
**Land in Climate Stabilization Modeling:
Initial Observations**

**Energy Modeling Forum
Stanford University
Stanford, CA 94305-4026**

Preface

The Energy Modeling Forum (EMF) was established in 1976 at Stanford University to provide a structural framework within which energy experts, analysts, and policymakers could meet to improve their understanding of critical energy problems. The EMF twenty-first study, “Multigas Mitigation and Climate Change,” assembled modeling teams from around the world in order to evaluate the cost-effectiveness of multigas mitigation options in stabilizing radiative forcing. The results from each of the individual modeling teams was published in 2006 in a special issue of *The Energy Journal*. EMF 21 was the first time many climate economic and integrated assessment models included non-CO₂ greenhouse gas mitigation options, as well as forest carbon sequestration mitigation options. However, given EMF 21’s focus on the overall mitigation picture, few land related results were provided and there was no analysis of land results across models.

This report assembles and analyzes the modeling results related to the role of land in climate stabilization scenarios. The report was produced as a follow-on and complement to the EMF 21 study, and as input to the EMF’s land modeling subgroup in the twenty-second EMF study on Climate Policy Scenarios for Stabilization and in Transition. Inquiries about the report should be directed to the Energy Modeling Forum, 448 Terman Engineering Center, Stanford University, Stanford, California 94305-4026, USA (telephone: (650) 723-0645; Fax: (650) 725-5362). Our web site address is: <http://www.stanford.edu/group/EMF>.

We would like to acknowledge the different modeling teams that actively participated in this report. Their willingness to provide results and modeling details facilitated interpretation and comparison and allowed us to provide an important detailed first look at global long-run land modeling. This report benefited greatly from peer review comments from Thomas Hertel, Andrew Platinga, Brent Sohngen, and Richard Tol. The authors also wish to acknowledge John Weyant for providing a forum and numerous opportunities for discussing and advancing the state-of-the-art in global long-run land modeling

This volume reports the findings of the EMF working group. It does not necessarily represent the views of Stanford University, members of the Senior Advisory Panel, any reviewers, or any organizations participating in the study or providing financial support. The lead author, Steven Rose, is responsible for any omissions and remaining errors. Comments or questions should be addressed to: rose.steven@epa.gov.

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EMF 22 Land Modeling Subgroup Participants

<u>Name</u>	<u>Affiliation (at the time of the study)</u>
Helal Ahammad	Australian Bureau of Agricultural and Resource Economics (ABARE), Australia
Keigo Akimoto	Research Institute of Innovative Technology for the Earth (RITE)
Ken Andrasko	The World Bank
Bas Eickhout	MNP-RIVM, The Netherlands
Thomas W. Hertel	Purdue University
Claudia Kemfert	German Institute for Economic Research
Tom Kram	MNP-RIVM, The Netherlands
Atsushi Kurosawa	The Institute of Applied Energy, Japan
Huey-Lin Lee	Purdue University
Bruce A. McCarl	Texas A&M University
Siwa Msangi	International Food Policy Research Institute (IFPRI)
Michael Obersteiner	International Institute for Applied Systems Analysis (IIASA), Austria
John M. Reilly	Massachusetts Institute of Technology
Shilpa Rao	International Institute for Applied Systems Analysis (IIASA), Austria
Keywan Riahi	International Institute for Applied Systems Analysis (IIASA), Austria
Dmitry Rokityanskiy	International Institute for Applied Systems Analysis (IIASA), Austria
Steven Rose	U.S. Environmental Protection Agency
Mark Rosegrant	International Food Policy Research Institute (IFPRI)
Ronald Sands	Joint Global Change Research Institute (JGCRI)
Jayant Sathaye	Lawrence Berkeley Laboratory
Uwe Schneider	Hamburg University
Roger Sedjo	Resources for the Future
Brent Sohngen	Ohio State University
Richard S.J. Tol	Hamburg University, Germany
Truong Truong	University of New South Wales, Australia
John Weyant	Stanford University
Liangzhi You	International Food Policy Research Institute (IFPRI)

