[80] Pontius, R.G. et al. 2004. Useful techniques of validation for spatially explicit land-change models. Ecological Modelling 179(4), 445-461; Pontius, R.G. et al. 2005. Comparison of the structure and accuracy of two land change models. International Journal of Geographical Information Science 19(2), 243-265; Pontius, R.G. et al. 2005.Uncertainty in extrapolations of predictive land change models. Environment and Planning B 32, 211-230.

[81] Dendoncker, N. et al. 2008. Exploring spatial data uncertainties in land-use change scenarios. International Journal of Geographical Information Science 22(9), 1013-1030; Also see Johannes Feddema, Department of Geography, The University of Kansas: Understanding and Reconciling land use/land cover data sets; 2008.

3.1.5 Model Documentation

Documenting model assumptions, sensitivities, uncertainties, and limitations is a key part of the modeling process.[82] Descriptions of a model's structure should always specify all key assumptions, document values and sources used for key parameters, outline the validation process the model has undergone, and highlight sensitivity of model output to various model inputs.[83] Most models offer some documentation at the web site of the institution responsible for the model and one or more peer-reviewed publications in economic or environmental science journals. Many of the models that are used to analyze bioenergy and land-use change have been developed over many years and have relatively complicated structures, which require a large amount of documentation and also a sophisticated, technical user with expertise in multiple aspects of the multidisciplinary models. It is difficult to understand the complexity of the models, especially the integrated frameworks, without considerable training. It is expected that each model should explicitly report the main parameters and assumptions impacting the results of land-use-change estimation, so that results may be compared and transparency assured. Too often, transparency and documentation of important input specifications and other assumptions are insufficient for the level of complexity of the models.

3.2 Data Limitations and Uncertainties

3.2.1 Uncertainties in Land-Use and Land-Cover Data

During the workshop, a recurring theme emerged in many different work groups: the current generation of land-use-change models is limited by the availability of relevant data sets. The current world database of land use and land cover is handicapped by inconsistently categorized data resources from different data sources that use varying conventions (for example, soil depth for carbon measurement), and which are often unconfirmed by on-the-ground sampling observation.

At the most fundamental level, there is a general lack of information on what combination of underlying factors are driving land-use change, with a particular lack of data on economic supply and demand and on the social drivers of land-use change. Remote-sensing data from satellites, although illustrative of many changes in the landscape, do not generally provide the level of detail necessary to predict the land available for biofuel production and what intensity of production the land can support. At this point, several questions still loom among the research community with respect to the use of land for the production of biofuel feedstocks:

- What data and combinations of data will be most valuable?
- Which countries are important?
- What are the qualities of the data and the methodologies used to generate them?
- To whom are the data available (i.e., the public)?
- Through what sources are the data available?

[82] Dale, V.H. and W. Van Winkle. 1998. Models provide understanding, not belief. *Bulletin of the Ecological Society of America* 79(2): 169-170.
[83] Aber, J. 1997. Why don't we believe the models? Bulletin of the Ecological Society of America 78(3): 232-233.

One specific problem encountered when investigating available datasets is that most do not consider land management and greenhouse-gas emissions, but only land-cover change (conversion). The datasets are not designed as part of a monitoring system for many proposed biofuel feedstocks such as crop residues and perennials or for facilitating the calculation of their greenhouse-gas budgets. Agronomic practices in developing countries, such as those involving the use of long term rotations and fire, are not adequately reflected in the data classifications, leading to large gaps regarding fundamental information on the amounts and locations of previously cleared land available for agricultural production. The variability in crops and global land management practices (which are directly linked to economics and greenhouse-gas emissions) cannot be modeled because no global data sets are available. Specifically, consistent and precise information about carbon stocks, nitrogen stocks, and land-use- and land-cover-specific fluxes of carbon and nitrogen, are not available at the global scale.

Land-use and land-cover data originate from different sources and inventory techniques, each with its own domain of applicability and quality standards. Generally, data are selected without explicitly considering the suitability of the data for the specific application, the bias originating from data inventory and editing and the effects of the uncertainty in the data on the results of the assessment. Standard data sets should be available for validation or verification of model results from back-casting. However, adequate validation of models to certify them for global use may not be feasible in the near term due to data limitations.

While remote-sensing data can provide a high spatial and temporal resolution, the raw imagery alone does not reveal how the land is managed. Furthermore, due to similarities in reflectance values among different land-cover types, uncertainty in land-cover information is often related to the level of thematic disaggregation and the land-cover type of interest. Census or survey data are mostly focused on the agricultural sector and may deviate widely between countries in terms of definitions of land-use classes and inventory techniques. However, if properly collected and reported, census data can provide a valuable source of information on land management that is highly relevant to bioenergy and climate change assessments.

Potential bias introduced as a result of temporal and spatial aggregation of the data is a valid concern when working with large datasets. Selecting an appropriate resolution for data analysis and aggregation procedures should depend on the characteristics of the landscape under study and the features of interest, not the convenience or cost of acquiring it. Direct comparison of different data sources is often hampered by differences in definitions of land-use or land-cover classes. Because of differences in the intended application of the data and the regional context, widely diverging definitions are used for similar land-use or land-cover types. Moreover, many changes in land use and management are not observable from land-cover data, which may lead to an underestimation of change and impacts. Newer, higher resolution satellite images (e.g. Ikonos[84], QuickBird[85]) may change this condition, leading to better estimates in the future.

Access to data was also mentioned as a problem at the workshop, because even in cases where data sets that could support relevant analyses exist, they may be too costly or unavailable to the public. This lack of relevant, accessible data contributes to overall uncertainty in model output

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[84] http://www.satimagingcorp.com/satellite-sensors/ikonos.html
[85] http://www.digitalglobe.com/index.php/85/QuickBird

and limits the applicability of models to answer key policy questions. Therefore, increased transparency and collaboration are necessary for improving estimates of indirect land-use change. The workshop was an important step towards achieving this.

Time-series analyses play a key role in estimating changes in land cover over time, yet these analyses are often problematic due to the use of different sensors over time, the use of different classification schemes between years, and the use of different definitions of various land-cover classes between regions and between data products. The danger that comes with these discontinuities is that land-cover changes that appear to be "real" may be no more than an improvement in data quality or a change in methods over time. For example, FAO conducts its Forest Resource Assessment every five years and requests that countries report their total forest area. As mentioned above, country-level data vary in quality and completeness and are often out of date. Although many countries report their national statistics to the FAO, these values do not necessarily reflect actual measurements of the parameter in question or the designated time period. Some countries may estimate current forest area based on the extrapolation of an approximate measurement that was made as much as ten or more years in the past. Furthermore, national perceptions affect the quality of the data because definitions of different land-cover classes can vary from country to country and region to region. Although FAO standardizes its forest definition, the definition of other land-cover types (e.g., savanna) can be much more variable and problematic. The result in the FAO example is an apparent loss in the same area of global forests several times over the past twenty years, as depicted in Figure 4.

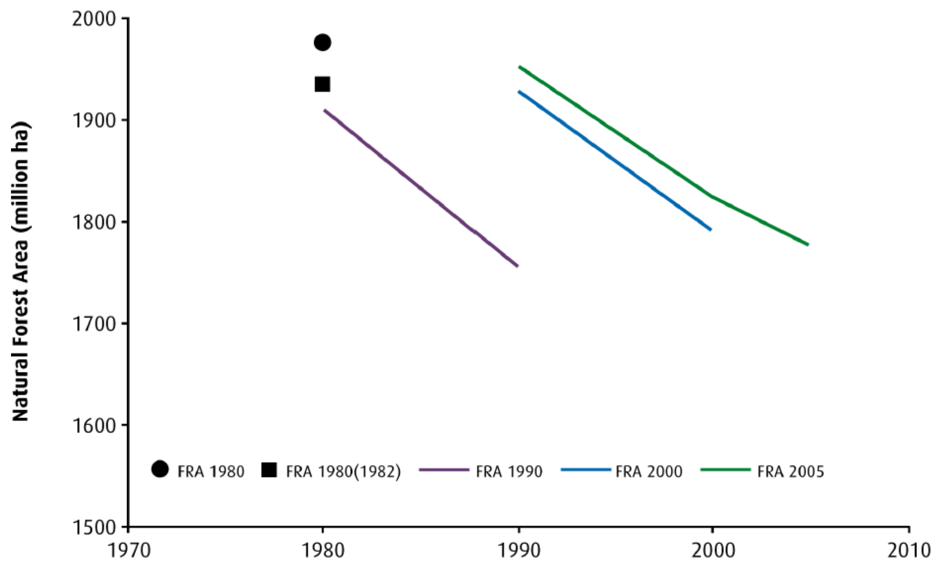

Figure 4. Estimates of tropical forest area decline in successive FAO surveys. Source: Grainger A., 2008. Difficulties in tracking the long-term global trend in tropical forest area. Proceedings of the National Academy of Sciences U.S.A 105: 818-823.

Specific problems with obtaining accurate data were identified during the workshop's breakout sessions.

- Cropland data, available after 1960 in a time series format from FAOSTAT, vary in quality and completeness from country to country and are often out of date.

Approximately one third of all countries in the database (typically the smaller and poorer ones) provide no information about the ways in which their data were collected. In contrast, another third of the countries have reported high quality data, with abundant detail about the ways in which they collected the data. To deal with the uneven quality of these data, analysts could conceivably limit their analyses to those countries with high ratings for data quality. Moreover, the manner in which data for the FAO's database are collected raises questions about the consistency in the temporal treatment of land-supply data by researchers. Data collected once every 10 years by member states but reported annually by FAO distort the temporal quality of the land data and analysis relying on such data.

- Some useful data are available from Landsat at moderate resolution (mostly 30-m). However, continuity of Landsat data is questionable because the satellites have already lasted past their predicted life spans, and Landsat ETM+ data acquired after May 31, 2003 contains data gaps due to the failure of the scan line corrector (SLC). Therefore, to perform land-use change analyses with Landsat data, several images would need to be acquired to fill data gaps due to the SLC failure.
- The accuracy of global-scale land-cover data is typically assessed through the generation of large confusion matrices, which describe how well training sites are classified when they are unknown by the classifier. The global accuracy of a commonly used MODIS land-cover data set (MOD12Q1) with 1-km resolution is 71.6%.[86] Accuracies vary among continents, with lowest accuracies in North America and Africa and highest accuracy in South America. The higher classification accuracy in South America may be partially explained by the vast tracts of contiguous forest cover present in the Amazon region, where canopy cover thresholds approach 100%, and partially explained by the disproportionately high number of training sites. In contrast, canopy cover in open African woodlands is much more variable and training sites are few in number, and thus MODIS, as well as all other global land-cover products, has a very limited ability to discriminate mixed classes characterized by a mosaic of trees, shrubs and herbaceous vegetation.
- Spatially explicit information on the locations and areas of marginal lands is severely lacking, hindered by the fact that definitions of these areas (often referred to as "degraded" or "idle") vary widely by country.
- Monitoring change requires repeated cycles; one can never rely on single-point snapshots. Land use needs to be monitored seasonally (e.g., at some particular time of year, every year), not continuously.
- Backcasting is difficult because satellites change and are reclassified from one range of years to another; continuous analysis is made difficult by sensor changes.
- Countries have different ways of classifying land-use and land-cover systems. Information on land-use and land-cover change, as well as the information needed to support land-use change models, needs to be available on a global scale.
- Reliable data are needed on the properties and boundaries of different soil types globally. This is a large data gap for land-use change modeling.

[86] http://modis.gsfc.nasa.gov/

- Currently, a disconnect exists between model needs and data availability; as a result, modelers are often forced to use data that are most accessible rather than those that are most appropriate for the analysis in question.
- Up until now, there have been no global land cover data sets for a given point in time with accuracies above about 70%; much less, accurate global data sets for changes in land *use* over time. With this degree of uncertainty in the land-cover baseline, what level of confidence can be assured when making projections of land use over time?

Despite these problems, methods have been developed to use existing data and to document the inherent information and uncertainties. A number of studies have combined remote-sensing data and census or inventory data to take advantage of the strengths of both data sources. For example, the area estimates and attributes of various land use classes are derived primarily from the inventory or census data, while the spatial distribution of these classes is based on remote-sensing data. A wide range of other techniques is also available to compare and integrate different data, such as the use of fuzzy logic or conceptual overlaps through semantic-statistical approaches. Improved validation techniques can contribute to accuracy assessments of different land-cover data, which can assist in the final selection of the data used for a specific application. Finally, uniform systems for documenting thematic information contained in land-cover data, such as the United Nations (UN) Land Cover Classification System, will facilitate judgment of both the contents and specific application domain of the data.

Possible approaches for improving the way in which land-use and land-cover data are selected and used for bioenergy modeling include:

- Awareness and documentation of data inconsistencies and uncertainties
- Careful selection of data and classification systems and scaling and aggregation methods, given the specific application requirements
- Combination of different data sources to optimize information content
- Collection of new, additional data for validation of models and improvement of coverage of regions and land-cover types with a high level of uncertainty
- Specific attention to the representation of land-use systems and mosaics within land-use and land-cover data
- A multi- and interdisciplinary team to interpret existing data and to develop new data
- The integration of social, environmental, and economic objectives in data collection, development and analysis techniques to develop appropriate models
- A multi-sectoral representation in model development and data collection groups
- Bootstrapping analyses in which models are validated against only the ‘high quality data’ and then applied to all data, or vice versa.