Land in climate stabilization modeling: Initial observations

**Steven Rose^a, Helal Ahammad,^b Bas Eickhout,^c
Brian Fisher,^d Atsushi Kurosawa,^e Shilpa Rao,^f
Keywan Riahi,^f and Detlef van Vuuren^c**

^a Corresponding author: U.S. Environmental Protection Agency, Washington, DC, USA, rose.steven@epa.gov

^b Australian Bureau of Agriculture and Resource Economics (ABARE), Canberra, Australia

^c Netherlands Environmental Assessment Agency (MNP), Bilthoven, The Netherlands

^d Charles Rivers Associates International, Inc., Canberra, Australia

^e The Institute of Applied Energy, Tokyo, Japan

^f International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

Abstract

This report presents and evaluates the role of land in climate stabilization scenarios. Specifically, we consider stabilization results from four of the EMF-21 study models, as well as more recent stabilization results from two of the EMF-21 modeling teams. We find that land based mitigation—agriculture, forestry, and biomass liquid and solid energy substitutes—are a part of the cost-effective portfolio of mitigation strategies for long-term climate stabilization; thereby, reducing the cost of stabilization. Agriculture, forestry, and biomass can reduce costs throughout the century with annual abatement increasing per year. Agriculture and forestry assume larger shares of annual abatement in the near term, while biomass assumes a substantial mitigation role in the second half of the century. Cumulatively, agriculture, compared to forestry and biomass, is projected to account for a smaller, though potentially strategically important, share of the total abatement required for stabilization. Biomass, in particular, may have a substantial abatement role and therefore a large effect of the total mitigation cost of stabilization. Overall, the current scenarios find that land mitigation provides flexibility and reduces total costs; however, large fossil fuel emissions reductions will still be required for stabilization. Land based mitigation technologies not only provide a potential bridge to future fossil fuel emissions mitigation strategies, but they could also provide a steady and significant opportunity for managing the cost of climate stabilization.

There are substantial uncertainties. There is little agreement about the magnitudes of abatement. Across the stabilization scenarios considered, land mitigation options contributed cumulatively over the century 94 to 343 GtC equivalent greenhouse gas emissions abatement, approximately 15 to 40 percent of the total abatement required for stabilization. Agriculture, forestry, and bio-energy cost-effectively contributed to stabilization, with mitigation of agricultural methane sources providing 10 to 37 GtCeq, agricultural nitrous oxide mitigation providing 7 to 20 GtCeq cumulatively over the century, forest sequestration providing 31 to 113 GtCeq, and bio-energy providing 31 to 204 GtCeq. Long-run land climate modeling is rapidly evolving and many key modeling challenges exist and are in the process of being addressed by on-going model development. This report provides a point of comparison for the new generation of land modeling, which should provide more rigorous and structured global land use baseline and mitigation modeling and better characterizations of land's long-run climate change and mitigation contributions.

Land in Climate Stabilization Modeling: Initial Observations

1 Introduction

The 21st Study of the Energy Modeling Forum (EMF-21) assembled modeling teams from around the world in order to evaluate the cost-effectiveness of non-CO₂ greenhouse gas mitigation options in stabilizing radiative forcing, i.e., whether or not they lower the cost of stabilization. The results from each of the individual modeling teams have been published in a special issue of *The Energy Journal* (see Weyant *et al.*, 2006). EMF-21 was the first time many climate economic and integrated assessment models included non-CO₂ greenhouse gas mitigation options, as well as forest carbon sequestration mitigation options. Given EMF-21's focus on the overall mitigation picture, land's specific role in stabilization received little attention. Land use related emissions and mitigation were modeled by a number of the modeling teams, but few land related results were provided and no analysis was done of the land results across models.