3.2.2 Uncertainties in Carbon Stock Data

Estimating indirect land-use changes associated with the introduction of biofuels presumes that we can actually measure or project these land-use changes and the greenhouse-gas emissions that result from these changes.

To date, research has focused primarily on quantifying past and predicting future areas of land-use change. However, to evaluate whether real reductions in greenhouse-gas emissions have taken place as a result of expanded biofuel use, research efforts must maintain an equal focus on generating accurate and precise estimates of both the area of land-cover change and the impact of these changes on greenhouse-gas emissions. Uncertainty bounds in greenhouse-gas emission estimates can be minimized only with accurate and precise estimates of both changes in area and changes in carbon stocks (emission factors). Table 4 provides an illustration of the importance of this point.

Table 4. Calculation of Total Uncertainty Around GHG Emissions Estimates, Based on Models of the Global Carbon Cycle.[87]

Area Uncertainty	Carbon stock uncertainty	Total uncertainty
5%	30%	31%
5%	20%	21%
5%	10%	11%

Using the Intergovernmental Panel on Climate Change (IPCC) Tier 1 Simple Propagation of Errors method for estimating uncertainty, even if the uncertainty for a given area change component were held constant at 5%, the uncertainty of the total final estimate of emissions is governed by the higher uncertainty in the carbon stock data of the land-use transition in question. The high uncertainties associated with data supporting global land-use change prediction are described in sections above. We now proceed to discuss the relative uncertainty of carbon stock estimates.

There is significant uncertainty around the carbon stocks of various land-cover types. As mentioned above, estimates of greenhouse-gas emissions from land-use change require accurate information on both area changes as well as carbon stock changes between the pre-existing and replacement land use. Regional-scale estimates of forest carbon stocks exist[88,89,90] and at the national scale, many countries are investing significant resources into the collection of medium to high resolution satellite imagery to produce more accurate estimates of land-cover change, but data on carbon stocks remains sparse. For example, Brazil has a highly sophisticated land-cover monitoring program for changes in forest area, Procedimento Desflorestamento (PRODES), but has not updated its national forest inventory since the 1970s, when 44 plots were measured as part of the Airborne Radar Images and Photographs of Brazil (RADAMBRAZIL) inventory. Carbon stocks for other non-forest land-cover types are even less certain. For example, IPCC default values for grassland biomass are available and presented in the 2006 Guidelines for Agriculture, Forestry and Other Land Use

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[87] Canadell JG, C Le Quéré, MR Raupach, CB Field, ET Buitenhuis, P. Ciais, TJ Conway, NP Gillett, RA Houghton, G. Marland. 2007. Contribution to accelerating atmospheric CO_2 growth form economic activity, carbon intensity, and efficiency of natural sinks. PNAS 104(47): 18866-18870.

[88] Gibbs, H.K. and S. Brown. 2007. Carbon pools in the forests of tropical Africa: An updated database using the GLC2000 Land Cover Product. NDP-017b. ORNL-CDIAC

[89] Saatchi, S., Houghton, R., Avala, R., Yu, Y., Soares, J-V., 2007, Spatial Distribution of Live Aboveground Biomass in Amazon Basin, Global Change Biology (2007) 13, 816–837.

[90] Brown, S., L.R. Iverson and A. Prasad. 2001. Geographical distribution of biomass carbon in tropical Southeast Asian Forests: A Database. Carbon Dioxide Information and Analysis Center, NDP-068, Oak Ridge, TN. Available at http://cdiac.ornl.gov/epubs/ndp/ndp068.html.

(IPCC AFOLU). Default values of aboveground biomass vary by ecological zone, with a reported error range of ±75% around the estimates. (No default values are presented for shrubland or savanna.) Belowground biomass for grassland, shrublands and savanna land-cover types is estimated using a default belowground to aboveground biomass ratio, and these values have even higher error ranges of ± 80 to 150%. If uncertainty is to be minimized around greenhouse-gas emissions from indirect land-use change, more precise estimates of carbon stocks are needed for all land-cover types.

4. ADDRESSING SCIENTIFIC, TECHNICAL AND METHODOLOGICAL ISSUES

4.1 Defining a Conceptual Framework for Land-Use Change

Many steps can be taken to improve land-use-change modeling and data collection, but an early priority is to construct a comprehensive conceptual framework for understanding land-use change. The framework should include the major drivers of land-use change along with those potentially associated with bioenergy. The framework would also describe evidence-based causal linkages related to land-use change and consider whether and to what degree the presence or absence of a driving factor determines a change. Such a framework should also be linked with a standard reference data set and well developed and agreed upon scenarios of change.

Comparisons between different fuel options, different crop placement designs, and/or different crop options would be facilitated by the development of a conceptual framework that:

- Incorporates elements currently missing from existing land-use change models
- Connects elements in life-cycle, economic, and land-use-change models
- Includes land classifications (e.g., pasture, scrub, and degraded) that are important to projections of land-use change for bioenergy and should be standardized.
- Improves communication across disciplines and among modelers.
- Facilitates comparison among land-use change models
- Provides a sound scientific underpinning for integrating land-use change in economic models, showing the relationships between intensification and extensification and how those relationships might be affected by land prices, yields, technology, expanding markets, etc.
- Incorporates a full sustainability assessment for effects of different land management scenarios (with and without bioenergy production) on greenhouse gas emissions, direct and indirect land-use change, hypoxia, water use and quality, soil conditions, biodiversity, food security, etc.
- Outlines approaches for comparing alternative fuels and alternative land uses that involve land-use models, standard reference data sets, reference scenarios, validation methods, and baselines.

This series of steps by no means leads to a "unified theory" of land-use change, but rather it is a systematic way to identify and deal with the myriad of influences on land-use change. To put the problem of land-use change in perspective, consider Figure 5, which illustrates some of the proximate (direct or local) and underlying (root) influences on tropical deforestation. The diagram attempts to reflect the relative importance of different factors that were identified and categorized based on the meta-analysis of 152 individual tropical deforestation studies around the globe. Five broad clusters of causal factors were found to drive tropical deforestation: demographic, economic, technological, policy/institutional, and cultural. These driving forces underpin proximate influences that were grouped into four categories: infrastructure extension, agricultural expansion, timber extraction and others (including predisposing environmental and biophysical factors). Geist and Lambin[91] concluded that, "Land-use change is always caused by multiple interacting factors" and the mix of driving forces varies in time and space. Therefore, it is important for a conceptual framework of land-use change to capture and reflect these factors and their interactions. They found that a recurrent set of economic, political and institutional forces were especially important. But the economic, political and institutional factors identified are currently poorly represented or missing in many current models and analyses of the impacts of bioenergy on land use.

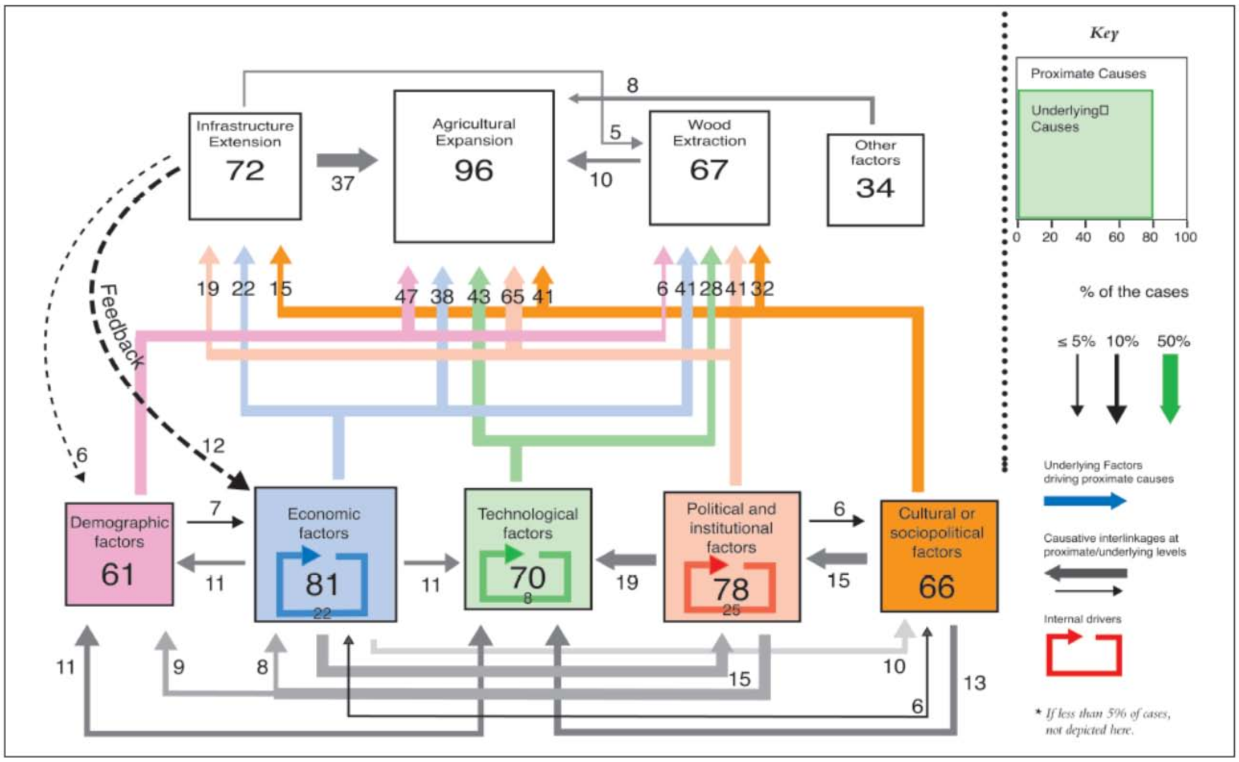

Figure 5. Causative Patterns of Tropical Deforestation [from Geist and Lambin (2002) **and used with permission (copyright, American Institute of Biological Sciences)] Numbers of deforestation studies (out of 152 studies) supporting each category of factors influencing land-use change are indicated.**

Results of individual studies are determined in great part by the classifications and boundaries applied. For example, when land-cover data classified as forest, pasture or agriculture are used, then any change from forest is guaranteed to be classified as pasture or agriculture – ignoring other potential drivers of change. Studies focusing on social factors, on the other hand, may find that most initial conversion is associated with governance issues or is set in motion by

[91] Geist, H. J. and E. F. Lambin. 2002. Proximate causes and underlying driving forces of tropical deforestation. BioScience 52:143–150.

infrastructure and investments from extractive industries (often oil and gas). Conclusions of what drives land-use change are not only site-specific but will depend largely upon what one is looking for, at what scales, and when and how data are collected.

4.2 Improving Data Collection and Availability

One of the central elements of land-cover/land-use change estimation in the broad context as well as in the context of bioenergy is the continuous availability of high quality data. Data of the appropriate scale (temporal, spatial, thematic, etc.) and type (ecological, socioeconomic) must be collected and synthesized so that uncertainties in output from land-use-change models can be reduced. Researchers who are applying the current suite of land-use-change models must have access to the data that are most appropriate to a given analysis rather than the data that are most readily accessible. Virtually all currently available land-use-change models rely mainly on extrapolation and projection due to a restriction in available data sets. Because land-use-change models are being used increasingly to inform important policy decisions, the quality and relevance of the data that feed into these models should be improved.

A concerted effort should be made by scientists to develop a list of priority data for collection so that the proper information can feed into land-use-change models. One recommendation to reduce uncertainty and facilitate comparison across models, is to develop a reference data set for bioenergy land-use analysis.

The following points were prominent in group discussions.

- **Need for an international institutional framework and center**: Efforts should be undertaken to develop and institutionalize a Global Land Use Center or Global Land Use Observatory to collect land-use data of the quality necessary for this initiative on land-use change and bioenergy and related research. An example that could serve as a model for this group exists for international forest monitoring, since plans for a World Forest Observatory are currently being assembled.[92] One possible design involves collaboration through a network of existing remote sensing centers, each responsible for a major world region. Each center would be linked with the sub-regional and national bodies throughout their region, and to a global hub for collating processed data. The primary concern of this new body would be to improve the monitoring and reporting of land use information using standardized formats. Given that many land cover and land use data sets are created and maintained by local agencies and governments, collecting these data sets for research will require new policies and agreements to make them accessible and compatible. While data sets needed for modeling land-use changes in the United States are often freely available, the same is not true for many other parts of the world. Thus, any new institution will need to work with stakeholders to develop policies and effective collaborations in order to succeed in making reliable and timely data available to end users
    - **Issue**: Is it possible to make these data sets freely available to all potential users?

[92] Grainger A., 2009. Towards a new global forest science. International Forestry Review 11: 126-133.

- **Catalog of key data sets**: A catalog of key data sets that are needed for all sectors involved in land-use change modeling, land-cover mapping, and monitoring should be developed. The data sets should include drivers for land-cover/land-use change, where known. The catalog should also capture metadata needed by the modeling community. The creation of a clearinghouse for key data sets may be important for efficiency of effort.
    - **Issues**: Should the data or metadata be deposited at a central server or will the data remain with stakeholders? If data sets are distributed, then how should versions, quality management, consistency, availability, etc. be managed?