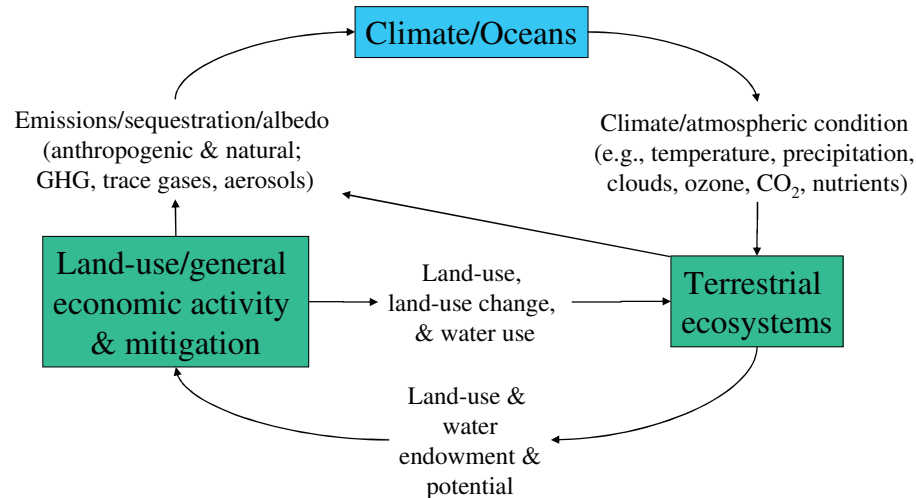
This report presents and evaluates the role of land in climate stabilization scenarios. Specifically, we consider stabilization results from four of the EMF-21 study models, as well as some more recent stabilization results from two of the EMF-21 modeling teams. This report was designed, in large part, to simply provide data to inform a growing interest in understanding land's role in climate change mitigation—by the Inter-governmental Panel on Climate Change, the land subgroup of the EMF-22 climate stabilization study, and a burgeoning global discussion on long-term mitigation potential of bioenergy. The report provides an initial analysis of the data; however, further elucidation of the underlying activity

and modeling will be useful. To that end, additional analyses are planned that will evaluate, among other things, acreage requirements, energy supply and demand implications, and regional roles; thereby, improving the characterization of land's competitive mitigation potential and facilitating more refined inter-model comparisons.

The next section provides a background discussion. After that, we present global modeling results on the cost-effective role of land based greenhouse gas mitigation in achieving climate stabilization targets. The section analyzes the data from a number of perspectives, including mitigation levels and timing, the relative role of land based mitigation, the implications of alternative baselines and stabilization targets, and the importance of biomass mitigation strategies. We also briefly reflect upon the forest mitigation results from the stabilization scenarios using detailed forest sector modeling estimates of forest carbon sequestration supply responses. We conclude with summary remarks and a few notes on some key modeling challenges.

2 Background

Land-use and land cover are crucial to climate stabilization for their atmospheric inputs, which are shaped by market demands for land-based goods and services and regional climate and atmospheric feedbacks. Even if land activities are not considered as mitigation alternatives by policy, land's dynamic atmospheric inputs role (emissions, sequestration, and albedo) is paramount, as is its susceptibility to changes in the atmospheric condition. Figure 1 portrays these relationships.

Figure 1: Land in long-term climate modeling

Over the past several centuries, human intervention has markedly changed land surface characteristics, in particular through large scale land conversion for cultivation (Vitousek *et al.*, 1997). Changes in land use and land cover represent an important driver of net greenhouse gas (GHG) emissions. Cumulative emissions from historical land cover conversion for the period 1920–1992 have been estimated to be between 56.2 and 90.8 GtC (McGuire *et al.*, 2001), and as much as 156 GtC for the entire industrial period 1850–2000, roughly a third of total anthropogenic carbon emissions over this period (Houghton, 2003). For example, in the 1990s, 6.4 GtC/yr was emitted to the atmosphere from industrial activities and 2.2 GtC/yr was the net flux from global land use, primarily from tropical deforestation (Houghton, 2003).¹ In addition, land management activities that occur as part of each land use (e.g., cropland fertilization and water management, manure management, and forest rotation lengths) also affect land based emissions of CO₂ and non-CO₂ GHGs. Agricultural land

management activities are estimated to contribute approximately 50% of global atmospheric inputs of methane (CH₄) and 75% of global nitrous oxide emissions (N₂O), for a net contribution from non-CO₂ GHGs of approximately 14% of all anthropogenic greenhouse gas emissions (USEPA, 2006a).