- **Standardization:** Standard definitions and relationships among classes (ontology) should be developed for all data sets associated with land cover and land use.
    - **Issues**: One of the major hindrances to the integration and ease of use of existing land-cover/land-use data sets is the inconsistency of thematic class definitions. No two classification schemes follow the same class definitions. The issue goes well beyond the simple class-name problem. Often classes are overlapping and hierarchical. Therefore it is important to create a standard ontology for land-cover/land-use data sets. Preferably, this would start by taking into account the current standards followed in the creation of major national-level land-cover/land-use data sets [e.g., Multi-Resolution Land Characteristics Consortium- National Land Cover Data (MRLC-NLCD), United States Department of Agriculture Cropland Data Layer (USDA-CDL), National Snow and Ice Data Center-Global Vegetation (NSIDC)].

- **Common data format**: A common data format for all data sets associated with land-use and land-cover issues should be developed and agreed upon and its use widely encouraged.
    - **Issue**: One of the major problems associated with using existing data on land cover and land use is the differing data formats used by different research teams or data banks. To simplify or even enable the use of existing data, existing formats should be harmonized or a new format should be created.

- **Creation of web services**: A web-services infrastructure should be developed for data discovery and easy downloading of the data sets available through the clearinghouse. One advantage with this approach is that users don't have to worry about searching for data at multiple locations or about differing formats/standards. Through web-services, users can use a single standard format (e.g., Open Geospatial Consortium-prescribed standards) or a few important formats commonly supported by Remote Sensing/Geographic Information Systems software or modeling tools.
    - **Issues**: What kinds of services are needed? How could funding be sustained? Can we leverage some of the technologies developed at ORNL for this purpose [e.g., Bioenergy Knowledge Discovery Framework or the Carbon Dioxide Information Analysis Center (CDIAC)]? Who will host and manage these services?

- **Generation and maintenance of data sets**: Where land-use data are questionable or unavailable, land-cover and in situ information should be exploited to help fill the voids.

However, all such deficiencies and limitations in land-use data must be clearly documented along with potential consequences, especially for the decision-maker audience. Additionally, future research should develop techniques to update land-cover maps based on MODIS or Advanced Wide Field Sensor (AWIFS) Normal Difference Vegetation Index (NDVI) time series.[93] Global temperature, elevation, and cloud-cover data can be combined with satellite time-series data to provide a context for a decision-rule classifier to categorize a pixel based on response, location on the landscape, and behavior of the pixels around the pixel in question.

  - **Issues**: For what conditions and places are the land-use data deficient? What problems, assumptions and uncertainties are created when land cover is substituted for land use? Are decision makers aware of the implications of using land cover information instead of land-use information?

- **Integration of the data sets:** Many of the land-cover data sets are created based on specific themes, such as forestry, agriculture, soils, etc. Also, many of these data sets were created at different spatial and temporal scales.
  - **Issues:** What is the best way to integrate these divergent data sets? What are the consequences in terms of validity and accuracy if they are integrated? What is the common resolution, and how can we aggregate these data sets?

- **Down-scaling the data sets:** Modeling tools often depend on aggregate inputs, for example, national scale GDP, for the lack of appropriate data at finer resolutions. However, many modeling problems in bioenergy relate to much finer spatial scales such as a state, county or even field-plot scale.
  - **Issues:** Fine resolution data are required over extended temporal periods; this is a demanding process in time and resources. Meanwhile, procedures need to be developed to facilitate down-scaling of data sets including methods to bring in ancillary or additional survey data to improve quality and consistency of down-scaled data.

Table 5 highlights key problems/issues associated with land-cover/land-use data sets.

[93] Funk, C, and Budde, M.E. 2009. Phenologically-tuned MODIS NDVI-based production anomaly estimates for Zimbabwe. Remote Sensing of Environment 113(1), 115-125; Doraiswamy, P.C. et al. 2007. Crop classification in the US Corn Belt using MODIS imagery. IEEE International Geoscience and Remote Sensing Symposium, Vols 1-12 – Sensing and Understanding Our Planet. 809-812, 2007; Didan, K. and Huete, A. 2004. Analysis of the global vegetation dynamic metrics using MODIS vegetation index and land cover products. IEEE International Geoscience and Remote Sensing Symposium Proceedings, Vols 1-7 – Science for Society: Exploring and Managing a Changing Planet. 2058-2061 2004.

Table 5. Characteristics of Data Associated with Land Cover and Land Use, as Discussed in the Workshop Breakout Session (this is not an exhaustive list).

Dataset	Creator/ Availability	Data Characteristics	Remarks
National Land Cover Data (NLCD)	Multi-Resolution Land Characteristics Consortium; 1992 and 2001; Free	• National Land Cover for U.S. • 2001 – 16 classes, conterminous U.S., Alaska, Hawaii, Puerto Rico. • 1992 – 21 classes, conterminous U.S.	Differences in spatial extents and class definitions, making it hard to identify changes
Cropland Data Layer (CDL)	USDA; 1997-2008; Free	• Crop-specific land-cover data for selected states and counties (U.S.) • Each year, only few states were updated, and the total number of states covered is increasing over time • Spatial resolution and number of classes varied over the collection period	
Global Land-Use Datasets	Multiple Agencies; Available through National Snow and Ice Data Center	• Major ecosystems • Wetland ecosystems • Cultivated Areas • Fractional Inundation • Soil Units	Coarse resolution (spatial, temporal, and thematic). For example, cultivation is by %; Vegetation classification follows UNESCO classification system (32 types); doesn't correspond well with NLCD/CDL classes.

In general, the modeling community requires spatially explicit land-use data updated on a year or seasonal basis. Special emphasis should be placed on degraded (previously-cleared or used) lands and connecting, to the best degree possible, the land-use-management data available from country agencies to the observed land-cover information.[94] The ongoing effort of Worldwide Fund for Nature and Conservation International to define a methodology for classifying and identifying abandoned lands (underutilized lands, degraded lands, previously-used lands, etc.) should be encouraged to develop a better understanding of the shifting nature of land use, abandonment, regeneration and reuse over time. An electronic, global atlas of such lands at 1-kilometer resolution over time would be useful. This effort should be combined with the development of a map of available, underutilized water resources, because development of the lands for biofuels or other productive uses may be largely determined by available water (precipitation potential, soils, irrigation infrastructure etc.).

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[94] Ramankutty, N., A. Evan, C. Monfreda, and J. A. Foley, Farming the Planet. 1: The Geographic Distribution of Global Agricultural Lands in the Year 2000, Glob. Biogeochem. Cycles, 22, GB1003, doi:10.1029/2007GB002952, 2008.

A standard reference data set should be developed for the existing biophysical models. This reference data set would be highly beneficial for model assessment and comparisons. This information is critical for the modeling community as well as being a communication tool for the user and policy-making community. The format of these data could influence the development of a standard format for data input to the biophysical models. Ideas about how development of such a data set could proceed are presented in this report under Topic 5.3.8.

The visualization and presentation of both data and scenario results remains an important challenge. Spatially explicit scenario studies present a wealth of data and maps, and presentation and visualization play an important role in communicating the results to stakeholders. Dockerty et al. (2006) provide some examples of visualization options for regional-scale studies with a special focus on biofuels.

4.2.1 Land-Cover Classification Example: Marginal Lands

Previously cleared lands that are not currently in production are a poorly understood category of land that forms a critical component of any assessment of direct and indirect land-use change effects associated with biofuels. Understanding the extent, location and factors that lead to underutilization is essential to design policies that can guide bioenergy effects in desired directions – e.g. to reduce total emissions and improve rural economies, among others. Assessments of land-use change from biofuels consider the expansion of cropland onto natural lands but often do not consider the potential alternative expansion onto underutilized areas. In part, this is because of scarce data and inconsistent definitions of these areas. For less-traditional feedstocks, research into the economic, technical, and environmental impacts of restoring marginal lands for production may be limited.

Research into these issues could provide data that are needed to improve existing models to better reflect biofuels' effects on land-use and emissions. Furthermore, this information could inform policies to enhance the attractiveness of underutilized lands rather than natural lands, mitigating biofuels' land-use change-impacts and enhancing the sustainability of biomass production. To advance our understanding of the relationship between these underutilized lands and biofuels' land-use change, the following research questions should be addressed:

- **How do we define marginal lands?** What are the physical (soils, vegetation, etc), temporal (possibility of regeneration, periodic use), ecological (importance for ecosystem services, biodiversity), social (economic or cultural) and political (tenure policies, historic uses) criteria that need to be considered to identify an area as "underutilized" or "degraded"? How are they currently used (are marginal populations dependent upon the marginal lands)? The definition of marginal land may vary depending on location. How much of the world's underutilized (unharvested) land area that was formerly cleared or classified as cropland, was marginalized due primarily to social and political factors rather than physical changes? (e.g. the nation of Zimbabwe was once the "breadbasket of Southern Africa" but policies over the past two decades have completely undermined the agricultural sector.)
- **What is the area and spatial distribution of these lands?** While underutilized land area estimates have been assumed in some biofuel assessments, the area and spatial distribution of these lands were typically based on order of magnitude estimates using

expert opinion. A data-driven approach for characterizing this potential biofuels land resource is needed that incorporates historical land-use data and remote sensing. Careful consideration of changing land-use definitions over time and integration of higher resolution data where available can make this research approach useful for quantifying the area and spatial distribution of underutilized lands at regional to global scales.

- **How will the underutilized land area change in the future given a range of dynamic baseline scenarios?** Underutilized lands may undergo significant change in the future due to a variety of factors including increased land-use efficiency, growing demand for land, and climate change. Research that addresses the relationship of underutilized lands to dynamic baseline scenarios could provide support for land-use change modeling.
- **What are the spatially explicit rates of carbon sequestration or emission from these lands under status quo and business as usual scenarios?** Underutilized lands may appear to be in varying stages of natural succession depending on the point in time they are observed, the spatial scale of observation, the rates of degradation and recuperation, climate, and other factors. Many economic analyses of indirect land-use change of biofuels assume that if the land is not used for biofuels, it would remain in a natural state. There is little empirical evidence to support this assumption. Data from developing nations indicate that 2 to 4 million km^2 burn every year predominantly in "agricultural frontiers" and marginally productive zones.[95]) The rates of carbon flux under business as usual and alternative future succession scenarios need to be accurately quantified in order to estimate the change that would occur if such land came into production. What are the costs and spatially explicit yields on these lands for a range of biomass and food crops? The costs associated with production of crops on underutilized lands and the expected yields are critical parameters in the treatment of these lands in land-use-change modeling. Previous assessment of underutilized lands in biofuel systems often assume crude relationships between the potential yields on these lands and the relatively better understood yields of prime agriculture lands. Emerging field trials on these lands make the extrapolation of these yields to larger scales with production models possible. Other factors being equal, it is less expensive to prepare 'previously used' lands for cultivation than areas that have not been previously used for agriculture. Shifting cultivation represents the predominant agricultural practice globally.[96]
- **How can these lands be incorporated into land-use change models with respect to land availability and yield elasticities?** Land-use change models make assumptions to estimate the expansion of cropland onto undisturbed lands, but they have not characterized the potential alternative expansion onto underutilized areas. Data on

[95] Tansey et al (2004) J.Geophys. Res., 109 ; Giglio L. et al., Atmos.Chem. Phys., 6, 957 (2006); FAO 2007: Forestry Paper 151. FAO, Rome, 2007 "Fire management - global assessment 2006. A thematic study" ftp://ftp.fao.org/docrep/fao/009/A0969E/A0969E02.pdf; FAO 2006: "FAO Global Forest Resource Assessment 2005." FAO, Rome. Supporting data from: http://www.fao.org/forestry/fra2005/en/ and http://www.fao.org/forestry/static/data/fra2005/global_tables/FRA_2005_Global_Tables_EN.xls; Santilli, M. et al. "Tropical deforestation and the Kyoto Protocol, an editorial essay" Climate Change 2005, 71: 267-276; de Mendon M.J.C., et al., Ecol. Econ. 49, 89 (2004); Mouillot F. et al., Geophysical Research Letters 33, L01801 (2006); http://na.unep.net/globalfire/brazfire/Brazil.html [March 30th, 1998 U.S. Global Change Seminar: "Origin, Incidence, and Implications of Amazon Fires"]

[96] Millennium Ecosystem Assessment, Condition and Trends Working Group. 2005. Ecosystems and Human Well-being: Current State and Trends. Cultivated systems. Millennium Ecosystem Assessment, Island Press, Washington, DC.

bioenergy crop models (yields, interactions, and integrated production systems) are also lacking. Incorporating the availability of these lands and potential production systems with a range of hypothetical policy incentives into models provides an opportunity to design policy incentives for sustainable biomass production.