Changes in land use practices are regarded as an important component of long term strategies to mitigate climate change. Modifications to land use activities can reduce emissions of both CO₂ and non-CO₂ gases (CH₄ and N₂O), increase sequestration of atmospheric CO₂ into plant biomass and soils, and produce biomass fuel substitutes for fossil fuels. Previous studies have suggested that land has the technical potential to sequester up to an additional 87 GtC by 2050 in global forests alone (IPCC, 1995; IPCC, 2000a; IPCC, 2001). In addition, current technologies are capable of significantly reducing CH₄ and N₂O emissions from agriculture (DeAngelo *et al.*, 2006; USEPA, 2006b).

¹ There are substantial uncertainties in historic global land-use change emissions. For example, the IPCC reports that gross emissions from 1990s deforestation and other land-use change activities in the tropics ranged from 0.5 to 2.7 GtC-equivalent/yr, with a central estimate of 1.6 GtC-equivalent/yr (IPCC, 2007).

The explicit modeling of land-based climate change mitigation in long-term global scenarios is relatively new and rapidly developing. As a result, until recently, assessment of the long-term role of global land-based mitigation had not been formally addressed in the IPCC's research assessments, including the Special Report on Land use, Land-use Change, and Forestry (IPCC, 2000) and the IPCC's 2001 Working Group III Third Assessment Report on Mitigation (IPCC, 2001). The IPCC's latest assessment reflects the scenarios presented in detail in this EMF report (IPCC, 2007).

Long-term energy modelers have historically focused their attention and time on characterizing energy and industry GHG emissions and mitigation opportunities (IPCC, 2001). However, recent developments in global non-CO₂ emissions inventories (USEPA, 2006a; Olivier, 2002), international agricultural mitigation cost data (DeAngelo *et al.*, 2006; USEPA, 2006b; Beach *et al.*, 2008), and land sector economic modeling (e.g., Sands and Leimbach, 2003; Sohngen and Sedjo, 2006; Rokityanskiy *et al.*, 2007) have facilitated explicit land modeling in climate stabilization analyses that considers the broad set of land related GHG fluxes, sources, and mitigation options.

A stabilization scenario is a particular application of top-down modeling that identifies a dynamic cost-effective portfolio of abatement strategies composed of the lowest cost combination of mitigation strategies over time from across all sectors of the economy that achieve the climate stabilization goal.² Many estimates of

mitigation potential in the literature are referred to as "bottom-up" estimates in that they are derived from detailed technological engineering and process data and cost data for individual technologies as applied at specific locations (e.g., USEPA, 2006b). These studies estimate how much mitigation is economic for a given carbon price and their estimates facilitate the introduction of emissions abatement technologies into top-down models that are more aggregate. Top-down models are used to evaluate the cost competitiveness of mitigation options and the implications across input markets, sectors, and regions over time for large-scale domestic or global adoption of mitigation technologies. Top-down models can take many forms—e.g., sectoral, national, economy-wide, and global integrated assessment. It is important to note that while both the bottom-up and stabilization modeling approaches can generate estimates of mitigation potential, the estimates are not always directly comparable. Most importantly, bottom-up estimates are frequently estimates of how much mitigation is available at a given carbon price, while stabilization estimates how much mitigation is used to achieve the given environmental goal at the lowest cost (from which an implied carbon price can be inferred).