4.3 Refining Model Approaches

Based on validation results and new insights into land-use-change processes, incremental improvements to current modeling approaches are possible. However, a further diversification of model structures and approaches for scenario studies may be a useful alternative. No agreed-upon paradigm exists for modeling land-use change, and the choice of models is often based on arbitrary decisions or data availability. Within the land-use modeling community, a wide range of land-use models are available and it would make sense to compare the results of different modeling approaches and explore their complementarities.[97] Although a large range of models were discussed at the workshop,[98] many of these approaches aim at visualizing patterns of land-use change and do not provide insights into decision-making structures. Other model types may be better able to consider planning and policy explicitly and in this way better incorporate feedbacks in scenario development. For example, how would policy respond to evolving changes in land use? Such questions require different modeling approaches and depend strongly on the requirements of stakeholders and the purpose of the study. For policymakers, it may be more important to keep the policy options exogenous to the model and so explore the effects of these policies on land use directly.

To address uncertainties and other limitations, several advances could be made in land-use change models and economic models and the data that support them.[99]

- State limitations, errors and uncertainties as clearly as possible.
- Model indirect land-use-change impacts stochastically to account for random elements that can affect the direction and magnitude of land use change impacts.
- Tie the classes of land use or land cover to ecological zones.
- Characterize the relative strengths of the underlying drivers of land-use change.
- Trace through historical changes and empirically link land-use changes to real-world drivers.
- Determine if, when and how biofuels serve as pathways for land-use change.
- Assess land-management practices and relate them to the status of carbon stocks.
- Identify the land-cover and land-use trajectories produced by land-management and technology changes.
- Improve the resolution of measurements to provide spatially explicit data.
- Improve data availability, especially for the developing world.
- Monitor land-use change and its effects.
- Integrate land-use change and economic models with biophysical models of the effect of land-use and land-use change on the environment.

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[97] Verburg, P.H. et al. 2004 .Landscape level analysis of the spatial and temporal complexity of land-use change. Ecosystems and Land Use Change 153, 217-230.

[98] See Panichelli L "Plenary presentation" on workshop site: http://www.ornl.gov/sci/besd/cbes.shtml

[99] Schaldach and Priess (2008), Verburg et al. (2006), Heistermann et al. (2006), and Stehfest et al. (2006) for global crops.

- Assess the potential collateral environmental effects of biofuel production that may attend land-use change caused by biofuel production (e.g., hypoxia in the Gulf of Mexico could be exacerbated or reduced depending on what energy crops are planted, where they are planted, and how they are managed[100]).
- Inventory and compare data sets and models involved in projecting land-use change potentially associated with bioenergy
- Integrate and rationalize the existing global land-use, land-cover, and carbon-stock data.
- Develop a proper and fair method to convert indirect land-use change results attributed to bioenergy to climate forcing (that is, changes in factors that affect the atmospheric concentration of greenhouse gases and thus influence global climate).
- Develop a method for calculating incremental change from indirect land-use change drivers, whether caused by biofuels or other land uses.

4.4 Improving the Model-Data Interface

A number of core models have been developed and are currently being further refined to analyze various components in the land-use-change and biomass feedstock-supply systems. Many of these models have gone through extensive development programs as well as verification and validation for specific purposes (although none for global land-use change) and have a large amount of resources invested in their development. However, many of the models are on legacy software platforms that restrict their ability to converse with other models and data sets. Converting the models into the new modeling standards and having them validated would be very costly and time consuming. While these software programs and data sets are valuable in stand-alone analyses, a coupled system accessing the analysis capabilities of the legacy models would be very useful.

The same discussion is relevant for data sets that have been compiled across the world. Data are the most essential component of all modeling exercises. These data sets are valuable even if they are incomplete or limited in scope. Being able to compare, couple, and extract the information contained in these data sets is a vital and extensive activity that will require a coordinated effort of many groups.

Performing robust and meaningful analyses for understanding and analyzing biomass/biofuel systems and their effects on both direct and indirect land-use change requires the use of data and models that address a wide range of variables and sensitivities. Models, data, and objects within the biomass/biofuel supply system must be interchangeable, transparent, and easily accessible. To leverage new analysis toolsets with previously established models, a plug-and-play analysis framework is needed to couple disparate models and data sets into an integrated analysis toolkit.

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[100] Dale, V.H., C. Kling, J.L. Meyer, J. Sanders, H. Stallworth, T. Armitage, D. Wangsness, T.S. Bianchi, A. Blumberg, W. Boynton, D.J. Conley, W. Crumpton, M.B. David, D. Gilbert, R.W. Howarth, R. Lowrance, K. Mankin, J. Opaluch, H. Paerl, K. Reckhow, A.N. Sharpley, T.W. Simpson, C. Snyder, and D. Wright. 2010. Hypoxia in the Northern Gulf of Mexico. New York: Springer.

The fundamental components of this framework are:

- A flexible and extensible data repository or linking to other data sources in a distributed architecture
- A visualization and model-integration toolkit facilitating the coupling of analysis tools, including analyses across time and physical scales
- The system modeling framework supporting discrete event simulation, sensitivity, and optimization
- A Geographic Information System (GIS) toolkit for spatial data acquisition and manipulation as well as geospatial visualization
- An integrated conversion modeling tool, such as Aspen, that couples the process modeling packages
- An analysis-processing module capable of presenting results
- A comprehensive web-service framework allowing remote interaction (web-based access) and varying levels of user abstraction

The technology for developing a model/data set coupling framework is being developed by several organizations (i.e., ModelCenter, VE-Suite[101]) and, individually or in combination, they would provide a foundation for this advanced data-analysis framework. This framework will be on the leading edge of software development and will require further development and refinement, but there are resources available through university and national-laboratory collaboration for developing this framework.

This framework could provide the interface between models and data sets that was identified by workshop participants as a priority research area. In addition, as noted above, the framework would include a visual component for displaying and analyzing the output of the coupled system. The framework should work seamlessly within the Knowledge Development Framework (KDF) being developed at Oak Ridge National Laboratory. The result would be an interface where the user can drag databases and models into a workspace and then link them in a meaningful path that would allow them to work in a configured manner. The models and data sets would have a wrapper that exposes the inputs and outputs of each model or data set, thereby removing the need for each user to understand the connectivity requirements of each component and concentrate on the overall modeling construct.

4.5 Developing Model Linkages

While it may seem to be an overly optimistic goal, the creation of an integrating model (see Figure 6) that is capable of communicating and interacting with a variety of other more detailed models could go a long way toward creating a "glue" for assembling the many components and outputs in such a way as to provide a coherent tool for policymakers.

[101] http://www.vesuite.org/

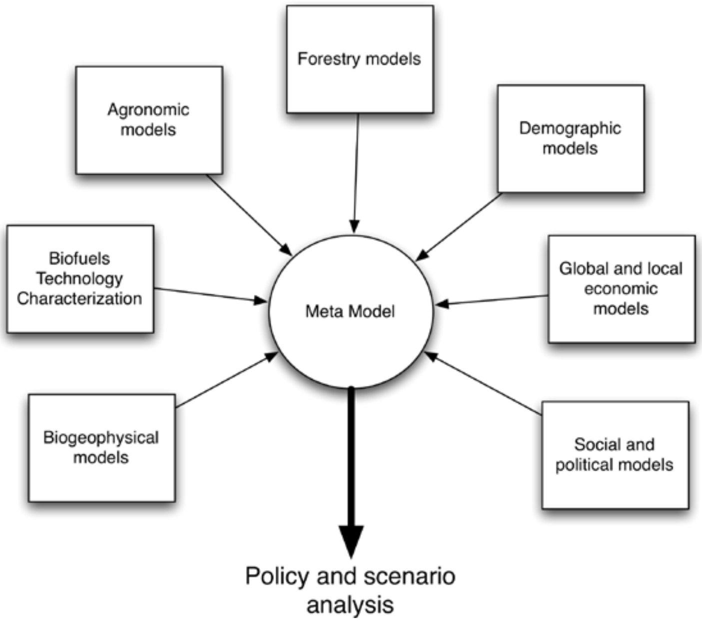

Figure 6. A Meta-Model that Would Poll and Use the Results from Several Types of Models to Provide Integrated Analyses of Biofuel-Related Land-Use Change.

Such a model could incorporate both the model interface discussed above and the conceptual framework, with an emphasis on major drivers of land-use change. By necessity, such a modeling tool would aggregate and simplify the data from other models and would have to take a more simplistic approach. There is value in this simplicity. It offers a more manageable laboratory for testing ideas about "how things work" in the global system of land management.

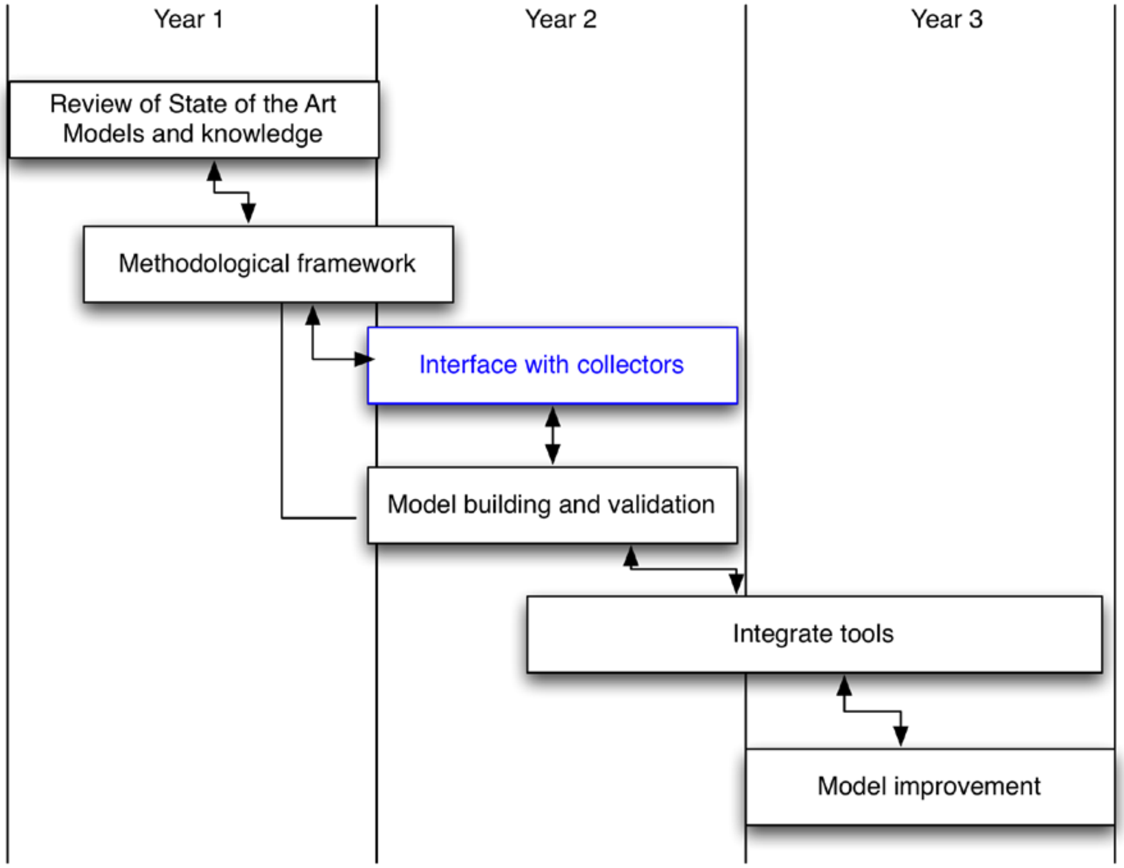

Figure 7. Proposed Steps and Timeline for the Development of an Integrated Modeling Framework for the Analysis of Biofuel-Related Land-Use Change.

This process of model development and improvement (see Figure 7) should

- Develop a series of improved models that incorporate cross-cutting disciplines and that accommodate changing policies, data available, technology, and scenarios
- Make current models more transparent
- Allow comparative analysis that uses common inputs and initial conditions to see whether the different models converge and what determines variability in results
- Ensure that models can incorporate changes in technology, data quality, and new policies over time
- Account for important random elements that can affect the direction and magnitude of land use change impacts

These model recommendations assume that the data needed for parameterization and validation of models are available (see Section 4.2).

4.6 Standardizing the Attribution of Climate Forcing

"Climate forcing" occurs as a result of changes in factors that affect the atmospheric concentration of greenhouse gases and thus global climate. The debate is ongoing about if and how indirect land-use change effects of bioenergy influence greenhouse gases and how this potential effect should be modeled.[102] Meanwhile, it is necessary to consider how to convert land-use-change estimates to a meaningful contribution to the carbon intensity of biofuels. In the following discussion, this is referred to as the "indirect land-use change contribution." Currently, this conversion is often done by equally distributing the indirect land-use-change emissions to each year in the period of time in which biofuels are assumed to be produced. As a consequence, the calculation of the indirect land-use-change contribution becomes dependent on an arbitrarily chosen production period.

Furthermore, the fact that land typically re-sequesters carbon when it is released from production (so-called land reversion) has been omitted from calculations of the indirect land-use-change contribution. If full reversion is assumed, then there would be no indirect land-use change effect (net emissions from land-use change would be zero).[103] Nevertheless, the conversion of land (e.g., from forest to cropland or from degraded pasture to perennial) and subsequent reversion will change climate forcing during the period in which the greenhouse-gas concentrations of the atmosphere have been temporarily increased or reduced.