There are also very meaningful structural differences in the two approaches. Bottom-up mitigation responses are typically more detailed and derived from modeling exercises with more extensive fixed market assumptions. Cost estimates are therefore more partial equilibrium in that some input

² In integrated assessment and economic climate stabilization scenarios, a climate target is prescribed (e.g., atmospheric concentration or radiative forcing level) and modeling identifies the cost-effective (i.e., least-cost) combination of mitigation technologies over time for realizing the climate target. This is inherently different from the economic optimization of discounted net benefits, where the difference between monetized benefits and costs is maximized

and the climate outcome is derived. See Sohngen and Mendensohn (2003) for an example of this later approach. Comparison of results from the two approaches is problematic because setting a climate target yields both monetized and non-monetized benefits, and non-monetized benefits are likely significant, while optimization is based solely on monetized benefits.

and output market prices are exogenous as can be key input quantities such as acreage or capital. Top-down mitigation responses consider more generic mitigation technologies and more endogenous changes in outputs and inputs (e.g., shifts from food crops or forests to energy crops) as well as changes in market prices (e.g., changes in land prices with increased competition for land). In addition, many current stabilization applications of top-down models make the optimistic assumption of immediate and simultaneous global adoption of a coordinated climate policy with an unconstrained, or almost unconstrained, set of mitigation options across sectors; assumptions that, *ceteris paribus*, bias stabilization cost estimates downward. A more constrained scenario, with less than comprehensive regional participation or available mitigation technologies, would increase the cost of stabilization.³

The notion that forest sequestration could be used to offset GHG emissions and stabilize climate is not new (see Dyson, 1977; Marland, 1988; Lashof and Tirpak, 1989). Furthermore, recent studies explicitly modeling land use and land use change have provided rigorous modeling showing how the costs of achieving long-run climate objectives can be reduced (Sands and Leimbach, 2003; Sohngen and Mendelsohn, 2003). Sands and Leimbach (2003) consider the role of a composite energy crop in stabilization, and Sohngen and Mendelsohn (2003) consider the role of forestry in economically optimal mitigation. However, data and model development have only recently permitted modeling of mitigation portfolios that include terrestrial sequestration and multigas emissions reduction land mitigation strategies. The scenarios presented in this report build upon the literature by assessing a more complete set of competing land mitigation options

across a number of models in achieving common climate stabilization goals.

The Energy Modeling Forum Study-21 (EMF-21) was the first coordinated stabilization modeling effort to include an explicit evaluation of the relative role of land in stabilization. With a common radiative forcing stabilization target of 4.5 Watts per meter squared (W/m^2) in 2100, the EMF-21 exercise provides a unique opportunity for comparing land modeling results across models. Only four of the EMF-21 study modeling teams explicitly evaluated the cost-effectiveness of including land based mitigation as stabilization strategies (Kurosawa, 2006; van Vuuren *et al.*, 2006; Rao and Riahi, 2006; Jakeman and Fisher, 2006). The data underlying their results are presented and analyzed in this report. The report also covers more recent stabilization results from two of the modeling teams that have subsequently improved upon their EMF-21 land modeling (Riahi *et al.*, 2007; van Vuuren *et al.*, 2007).

3 Cost-effective land-based mitigation in climate stabilization modeling

Table 1 presents an overview of land modeling characteristics for each of the studies considered in this report. Table 1 reveals clear differences in modeling, and specifically in the modeling of land—land types considered, emissions sources, mitigation alternatives, and implementation. These unique characteristics, in addition to other factors, imply different opportunities and opportunity costs for land related mitigation; and, therefore, suggest different outcomes.

³ This issue is not unique to top-down modeling. Bottom-up estimates, aggregated or not, can make the same assumptions—implicitly or explicitly.

**Table 1: Overview of stabilization modeling studies considered
(2100 radiative forcing relative to pre-industrial times)**

Source	Primary model name	In EMF-21?	Modeling type	Climate policies in 2100*	Land GHG emissions/sequstration represented	Land-based GHG abatement	Land types modeled
<i>Kurosawa (2006)</i>	GRAPE	yes	Integrated assessment model	Stabilize radiative forcing at 4.5 W/m ²	LUCF, enteric, manure, paddy rice, fertilized soils, biomass combustion	Agriculture (non-CO ₂ MACs); afforestation & avoided deforestation (Kurosawa, 2004); solid and liquid biomass from residues (endogenous)**	Forest, cropland, grassland
<i>van Vuuren et al. (2006)</i>	IMAGE 2.2	yes	Integrated assessment model	Stabilize radiative forcing at 4.5 W/m ² . Additional stabilization targets also ran (with 3.7 and 5.3 W/m ² in 2100). Detailed land mitigation data only available for 4.5 W/m ² scenario.	LUCF, soil processes, paddy rice, fertilizer use, livestock, manure and biomass & agricultural waste burning	Agriculture (non-CO ₂ MACs); afforestation (IMAGE model based MACs); biomass primarily for liquid fuels from maize, sugar, and woody crops (TIMER energy model MACs)	Food crops (e.g., cereals, rice, maize, pulses, roots & tubers, oil crops), biofuel crops, grass & fodder, forest (11 types), 6 other land cover types
<i>Rao and Riahi (2006)</i>	MESSAGE	yes	Energy model in integrated assessment framework	Stabilize radiative forcing with 4.5 and 3.0 W/m ² in 2100	LUCF, enteric, manure, paddy rice, soil n ₂ o, and biomass & agricultural waste burning	Agriculture (non-CO ₂ MACs); afforestation, forest management, avoided deforestation (multiple iterations with Sohngen and Sedjo, 2006, model for core scenarios; forest carbon supply curves from DIMA forest model, Rokityanskiy et al., 2006, for sensitivity scenarios); liquid, solid, hydrogen, and gas biomass from forests and woody crops, includes bioenergy with geologic sequestration option (DIMA model for biomass feedstock curves)	Not explicitly modeled for core scenarios; forest, cropland, and forest biomass land modeled for sensitivity scenarios
<i>Jakeman and Fisher (2006)</i>	GTEM	yes	Computable general equilibrium model	Stabilize radiative forcing with 3.6 W/m ² for 2050 (based on 4.5 W/m ² 2100 target)	LUCF, fossil fuel combustion, livestock and fertiliser, paddy rice	Agricultural non-CO ₂ and fossil fuel CO ₂ (endogenous); afforestation, forest management, avoided deforestation (MAC from Sohngen and Sedjo, 2006)	Not explicitly modeled
<i>Riahi et al. (2006)</i>	MESSAGE	no	Energy model in integrated assessment framework	Stabilize radiative forcing at 4.5 W/m ² . Numerous additional stabilization targets with alternative baselines. Detailed land mitigation data only available for 4.5 W/m ² scenario.	LUCF, enteric, manure, paddy rice, soil n ₂ o, and biomass & agricultural waste burning	Agriculture (non-CO ₂ MACs); forestry (DIMA model forest carbon supply curves); liquid, solid, hydrogen, and gas biomass from forests, woody crops, and crop residue, includes bioenergy with geologic sequestration option (DIMA model for wood biomass feedstock curves, AEZ/BLS agriculture model for crop residue biomass potential)	Forest, arable land, forest biomass land, and urban land
<i>van Vuuren et al. (2007)</i>	IMAGE 2.3	no	Integrated assessment model	Stabilize CO ₂ eq concentrations with 650, 550, and 450 ppm in 2100 (~4.5, 3.7, and 2.9 W/m ²).	LUCF, soil processes, paddy rice, fertilizer use, livestock, manure and biomass & agricultural waste burning	Agriculture (non-CO ₂ MACs), afforestation (IMAGE model based MACs), biomass solid & liquid fuels from maize, sugar, woody crops, and residues (TIMER energy model MACs)	Food crops (e.g., cereals, rice, maize, pulses, roots & tubers, oil crops), biofuel crops, grass & fodder, forest (11 types), 6 other land cover types

Notes: LUCF = Land Use Change and Forestry net emissions (e.g., deforestation, afforestation, reforestation, grassland conversion), MAC = Marginal Abatement Curve

* Radiative forcing levels in 2100. Stabilization targets below 4.5 W/m² do not stabilize until after 2100.