Global models simplify complex processes to try and understand relationships. The current economic models used to estimate indirect land-use change are based on selected variables, limited land cover data and simplistic treatment of land-use changes. Static models, by definition, do not account for the dynamic land-use baseline (i.e., shifting land uses that occur regardless of biofuel production). Dynamic economic models may account for changes in cropland or pasture over time, but few of these models include interactions between agriculture and all of the other important land uses, such as forestry. In reality this baseline is constantly changing and evolving due to different drivers of land-use change. Even models that do attempt to model the dynamic baseline would benefit from new global data sets that can better represent temporal dimensions of land-use change.

Because of the shortcomings of the current methods used to convert land-use-change results from economic models to an indirect land-use change contribution for a given unit of biofuel consumption, workshop participants discussed the need to review current approaches and make them more compatible. For example,

- Standard approaches should be developed to address decisions that are necessary when analyzing land-use impacts (e.g., choice of discount rates).
- The standard methodologies should take account of the temporal aspects of atmospheric greenhouse-gas concentrations, thereby addressing issues such as land reversion and the choice of radiative forcing metrics (e.g., 100 years global warming potential).

At the workshop, J. Kløverpris[104] revealed some preliminary thoughts on how to develop a method to account for the variable time profile of emissions resulting from land-use changes. The basis for these considerations is to acknowledge that any indirect land-use change from biofuels will take place at the frontier between nature and agriculture or at the frontier between

[102] Mathews J.A. and H. Tan. 2009. *Biofuels, Bioproducts and Biorefining* 3:305-317; Geman B. September 24, 2009. EPA rule will reflect 'uncertainty' on indirect biofuels emissions, fending off amendment. *New York Times.*
[103] The rationale to omit land reversion in EPA's draft rule can be found here: http://www.epa.gov/OMS/renewablefuels/rfs2-peer-review-emissions.pdf
[104] See Kløverpris J "3X5" on workshop site: http://www.ornl.gov/sci/besd/cbes.shtml

two types of land use and management (e.g., cropland and pasture at coarse scales, or among different cropping systems at finer scales). Due to factors such as population increase (driving land demand up) and crop yield increases (driving land demand down), these frontiers are constantly moving – regardless of biofuels. It is the *additional* effect of biofuels seen in the perspective of this dynamic baseline that must be identified. The general expectation reflected in ILUC modeling is for biofuel expansion either to contribute to land conversion or to decelerate land recuperation, as compared to a scenario where biofuel expansion did not occur. However, if biofuel policies contribute to higher yields and improved land-use practices around the world, different effects are possible. Data from the U.S. (2001 to 2006) show total cropland area decreased and reversion increased in conjunction with rapid biofuel expansion, and all the while maintaining corn exports.[105] These historic data do not tell us whether there might have been larger or smaller reductions in cropland without biofuel expansion, but they do, at least, reflect the complex nature of land-use patterns.

Assuming for the moment that the general expectations of ILUC modeling are correct, the *additional* climate forcing from biofuels (the indirect land-use change contribution) would be associated with the greenhouse-gas emissions released *earlier* than they otherwise would have been (in the case of accelerated land conversion) or the climate forcing from the CO_2 sequestered *later* than it otherwise would have been (in the case of delayed land reversion). In other words, it is necessary to look at the *difference* in atmospheric greenhouse-gas concentrations while comparing a scenario where biofuels cause indirect land-use change and in the *baseline situation* (without biofuels) where land-use change evolves as a result of other drivers (the dynamic baseline); see Figure 8.

[105] See Kline and Oladosu presentation at the January 2009 Purdue Workshop on LUC at: http://www.agecon.purdue.edu/staff/tyner/.

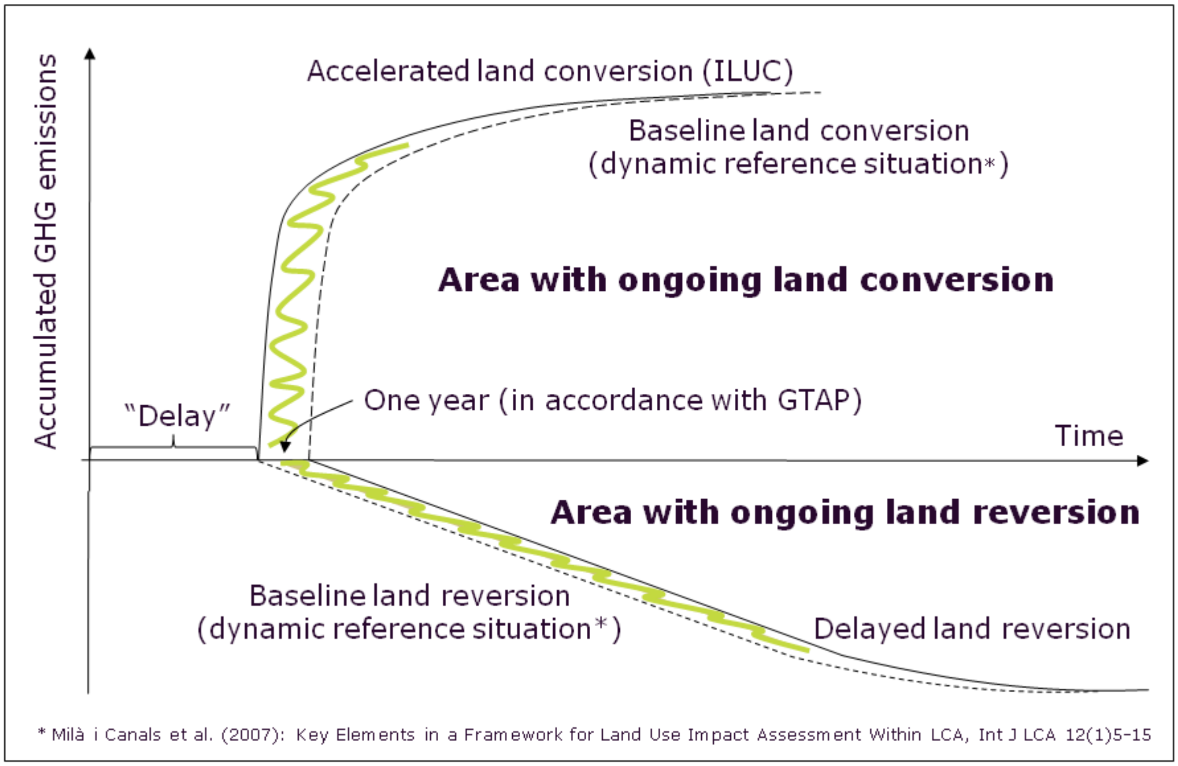

Figure 8. Conceptual Illustration (not to scale) of a Possible Framework for Assigning Greenhouse Gas Emissions from Indirect Land-Use Change to Biofuels (see further explanation below)

Figure 8 shows two distinct situations. The first one (above the time axis) represents an area of land at the frontier between agriculture and nature. In this area, land conversion is taking place, and that is the dynamic baseline for comparisons. This is equivalent to the *dynamic reference situation* described by Milà i Canals et al. (2007). The dashed curve (above the time line) represents the accumulated greenhouse-gas emissions from land conversion in the dynamic baseline. The solid curve represents the accumulated greenhouse-gas emissions when indirect land-use change attributed to biofuels is imposed on the baseline. The area between the two curves (indicated by the green zigzag) represents the additional greenhouse gases in the atmosphere due to indirect land-use change from biofuels for that time period. (Note, under some alternate paradigms, such as those presented by Kline in the workshop, the green area could represent the additional greenhouse-gas reductions that result as an indirect effect of biofuel policies that reduce fires and slow deforestation compared to the dynamic baseline). In either case, the calculation of the indirect land-use change contribution should be based on the *difference* in the amount of greenhouse gases in the atmosphere – taking into account the temporal aspects of the climate forcing caused by these greenhouse gases.

The second situation shown in Figure 8 (below the time axis) represents an area in which land that was previously cleared is being released from production and therefore starts to sequester more carbon from the atmosphere. The dashed line (below the time axis) represents the accumulated greenhouse-gas emissions (negative in this case, e.g. carbon sequestration) from land reversion in the dynamic baseline. The solid curve represents the accumulated *delayed* carbon sequestration caused by indirect land-use change from biofuels. The area between the two curves (indicated by the green zigzag) represents additional greenhouse gases in the atmosphere due to indirect land-use change from biofuels. Just as for accelerated land conversion, the calculation of the indirect land-use-change contribution from delayed reversion should be based on this additional amount of greenhouse gases in the atmosphere, taking into account the temporal aspects of the climate forcing caused by these greenhouse gases.

The concept illustrated in Figure 8 was offered during the workshop "as an inspiration for future improvement" in approaches for converting land-use-change estimates generated by economic models to an indirect land-use change emission contribution that can be added to the direct greenhouse-gas emissions related to biofuels for comparison to the greenhouse-gas emissions from fossil fuels.

The above approach attempts to view biofuel effects within a dynamic system of land-use decisions. Ideally, a standardized methodology such as this could be used to measure the climate forcing of other drivers of land-use change, including the cultivation of animal feeds, sub/urbanization, etc. A standard method for generating dynamic reference situations is important to permit more equitable comparisons, for instance, between the indirect land-use change impacts of expanding urban industrial areas into farmland and forests compared with maintaining rural farms for production of grains and cellulose. This approach could also allow for adjustments in the dynamic baseline from changing technology and the move to more sustainable bioenergy systems (e.g., integrated systems to produce food, feed, fuel, fiber and ecological services).

4.7 Additional Questions Requiring Research

A number of additional questions were articulated at the workshop.

- **What is the experience in the U.S.A. regarding bioenergy and land-use change?** How has land use changed over time from past policies, shocks and recent biofuel production? This is a question that can be addressed with relatively good data to better qualify and identify key drivers, allocations and elasticity factors that could be used in models. Through rigorous analysis of the causes and processes driving land-use changes in the U.S., this research could help develop an improved assessment methodology and data to answer questions of direct and indirect land-use effects of bioenergy.

- **What are the data supporting the choice of particular input values for the key variables that affect land use in models?** Examples of key variables include land supply, land productivity, market drivers (petroleum prices, tariffs and taxes), and co-products.

- **How does land-use change in response to changes in demand?** Improved crop production (food, feed, fiber) models could be developed based on empirical data, for example for sugarcane in Brazil. Crop production models from around the globe could be assimilated that would permit better modeling. The underpinning data of these models should be gathered and gaps identified including agro-biological, cultural, land management and economic data as well as producer characteristics.

- **What ethical questions need to be further explored?** Again, better data and analysis are required. For example, is it ethical for the developed world to impose penalties on less-developed nations for deforestation when the conversion is part of a national land-sue plan for production on prime agricultural land? Does bioenergy reduce global food consumption or help stabilize and expand markets and increase the incomes of impoverished rural populations? Does bioenergy increase food prices or increase investment and efficiency in more sustainable land-use systems?

- **What best practices should be used in reporting on land-use change analyses for biofuels?** These practices would include transparency in model inputs and assumptions and the use of open-source software so that results and sensitivities could be verified. Baseline conditions and parameters should be defined as one or more reference case(s).

- **What opportunities exist to mitigate land-use change effects through production of feedstocks on previously cleared, "degraded" or underutilized lands**? What can be done to build consensus on an acceptable definition of these lands (often referred to as "idle" or "marginal")? What are the dynamics leading to degradation and recuperation? Where do these lands exist, how much land is available, and how can they be modeled? What are the economic, technical, and environmental implications of putting this land into production?

Research is also needed to quantify uncertainty and its impacts on decision making. Constructive discussion of how to handle uncertainty and the research needed to quantify and reduce uncertainty in current modeling, were recurring themes in the workshop. In addition to the broad research areas outlined in the appendix, participants suggested at least three research areas to help address uncertainty.

- Development of frameworks to characterize the uncertainty associated with estimates of land-use change effects of bioenergy. This research would involve theoretical development, probably starting with Bayesian principles.
- Case studies of decision-making procedures that use uncertain scientific data to generate regulations. These could include participant-observer studies, field observer placement of researchers with cooperating agencies, review of document and internal memo histories, and retrospective interviews with key participants.[106]
- Development of frameworks for biofuel-relevant regulations and legislation that are more "uncertainty-friendly" than current, conventional models. Instead of forcing uncertain scientific results into a single value of a scalar, it may be possible to find new techniques of governance that incorporate both uncertainty and scientific advances over time without inhibiting innovation.

[106] See related case studies in environmental policy in Repetto, RC. 2006. *Punctuated Equilibrium and the Dynamics of U.S. Environmental Policy*. Yale University.

4.8 Alternative Paradigms for Land-Use Change

This section describes other topics that were mentioned by workshop participants with an emphasis on strategies for sustainability. Although these were not central or dominant themes of the workshop, the topics are included in this report for the sake of completeness.