** GRAPE biomass residue feedstocks include residues from agriculture, forestry, industry, and households

The integrated assessment and general equilibrium models represented here have relied on detailed sectoral models or engineering studies to model the costs of forest and agricultural mitigation respectively. For example, Jakeman and Fisher (2006) introduce sequestration supply curves from the global forestry model of Sohngen and Sedjo (2006) into a general equilibrium model, and Sands and Leimbach (2003) and Rao and Riahi (2006) iterate energy models with land sector models in integrated assessment modeling frameworks. Meanwhile, Kurosawa (2006) uses abatement supply schedules from DeAngelo *et al.* (2006) in an integrated assessment model. Finally, van Vuuren *et al.* (2006; 2007) used afforestation supply curves derived from IMAGE calculations as shown in Strengers *et al.* (2008). Avoided deforestation is not considered in van Vuuren *et al.* (2006; 2007), in contrast to Rao and Riahi (2006), Jakeman and Fischer (2006), and Kurosawa (2006). Currently, abatement supply schedules (or marginal abatement curves, MACs), developed by other studies, are heavily used to model agricultural and forestry GHG mitigation costs and GHG reduction potential. There are no standard practices for how MACs are implemented across models. Only GTEM (Jakeman and Fisher, 2006) has fully endogenous agricultural mitigation costs (but exogenous forestry mitigation). The other models implement the agricultural and forestry MACs with some degree of exogeneity.

Overall, in line with the overall findings of EMF-21, the four EMF-21 studies found that it was cost-effective to include land based mitigation in the set of eligible stabilization strategies. Including these options (both non-CO₂ and CO₂) provided greater flexibility within and across time periods. For example, Jakeman and Fisher (2006) provided an explicit estimate of the cost savings associated with including land-use change and forestry mitigation options.

Including agriculture and forestry options reduced the emissions reduction burden on all other emissions sources such that the projected decline in global real GDP associated with achieving stabilization was reduced to 2.3 per cent at 2050 (US\$3.6 trillion in 2003 dollars), versus losses of around 7.1 per cent (US\$11.2 trillion) and 3.3 per cent (US\$5.2 trillion) for the CO₂-only and multi-gas (without forest sinks) scenarios respectively. None of the EMF-21 papers isolated the GDP effects associated with biomass fuel substitution or agricultural non-CO₂ abatement. As is shown below in the next section, all of the studies listed in Table 1 find agriculture, forest, and biomass mitigation strategies to be cost-effective and to lower the cost of stabilization.

3.1 Magnitude, timing, and relative roles

Figures 2 through 5 present the total annual abatement trajectories taken by the four EMF-21 models in achieving the 4.5 W/m² stabilization target by 2100 compared to pre-industrial times (see the appendix for the tabular data).⁴ In Figures 2-5, the left-hand panels identify the dynamic abatement roles of “Land” and all “Other” non-land activities in the stabilization emissions abatement trajectories. Total Land abatement includes net reductions from agriculture, forest, and biomass. Total Other abatement includes activities not associated with land-use, e.g., non-biomass energy, industry, and transportation activities. The right-hand panels disaggregate the annual land abatement trajectories into agricultural non-CO₂ emissions reductions (CH₄ and N₂O),⁵ additional forest carbon sequestration, and commercial biomass related abatement. Biomass abatement from the MESSAGE model is further subdivided into biomass sequestration and biomass energy combined with carbon dioxide

⁴ Note that the GTEM model time horizon is 2050, while the time horizon is 2100 for all of the other models.