The analysis of land-use change information is always dependent on the scales of time and space. The interpretations are affected by both the temporal and the spatial extent of the analysis (that is, as to whether the approach is based on five or 50 years or 10 or 1000 ha). This dependence is important because land cover and land use are in almost constant transition.[107]

In fact, the world is in a time of profound transitions. Land-use practices, levels of greenhouse gases, patterns of food production, energy supply and security, and economic opportunities for the world's poor are changing rapidly and profoundly. To some degree, these changes are linked through bioenergy production. It seems obvious that small changes to "business as usual" patterns will not achieve a secure, sustainable future. However, most analyses of bioenergy production, including existing analyses associated with land-use change, have assumed that bioenergy production is imposed on an overall system that otherwise does not change. Sustainability goals will not be achieved with such a narrow approach. It is important to envision multiple, large, complementary changes in how we feed and fuel ourselves if we are to achieve a more sustainable future. A few ideas discussed by one or more workshop participants along this vein are presented below, but these examples are certainly not the only ones that should be considered.

4.8.1 Changes in Trade

Inter-regional trade can impact the direct and indirect land-use change associated with the expansion of biofuels and other energy options. Trade can provide a means for countries to mitigate resource constraints or price impacts they may experience when trying to promote domestic biofuel production or when trying to adapt to stresses imposed by global environmental and socio-economic changes.

In the case of biofuels, trade already occurs both in ethanol (primarily exports from Brazil) and in conventional feedstock commodities such as corn and sugarcane. Trade can allow countries that are unable to produce sufficient quantities of these commodities at competitive prices to import them from countries with surplus production. Whether it is based on feedstocks or the biofuel product itself, trade can contribute to more efficiently meeting targets for renewable fuels. However, the role of trade is governed by the complex interactions of policies around the globe that include tariffs, tax credits, subsidies, and mandates for many diverse sectors that impact biofuels. Depending on the interaction of these policies, they could lead either to increased production and use of renewable fuels or to encouraging the consumption of fossil-fuels.

[107] See Kline KL "3X5" on workshop site: http://www.ornl.gov/sci/besd/cbes.shtml

4.8.2 Changes in Diet

Human diet preferences shape land use. In the U.S., roughly 90% of managed lands are dedicated to feed and fiber rather than food for direct human consumption. The majority of land is managed as pasture for ruminant animals, beef and dairy cattle. Approximately 30 million acres of U.S. cropland (about 6% of total U.S. cropland) could provide enough protein and calories to meet basic human requirements. Another 30 million acres (6%) could support enough poultry and swine to include significant animal protein in diets.

Insights on diet were raised for three reasons. First, diets can and do change. In recent decades, U.S. consumption of red meat has declined and poultry consumption has risen. Meanwhile, animal protein consumption has risen rapidly among newly prosperous populations in Southeast Asia and elsewhere. Such trends have significant impact on demands for land. Second, it is important to anticipate how dietary preferences might change over time and to consider how these preferences might be better reconciled with the needs of society when projecting future land-use scenarios. Third, rather than viewing biofuels in terms of "food versus fuel," several other alternatives are possible. Systems to more sustainably produce food, feed and fuel, particularly as cellulosic biofuels become commercially competitive, could offer large land-use savings. Such opportunities are further outlined below

4.8.3 Better Management of Existing Land

We can manage our existing land, if we so choose, to provide both more animal feed and more feedstocks for bioenergy production. For example, cover crops, double crops, and companion crops could be grown on active cropland in conjunction with traditional crops such as corn, without bringing new acres to cultivation. These crops could sequester large amounts of soil carbon and reduce greenhouse gas emissions, for example, by preventing considerable nitrogen from escaping as nitrous oxide (a potent greenhouse gas) or as nitrate. Additional animal feed protein might also be recovered from such crops, reducing the total land required to feed and fuel ourselves. A growing market for crop residues and farm wastes as bioenergy feedstocks could promote environmental services while increasing farmer income, one example of the multiple, large complementary changes that are needed. A holistic approach to land management would also consider effects on a variety of ecosystem services (e.g., water quality, soil quality and biodiversity).

4.8.4 Use of New Technology

A developing bioenergy/biofuel sector will generate new technology. While we cannot predict the exact new technology that will emerge, we can identify the general patterns of change and thus some of the likely consequences of technology development.[108] For example, economical biofuel production from cellulosics via the "sugar platform" requires pretreatment to disrupt the structure of cellulosic biomass and allow access to enzymes and micro-organisms. Pretreatment may also therefore open up cellulosic biomass to more effective ruminant animal digestion, with

[108] Lynd LR, Larson E, Greene N, Laser M, Sheehan J, Dale BE, McLaughlin S, Wang M. 2009. The role of biomass in America's energy future: framing the analysis. BIOFUELS BIOPRODUCTS & BIOREFINING-BIOFPR 3(2): 113-123

very large positive consequences for how we feed dairy and beef animals. Preliminary analysis indicates that literally millions of acres of land might be freed up for bioenergy production if better ruminant feeds could be developed from cellulosic co-products of biofuels.

In the so-called "thermochemical platform", we might coproduce liquid biofuel feedstocks (called "bio-crude") along with a solid "biochar". The biochar could be returned to the land, thereby sequestering large amounts of carbon and increasing soil fertility. This process might be most appropriate for woody materials, including wood residues and wood wastes, neither of which would have any impact on food production or land devoted to agriculture.

4.8.5 Scenario Development: What Might Our Choices Produce?

To better understand the implications of these and other choices, we suggest analysis of the impacts (on land use, environmental metrics, social benefits, etc.) in various systems. Several place-based scenarios might be explored[109] and were mentioned in workshop discussions along with their associated research questions. Scenarios for particular locations that were discussed included the following examples:

- *Regional Biomass Processing Centers*. The DOE Great Lakes Bioenergy Research Center (GLBRC, funded by the Office of Basic Energy Sciences) is pursuing the bioenergy system analysis in the context of regional (multicounty) cropping systems feeding a regional biomass processing center. The analysis is designed to determine how existing landscapes and biofuel production might be operated as a system for environmental and economic benefits. Similarly, the Center for Bioenergy Sustainability (CBES) at Oak Ridge National Lab is pursuing research to define an optimal landscape design for bioenergy crops based on a case study in Tennessee. The work is done in cooperation with the Southeastern SunGrant Center at Vonore that is growing switchgrass for a cellulosic biofuel facility. Much of the switchgrass is grown on underutilized pasture land with important implications for the land-use impact of biofuel systems.
- *Sustainable Forest Initiative*. The University of Minnesota recently concluded a study of the transportation, logistics, and densification of woody materials for bioenergy production. That study should be examined for important lessons it might provide for the larger bioenergy industry.
- *Impact of New Bioenergy Technology*. New bioenergy technology developments can be envisioned and several are already evident as seed improvements not only improve yields, but are designed to reduce input requirements and tillage costs/impacts. Increasing yields and developing crop systems designed for multi-crop, companion and rotation production, can have profound potential impacts on how land might be used more efficiently. As noted above, production of animal feed proteins from double crops and enhanced ruminant feeds from pretreated biomass can rather easily be foreseen and their potential land-use-change effects explored.
- *Case Study in Brazil*. Along with the United States, Brazil is a leader in bioenergy production. Brazil is expanding use of its land to grow sugarcane for ethanol and

[109] Laser M, Larson E, Dale B, Wang M, Greene N, Lynd LR. 2009. Comparative analysis of efficiency, environmental impact, and process economics for mature biomass refining scenarios.
BIOFUELS BIOPRODUCTS & BIOREFINING-BIOFPR 3(2): 247-270

bioelectricity, and the legislature has proposed agro-ecological zoning of sugarcane to manage future sugarcane expansion.[110] There is now pressure to refrain from traditional burning of the "cane trash" (tops and leaves).

5. FINAL CONCLUSIONS AND RECOMMENDATIONS

Workshop participants recognized the importance of biofuels in a sustainable energy future and recommended that a comprehensive framework to understand the impact of bioenergy policy on land-use decisions be developed. There was strong agreement regarding the uncertainty surrounding current use of global economic models to project land-use-change effects of bioenergy. Research is needed to improve the understanding and modeling of initial land-use change, to discern the environmental effects of the many variations and transitions inherent with land-use change processes, and to link the land-use change framework to existing global economic models. It was recognized that integrating those approaches is no small task. A push to improve land-use-change research is important now because policy and public determinations, and industry development and research, are moving forward and will benefit from better - informed science, debates, and models.

As a result of the workshop, several proposals were quickly assembled. While several short-term actions were identified, those should not divert attention from some longer-term issues that were raised. This workshop focused on the qualities of current models and data sets, and the need to improve conceptual models and to standardize and validate data collection, storage, and distribution so that researchers can reduce the likelihood that poor data will lead to poor model results.

5.1 Information Sharing, Networking, and Collaboration

Two workshop goals involved "collaborations to measure and analyze land-use and land-cover changes around the world" and "developing plans for enhanced information sharing, networking, and collaboration to embrace the opportunities identified." The attendees of the workshop represented a variety of disciplines, including agronomists, economists, ecologists, geographers, and engineers. A frequent comment to the organizers of the workshop was that attendees appreciated meeting researchers outside of their fields who were also interested in land-use change and bioenergy issues. The structure of the workshop (as well as the relatively isolated conference venue) fostered intense and extended discussion among participants. Even remote participants have expressed interest in collaborating on future research. For example, one institution that participated remotely has written, "Our net assessment is that we could really be helpful to assess many of the questions that were raised and could also help and benefit in the data issue side." Workshop organizers and many participants have expressed the hope that the relationships formed will develop in the future and lead to collaborations in modeling and data collection and archiving that will enhance the ability of all land-use modelers to represent and forecast more realistic and complex situations.

The workshop participants recommended several specific paths forward for communication and collaboration:

[110] http://www.cnps.embrapa.br/

- Using the DOE-hosted Sharepoint website for workshop participants to share papers, discussions, upcoming meetings, etc.
- Using a public web portal such as that at Idaho National Laboratory
- Fleshing out the eight preliminary research plans that were developed as a result of the workshop and involving additional partners and more specific collaborative opportunities
- Seeking out groups of researchers who were unable to attend this workshop, including members of the U.S. land-use-change modeling community
- Establishing a formal listserv for future communication or using the Global Land Project (GLP) listserv for this purpose
- Developing more formal collaborations between modelers, remote-sensing experts, and field scientists.
- Establishing working groups in subdisciplines, such as economic modelers, biophysical modelers, and remote sensing experts interested in land-use change and bioenergy

Another suggestion was for a group of participants to develop a white paper to be presented in Copenhagen at the UN Framework on Climate Change in December of 2009. It was pointed out that, to influence policy, such a white paper needs to be developed and disseminated with significant lead time.

5.2 General Research Topics

The breakout groups identified and articulated several topics that could benefit from additional research and contribute significantly to (1) a fuller understanding of the process, causes, and impacts of land-use and land-cover change and (2) a better representation of reality in more-robust models of that process. Some of the more salient research topics from the first series of breakout groups include:

- Determine realistic scenarios for sustainable biofuel feedstock production systems, consider various models, and hold a workshop to review the results.
- Attribute climate forcing to products (functional unit of fuel or other drivers) according to a temporal climate forcing framework and converting indirect land-use change results.
- Improve the framework for understanding the driving forces for land-use change and relative degrees of bioenergy attribution by reviewing the current state of knowledge, and developing better tools and understanding of the factors that affect land-use decisions.,
- Characterize underutilized lands and their potential for biofuel feedstock production by comparing the best available data sets and analyses (studies of idle, degraded lands, studies of abandoned lands, and the Global Agro-ecological Zones potential versus Ramankutty's data set of global cropland use) and identifying the land supply for bioenergy and underutilized lands by (1) conducting more-detailed mapping and sampling analysis (for the United States and Brazil) to characterize land and compare local data to global analysis; (2) determining the extent and location of available lands (previously cleared, not in active production); (3) assessing the potential to integrate biofuel crops and raise productivity; and (4) conducting data-driven estimates of the area, yield, and carbon sequestration rates of abandoned agriculture lands using historical databases and remote sensing.

- Develop science-based information for biofuels policies by determining how to create an uncertainty-friendly biofuel policy analysis, considering how other sectors deal with high degrees of uncertainty, and conducting case studies.
- Improve the interface between the land-use data and models and economic models being used for indirect land-use change estimates for biofuels by characterizing existing models and interfaces and identifying short-term improvements; comparing models' estimates for land-use change effects through systematic model validations; and developing a new architecture for improved modeling (capable of backcasts and forecasts).
- Conduct data inventory and collection for biofuel land-use change analysis by compiling, assessing, and synthesizing high-resolution data sets; compiling a meta-data set of key data sets; developing a standard reference data set and web-based clearinghouse, and developing strategies for institutional frameworks that could support this process.
- Quantify and reduce uncertainty in land-use change models for biofuels by consolidating information on what has been done to date; assessing the feasibility of addressing uncertainty; and developing an uncertainty analysis framework appropriate for bioenergy indirect land-use change models.

Other research needs identified during the second round of working-group sessions (which focused on improving the science used by the land-use-change-analysis community) are to:

- Develop a "dynamic reference case" systems approach for land-use change modeling to permit fair comparisons of biofuel policy options
- Expand data collection and pilot demonstrations of sustainable biofuel feedstock-production systems, potentially coupled with adaptive management
- Conduct a systematic statistical/econometric analysis (with a system for allocation of particular land-use changes to biofuels among all other factors) in selected nations with relatively good historic data and experience in bioenergy production (e.g., U.S., Brazil, and Thailand) to document and understand past market-mediated land-use change patterns
- Propose a break-out session at the UN COP 15 on Climate Change meeting in Copenhagen (December 2009) with presentations of the best current research (to better inform the international political community)
- Conduct a historic analysis of how land management affects land-use patterns

5.3 Major Research Topics for Priority Consideration

Based on the general research topics outlined in Section 5.2 above, the workshop participants focused on eight research areas that deserve immediate attention:

- Scenario development for sustainable bioenergy systems
- Attribution of climate forcing to bioenergy
- Improvement of the conceptual framework of the driving forces for land-use change with special consideration of biofuels production
- Characterization of underutilized lands for biofuels
- Examination of the role of science in biofuel policy implementation and approaches to manage the uncertainties in the science

- Inquiry into the interface between land-use and economic models in the bioenergy context
- Quantification and reduction of uncertainty in indirect land-use change models for application to bioenergy
- Inventory of best available global data required for bioenergy land-use change modeling

The participants were then asked to form breakout groups to consider and to develop a preliminary research plan for each of these topics, identifying the central problem to be addressed, the objective of the research, the key actions to be undertaken by the researchers, potential collaborations, and a launch activity that would put the plan in motion. The preliminary research plans that resulted from these small group efforts are described in Appendix C.

It was also agreed that it will be difficult to make progress in tackling these priority research areas without a dramatic improvement in the quantity and quality of data on land cover and corresponding land uses throughout the world. Establishment of a Global Land Use Observatory was proposed as an institutional framework for collecting these spatial data using the full range of available remote sensing techniques. Several agencies and research institutes already have expertise in this area and could form the core network for this new body, in collaboration with prominent research institutes overseas.

5.4 Workshop Wrap-Up

The workshop underscored the fact that land-use changes may have consequences that go beyond the borders of a single nation. Energy and agricultural policies made in the United States, Europe, and other locations can have repercussions all over the world. Efforts to estimate these repercussions have rapidly fueled a debate on biofuels and land-use change. In this context, the workshop took steps to identify research areas that may improve our understanding of land-use change and support better development and use of bioenergy resources in the future.

APPENDICES

APPENDIX A. Preliminary Research Plan Summaries for Selected Focus Areas

Small working groups were asked to develop a preliminary research plan that is actionable in the short term, improves the scientific basis for understanding and describing land-use change, fosters collaborative efforts, and focuses on biofuels. The results are summarized below.

A.1 Scenario Development for Sustainable Bioenergy Systems

Objective: To use modeling and analysis to develop place-based scenarios for sustainable bioenergy systems up to the biorefinery gate.

Key Actions: Compile, assess, and synthesize the existing data and identify data gaps and data requiring collection prior to modeling and analyzing biofuel-related land-use-change

- Create an international institutional framework to facilitate the collection of agency data, such as high-resolution spatial data, carbon stocks, and economic data.
- Identify key data sets and create a catalog of metadata
- Identify gaps (and determine costs, time, and methods) by talking to modelers, users, survey respondents, etc.
- Develop a standard reference data set and create web services

Action plan: In the next 6 months to 1 year, hold a workshop to invite collaborators to write a proposal for the modeling scenarios study.

A.2 Methods for addressing temporal issues in the attribution of climate forcing to biofuels, food, and petroleum products

The conversion of results generated by global economic models (e.g., estimated indirect land-use change values) to a standardized unit to reflect greenhouse gas emissions and allow comparisons among fuels, relies on an arbitrary selection of time scales and discount rates. See Section 4.6 of this report for more details.

Objective: To develop a methodology to assign climate forcing to a functional unit of fuel and/or other drivers of land-use change (taking into account temporal aspects of atmospheric greenhouse-gas concentrations).

Key actions:

- Propose methodological framework to convert direct and indirect land-use change results (e.g., from GTAP) to *additional* climate forcing as compared to dynamic baseline.
- Define/redefine dynamic baseline based on new temporal land-use change data set
- Compare *additional* climate forcing of petroleum fuels to biofuels
- Scenario analysis/validation (e.g., a business-as-usual plus biofuels scenario as compared to advanced combined feed-biofuels production

Action plan: Finalize Temporal Climate Forcing Framework (TCFF)

A.3 Improvement of the Conceptual Framework of the Driving Forces for Land-Use Change with Special Consideration of Biofuel Production

Objective: To quantify the relationship between bioenergy and other factors with land-use change

Key actions or steps that need to be done during the next four years to implement the plan:

- Assess the current state of knowledge of the drivers of land-use change and state of the art of the models (considering existing literature, data, models)
- Develop methodological framework for identifying land-use change mechanisms and driving forces (both proximate and ultimate)
- Develop, validate and use new models, update or modify existing models and tools, and seek out new knowledge relevant to the construction of a conceptual modeling framework for land use, such as empirical/econometric analysis of recent trends.
- Integrate tools and knowledge in a form useful to policymakers

Action plan: The first step is to propose and secure funding for this effort from public and private entities (i.e., British Petroleum or state, federal, international governments). Action Item 1 can then be conducted in year one, and Action Items 2, 3 and 4 are completed in years two and three.

A.4 Characterization of Underutilized Lands for Biofuels

Objective: To characterize underutilized land with an eye toward potential biofuel production requires defining what is underutilized land (recognizing that there are different definitions in different regions).

Key actions:

- Compare Global Agro-Ecological Zoning (GAEZ) to Ramankutty's harvested cropland data set to identify inconsistencies and underutilized lands at gross scale.
    - Where are crops being grown that GAEZ indicates cannot be grown?
    - Where are crops not being grown where GAEZ indicates they could?
- Do more detailed mapping and sampling analysis (for U.S., Brazil and Thailand) comparing detailed national data statistics to global results. "Ground-truthing" of initial results.
    - Collect data on past (history) current and potential land use for sampled sites.
    - Analyze results. Develop model or training tool for data.
- Full-scale (global) mapping and analysis guides depending on results from prior step.
- Analysis of land-management options:
    - Potential to increase productivities
    - Greenhouse-gas emissions for different use scenarios
    - Biofuels potentials

Action plan: Write pre-proposal and convene key collaborators.

A.5 Examination of the Role of Science in Biofuel Policy Implementation and Approaches to Manage Uncertainty

Objective: To develop biofuel policies which are more science-based and more robust to uncertainties and change.

Key actions:

- Ethnography/sociology: How regulators use/see uncertainties now
- Decisions/statistical theory: Consider classical Bayesian models and other statistical approaches to uncertainty
- "Uncertainty-friendly" policy designs
- Develop Case studies: Biofuels – climate (generally throughout)
- Current biofuel policies and success/failure role of uncertainty

A.6 Inquiry into the Interface Between Land-Use and Economic Models in the Bioenergy Context

The major problem with the application of current land-use-change models in the context of the assessment of bioenergy is that yield potential is driving land-use models. There is no theoretical framework involving the key drivers of land-use change that includes or eliminates bioenergy as a driver and guides the components and linkages in the current suite of land-use-change models.

Objective: To improve the linkages among spatial land-use-change models, economic models, and biophysical models to understand the effects of bioenergy production.

Key Actions:

- Review the strengths and weaknesses in the current interfaces among these models; review the literature and contact key players for clarification; and build on the standard model-comparison methods.
- Characterize the ideal interface among models, considering spatial and temporal scales as well as feedbacks and recommending improvements in various component models.
- Short term (1 to 2 years): Implement interface improvements on the basis of available data and models and compile and assimilate data, models, and scenario simulations in a transparent way with consideration of sensitivity factors.
- Long term (3 to 10 years): Develop new knowledge architecture for identifying, verifying, monitoring, and modeling land-use changes.

Action Plan: Hold an independent review that results in a model-comparison parameter table. This activity will feed into a Standard Model Comparison Workshop that leads to a publication or special journal issue on biofuel land-use change.

A.7 Quantification and Reduction of Uncertainty in Indirect Land-Use-Change Models for Application to Bioenergy

Objective: To identify major sources of uncertainty in existing indirect land-use change models used for bioenergy analysis and the data supporting them. To identify the most important variables (i.e., variables to which models are most sensitive) in order to focus data collection on these values. Collect new data where required and feasible.

Key action

- Implement uncertainty analysis:
    - Quick review of categories of uncertainty and uncertainty analysis frameworks
    - Feasibility assessment for what aspects of model and data uncertainty can be quantified in two years (assessing constraints, what info exists already)
    - Selection of two indirect land-use change models for which uncertainty analysis can have timely influence on policy
    - Implementation of uncertainty analysis for two models
    - Identification of sources of uncertainty
    - Reduction of uncertainty—collect data, incorporate new variables in model (e.g., add dominant land-use-change drivers)
    - General goal: develop uncertainty analysis framework
- Implement sensitivity analysis:
    - Quantify approximate coefficients of variation for parameters
    - Select major variables (those to which models are the most sensitive). Likely already available from modeling groups
    - Collect suite of available data supporting choice of selected input variables.
    - Where data are sparse, uncertain or conflicting, collect new data. May include crop yields, local crop economics, agricultural practices, trade information (tariffs or other barriers/incentives).

Potential barriers/blocks:

- Unquantifiable uncertainties
- Tight timeframe
- Data availability
- Resources

Action plan: Convene key collaborator including those from modeling groups, uncertainty analysis experts, and subject area experts such as agricultural economists, GIS experts, agronomists.

A.8 Inventory of Best Available Global Data Required for Bioenergy Land-Use-Change Modeling

Objective: To compile, assess, and synthesize existing data and identify gaps and needs for further data collection related to biofuel/bioenergy and land-use change.

Key actions:

- Identify key databases and create an archive, catalog, metadata, and critical review for those data as the Carbon Dioxide Information Analysis Center, based at Oak Ridge National Laboratory, does for carbon dioxide data. Land-cover data are probably easier to obtain than land-use data. Other social data from certain nations are deemed more sensitive and may be more difficult to obtain. This activity would require the establishment of an international institutional framework to facilitate collection of high-resolution data.

- Provide a service for researchers to access a multitude of land-use/land-change data that may not be otherwise accessible to many. Create a web-based (data discovery) clearinghouse
- Identify gaps and costs for filling gaps; identify models and their sources
- Develop a common data format to be used by all stakeholders working with land-use and land-cover data (data collectors and data users) by creating a common data format
- Develop a standard reference data set for all data associated with land-use and land-cover change data and create a web service to make it available to the land-use-change research community.

Action plan: Convene key data providers and land-use modelers at a workshop.

APPENDIX B. Definitions Pertinent to the DOE/ORNL Land-Use Change and Bioenergy Workshop

Best Management Practices (BMPs): Effective, practical, structural or nonstructural methods that are designed to prevent or reduce the movement of sediment, nutrients, pesticides and other chemical contaminants from the land to surface or ground water, or which otherwise protect water quality from potential adverse effects of agricultural activities. These practices are developed to achieve a cost-effective balance between water quality protection and the agricultural production (e.g., crop, forage, animal, forest).

Bioenergy: Useful, renewable energy produced from organic matter - the conversion of the complex carbohydrates in organic matter to energy. Organic matter may either be used directly as a fuel, processed into liquids and gasses, or be a residual of processing and conversion.

Biomass: Any organic matter that is available on a renewable or recurring basis, including agricultural crops and trees, wood and wood residues, plants (including aquatic plants), grasses, animal residues, municipal residues, and other residue materials. Biomass is generally produced in a sustainable manner from water and carbon dioxide by photosynthesis.

Calibration is the iterative process of determining the set of parameter values that produces the most appropriate model outcomes given available information.

Cellulosic ethanol: Ethanol that is produced from cellulose material; a long chain of simple sugar molecules and the principal chemical constituent of cell walls of plants.

Conservation Reserve Program (CRP): CRP is one of several government programs that provides participant farmers with payments in exchange for retiring environmentally sensitive cropland from production for a specified contractual period (up to 10-15 years). In 2002, Congress reauthorized CRP and increased the enrollment limit to 39 million acres. The 2008 Farm Bill brought the CRP ceiling back to 32 million acres while expanding alternative farmland conservation incentive programs. Under CRP, producers can offer land for competitive bidding based on an Environmental Benefits Index (EBI) during periodic signups (the most recent sign-up was 2006). Other terms apply to acreage enrolled under continuous sign-up sub-programs (such as FWP) managed by the Farm Services Agency (FSA), special programs co-sponsored by state and local governments, and other easements and conservation set-asides managed by other agencies, such as the Wetland Reserve Program (WRP) managed by the NRCS. The areas enrolled under other conservation programs are not accounted for in CRP data.

Conservation practices (CPs): Actions taken to produce environmental improvements, particularly with respect to agricultural nonpoint source emissions. The term is used broadly to refer to structural practices, such as buffers, as well as nonstructural practices, such as in-field nutrient management planning and application. Conservation Practice standards have been developed by NRCS and are available at:
http://www.nrcs.usda.gov/Technical/Standards/nhcp.html.

Corn stover: Corn stocks (leaves and stalks) that remain after the corn is harvested. Such stocks are low in water content and very bulky.

Edge-of-field nitrogen loss: A term that refers to the nitrogen that is lost or exported from fields in agricultural production.

Emissions: Waste substances released into the air or water.

FASOM: Forest and Agricultural Sector Optimization Model, a dynamic, nonlinear programming model of the forest and agricultural sectors in the United States. The model projects the allocation of land within and between forest and agricultural sectors and has been developed for the U.S. Environmental Protection Agency to assess welfare and market impacts of alternative environmental policies for climate change mitigation.

Greenhouse gases: Gases that trap the heat of the sun in the Earth's atmosphere, producing the greenhouse effect. Common greenhouse gases are water vapor, carbon dioxide, methane, ozone, chlorofluorocarbons, and nitrous oxide.

Global Trade Analysis Project (GTAP): Economic policy analysis project based at Purdue University, Indiana, U.S. A. The GTAP model is a global computable general equilibrium model. This model has been used in an analysis of the indirect land-use impacts of corn ethanol and other food-crop-based biofuels for the California Air Resources Board in an effort to measure the “life cycle carbon intensity” of various transportation fuels.

IMAGE: Integrated Model to Assess the Global Environment. Simulation framework created under the authority of the Netherlands Environmental Assessment Agency (PBL) to investigate global change in relation to complex systems. More specifically, the model examines interactions between the socio-economic system (demography, world economy, agricultural economy and trade, and energy supply and demand), the earth system (managed land, natural vegetation, the atmosphere-ocean system, and atmospheric chemistry), land allocation processes, emissions processes, impacts (climate impacts, land degradation, water stress, biodiversity, and water and air pollution) and policy options. http://www.mnp.nl/en/themasites/image/index.html

Indirect land-use change (indirect land-use change): Land that has been put into agricultural production because other agricultural land has been converted to bioenergy crops or because of increased demand of food crops as a result of bioenergy cropping.

Indirect effects of land-use change: Emissions or other impacts from land that has been put into agricultural production because other agricultural land has been converted to bioenergy crops or because of increased demand of food crops as a result of bioenergy cropping. For example, if U.S. farm production is used for fuel instead of food, some argue that food prices rise and farmers in developing countries respond by growing more food. This response may require clearing new land and burning native vegetation and, hence, releasing carbon.

Land cover: The ecological state and physical appearance of the land surface. Examples of land-cover types or categories include closed forest, open forest, grassland and cropland. Change in land cover is the conversion of land from one type of dominant vegetation or built environment to another. Land-cover categories and characteristics may be determined from on-the-ground measurements or remotely sensed images. These methods have different uncertainties.

Land management is the administration of a given land use by humans. Land management can affect ecological processes without changing the basic land use. For example, management of livestock grazing can be minimal or intensive and regulated or unregulated.

Land use refers to the land-management practices of humans. Examples are protected areas, timber harvest, row-crop agriculture, grazing, and human settlements. Change in land use may or may not cause a significant change in land cover.

Life cycle analysis: Evaluation of the environmental impacts of a given product or service caused or necessitated by its existence. LCA considers raw material production, manufacture, distribution, use and disposal, including all transportation steps necessary for or caused by the product. The goal of LCA is often to compare the full range of environmental and social damages attributable to products and services.

Marginal land: The definition of "marginal land" (also called “degraded,” “idle,” “underutilized,” etc.) varies widely by country, institution and local conditions. It is a relative term; the same qualities used to classify a site "marginal" in one place or for one purpose can result in land being considered productive in another place or for a different purpose. Therefore, there are great uncertainties among the wide-ranging estimates of availability and suitability of marginal land. Economically, land is marginal if the combination of yields and prices barely covers cost of production. In practice, the term is generally used more broadly to describe any lands that are not in productive use, in contrast to lands yielding rents from services. Depending on time and place, marginal land may also refer to idle, underutilized, barren, inaccessible, degraded, excess and abandoned lands, or to lands occupied by politically and economically marginalized populations, or land with characteristics that make a particular use unsustainable or inappropriate. Furthermore, the classification of marginal lands by remote means (using satellite imagery or land-cover data sets) can lead to many errors and high uncertainty. For example, what may be seen from above as idle lands may actually be fallow land between cropping regimes, recently harvested lands, or areas that are being mismanaged.

Models are tools that represent essential features of a system so that relationships can be analyzed within established boundary conditions. Models may be conceptual or mathematical. Modeling may be used to simulate natural conditions and scenarios of resource use. Analyses of models can be used to examine potential impacts of a decision. Ecological models are a tool for environmental managers to enhance understanding of both the complexities and the uniqueness of a given situation and its response to management or change. Economic models represent economic processes using variables and logical or quantitative relationships between them. Land-use change modeling makes use of economic, agricultural, and ecological models, as well as often putative socioeconomic drivers. Climate change models are numerical simulation projections that incorporate meteorological variables but also may incorporate land-cover variables as inputs. Models allow managers to summarize information on the environment, determine where gaps exist, extrapolate across the gaps, and simulate various scenarios to evaluate outcomes of environmental management decisions.

Pastureland: (1) Land managed primarily for the production of introduced or native forage plants for livestock grazing (land-use category). (2) Land with vegetative cover of grasses, legumes, and/or forbs (land-cover category). (3) Land identified through remote sensing as resembling (1) or (2) but possibly other land-cover or land-use category.

Primary productivity: The conversion of light energy and carbon dioxide into living organic material.

Projections: Estimates of future possibilities. Model results *always* contain uncertainties because they are based on current understanding of interactions and field and laboratory studies. That is why we generally refer to model results as *projections* rather than *predictions* (an output or outcome that is declared with confidence in advance).

Rural living: Term relating to country people and the land uses of agriculture, ranching, and forestry that support country life. Rural life requires large areas of managed land, few natural disturbances, and an abundance of ecosystem services (e.g., clean water, clean air, etc.).

Scale of models: Choice of spatial and temporal scale of a model should be determined by the question being addressed. The scale of a model is critical to determining which parameters and processes are included. Often knowledge of a system is limited to particular scales; yet management questions are at a different scale. In such cases, it may be necessary to change the scale of the model projections.

Scaling up: Re-projecting or re-estimating information at a larger spatial scale. Scaling up of information often leads to a loss of information on the finer-scale spatial pattern and heterogeneity. Thus, techniques for rescaling that maximally retain information on finer-scale heterogeneity are desirable. For example, a scaling-up process might lose spatially explicit, geographically specified information on resource-use type at particular spatial coordinates but retain information on fine-scale heterogeneity (e.g., diversity) of resource use as probability distributions (e.g., describing the frequency of land-use types).

Sensitivity analysis: A technique used to determine how different values of an independent variable impact a particular dependent variable under a given set of assumptions. This technique is used within specific boundaries that depend on one or more input variables.

Sustainable development: Development that meets the needs of the present without compromising the ability of future generations to meet their own needs (Bruntland 1987). *Ecological sustainability* is the tendency of an ecological system or process to be maintained over time without loss or decline. For instance, sustainable forestry practices maintain forest structure, diversity, and production without long-term decline or loss over a region. Sustainable water use provides for the water needs of a human community without reducing water quality or quantity to levels that might compromise ecological processes. Resource use can be locally sustainable over the long term based on external subsidies from other areas, but this practice can result in degradation of the larger system. Thus, sustainability needs to be viewed from a broad perspective in both time and space. Sustainability is widely regarded as economically and ecologically desirable; in the ultimate sense, it is the only viable long-term pattern of human interactions with the environment.

Uncertainty analysis indicates the influence of a parameter, given the actual variation it represents, on the output variable. Thus, uncertainty analysis complements sensitivity analysis. Identifying the sources of uncertainty in a model helps a user know when the limits of the model's applicability have been reached.

Validation is the process of determining the soundness and accuracy of the model outcomes. Often however, independent data for validation are not available at the time the model is developed. In that case, validation must wait until new information is available

APPENDIX C. List of Acronyms

AFO – animal feeding operation
ARB –Air Resources Board (State of California)
ARS – Agricultural Research Service (U.S. DA)
AWIFS – Advanced Wide Field Sensor
BMPs – best management practices
BRDI – Biomass Research and Development Interagency Board
Bu/A – bushels per acre
C – carbon
CAFO – confined animal feeding operation
CARB – California Air Resources Board
CBES– Center for Bioenergy Sustainability
CC or Ccc – continuous corn
CCOA – corn-corn-oat-alfalfa (crop rotation)
CDIAC - Carbon Dioxide Information Analysis Center
CDL – Cropland Data Layer
CEAP – Conservation Effects Assessment Project
CEC - California Energy Commission
CENR – Committee on Environment and Natural Resources
CIFOR – Center for International Forestry Research
Cm – corn-meadow (crop rotation)
COAA – corn-oat-alfalfa-alfalfa (crop rotation)
CO_2 – carbon dioxide
CREP – Conservation Reserve Enhancement Program
CRN – controlled – and slow release N fertilizers
CRP - Conservation Reserve Program
CS or CSb – corn soybean rotation
CSP – Conservation Security Program
CTA – Conservation Technical Assistance
CVs – coefficients of variations
DART – Dynamic Applied Regional Trade (model)
DDGS – distiller's dried grains with solubles
DOE – Department of Energy
EBI – Environmental Benefits Index
EERE – Energy, Efficiency and Renewable Energy
EISA – Energy Independence and Security Act
ENR – enhanced nutrient removal
EPA – Environmental Protection Agency
EPPA – Emissions Predictions and Policy Analysis (MIT model)
EQIP – Environmental Quality Incentives Program
ERS – Economic Research Service (USDA)
ESM – Earth System Model
FAO – Food and Agriculture Organization of the United Nations
FAOSTAT – Food and Agriculture Organization Statistics
FAPRI – Food and Agricultural Policy Research Institute

FARM – Future Agricultural Resources Model
FASOM – Forest and Agricultural Sector Optimization Model
FWP – Farmable Wetlands Program
GAEZ – global agro-ecological zones
GAO – General Accounting Office
GDP – gross domestic product
GHG – greenhouse gases
GIS – geographic information system
GLBRC – Great Lakes Bioenergy Research Center
GLC – global land cover
GPS – global positioning system
GREET – Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (model)
GTAP – Global Trade Analysis Project
HEL – highly erodible land
HUC – Hydrologic Unit Code
IAM – Integrated Assessment Model
IATP – Institute of Agricultural and Trade Policy
IBIS – Integrated Biosphere Simulator (model)
IIASA – International Institute for Applied Systems Analysis
ILUC – indirect land-use change
IMAGE: Integrated Model to Assess the Global Environment.
IPCC – Intergovernmental Panel on Climate Change
ISNT – Illinois Soil Nitrogen Test
KDF – Knowledge Development Framework
LCA – Life Cycle Assessment
LCFS – Low Carbon Fuel Standard
LEITAP – Agricultural Economics Research Institute (LEI) Trade Analysis Project
MOD12Q1 – MODIS Land Cover Type 96-Day L3 1km
MODIS – Moderate Resolution Imaging Spectroradiometer
MRLC – Multi-Resolution Land Characteristics Consortium
N – Nitrogen
N_2 – Nitrogen gas (colorless, odorless, and tasteless gas that makes up 78.09% of air)
N_2O – Nitrous Oxide
NANI – Net Anthropogenic Nitrogen Inputs
NAS – National Academy of Sciences
NASA – National Aeronautics and Space Administration
NDVI – Normalized Difference Vegetation Index
NLDC – National Land Cover Data
NO_2 – Nitrite Nitrogen (NO_2^-) if in water and nitrogen dioxide (NO_2) if in air
NO_3 – nitrate nitrogen
NOx – mono-nitrogen oxides, or the total concentration of nitric oxide (NO) plus nitrogen dioxide (NO_2)
NOy – reactive odd nitrogen or the sum of NO_x plus compounds produced from the oxidation of NOX, which includes nitric acid, peroxyacetyl nitrate, and other compounds
NPDES – National Pollutant Discharge Elimination System
NPSs – nonpoint sources

NRC – National Research Council
NRCS – Natural Resources Conservation Service
NRI – National Resources Inventory
NSIDC – National Snow and Ice Data Center
NSTC – National Science and Technology Council
OBP – Office of Biomass Program
OM – organic matter
ORNL– Oak Ridge National Laboratory
P – phosphorus
POC – particulate organic carbon
ppmv – parts per million by volume
ppt – parts per thousand
PRODES – Procedimento Desflorestamento (Brazil)
PS – point source
PSNT – Pre-Sidedress Nitrate Test
RADAMBRAZIL – airborne radar images and photographs of Brazil
RFS – Renewable Fuel Standard
SD – standard deviation
Si – silicon
SOC – soil organic carbon
SOM – soil organic matter
SON – soil organic nitrogen
SRP or DRP or ortho P – soluble reactive phosphorus, dissolved reactive phosphorus, orthophosphate
STATSGO – State Soil Geographic database
STELLA – Systems Thinking Experimental Learning Laboratory with Animation
STORET – STOrage and RETrieval data system (USEPA)
STPs – sewage treatment plants
TCFF – Temporal Climate Forcing Framework
TIMER–Targets Image Energy Region
TKN – total Kjeldahl nitrogen
TN – total nitrogen
TP – total phosphorus
TSS – total suspended solids
UAN – urea ammonium nitrate
USDA – United States Department of Agriculture
USEPA or EPA – United States Environmental Protection Agency
USGS – United States Geological Survey
WRP – Wetlands Reserve Program