⁵ Agricultural soil carbon abatement options are not currently modeled by integrated assessment models.

capture and geologic storage (BECS). In both panels, the upper boundary of the coloured sections represents baseline emissions, in total and for the land sectors respectively. Therefore, agricultural and forestry mitigation represent emissions reductions or additional terrestrial sequestration from the baseline respectively, while biomass mitigation represents offsets of fossil fuel combustion emissions, or bioenergy combustion emissions in the case of BECS. As a result, total land abatement produces a large net sequestration (vs. net emissions) effect in some of the scenarios (see the right-hand panels where the bottom boundary projects negative remaining land emissions).

To gain further insight into land's relative abatement role, we have also computed cumulative abatement shares by activity type for different time periods: 2000-2030, 2000-2050, and 2000-2100 (Table 2). The upper block of results in Table 2 corresponds to the annual emissions reductions for the 4.5 W/m² EMF-21 stabilization scenarios illustrated in Figures 2-5. The lower block of results in Table 2 correspond to scenarios discussed in subsequent sections (and an additional 4.5 W/m² MESSAGE scenario that is discussed later). In Table 2, very different cumulative responses for 4.5 W/m² are observed across models due to the confluence of numerous uncertainties—including baseline emissions, mitigation option sets, and the relative costs of land mitigation options with respect to each other and non-land options.

In Figures 2-5, there are clearly different land based mitigation pathways being taken by the models. However, the studies agree on a number of points. First, agriculture, forestry, and biomass mitigation options are used by each of the models. Therefore, each is helping to lower the overall cost of stabilization. Second, total annual GHG abatement grows over time, with increasing annual abatement in both the "Other" and

"Land" sectors. Other sector annual abatement grows faster than Land abatement throughout the century for all four scenarios. Third, despite the fact that the Other sectors perform the majority of abatement, the land based mitigation strategies are a significant part of the mitigation portfolio, abating 23 to 44 cumulative GtCeq by 2050 (18 to 72% of total abatement; Table 2) and 94 to 223 cumulative GtCeq by 2100 (15 to 44%).⁶

There are clear differences in abatement trajectory mitigation levels and timing. The magnitude of abatement in any particular time period—overall, from land, and from the specific land abatement categories—varies across models. For example, in 2040, forests abate 1.22 GtCeq with the GRAPE model; while the IMAGE, GTEM, and MESSAGE models project forest abatement of 0.33, 0.72, and 0.04 GtCeq respectively (see Appendix). Similarly, GTEM projects approximately 0.37 GtCeq of agricultural nitrous oxide abatement in 2040, while the other models project 0.19 GtCeq or less. After biomass, the next most dominant land mitigation strategy over the century is forestry for all of the scenarios. Annual forest mitigation grows or remains fairly constant over time for all the models except GTEM, which shows a slight decline in forest mitigation that is offset by an increase in agricultural mitigation.⁷ Agricultural CH₄ mitigation is significant for IMAGE and MESSAGE, while agricultural N₂O abatement is relatively more important in magnitude than agricultural CH₄ for GRAPE and GTEM.

⁶ The high percentage in 2050 comes from scenarios (e.g., GRAPE) that estimate a modest amount of cumulative abatement from 2000 to 2050, with forestry and agricultural abatement options providing the majority of the abatement.

⁷ The GTEM result (Jakeman and Fisher, 2006) is highly dependent on the GTEM implementation of forest carbon responses from Sohngen and Sedjo (2006) where profitable rotational harvesting is projected mid-century. Also, Jakeman and Fisher implemented a high carbon price scenario from Sohngen and Sedjo that includes a relatively high mitigation response over the early decades.

Figure 2: Annual emissions reductions for the GRAPE model from EMF-21. Stabilization with target 4.5 W/m² in 2100 with multigas and sinks mitigation.

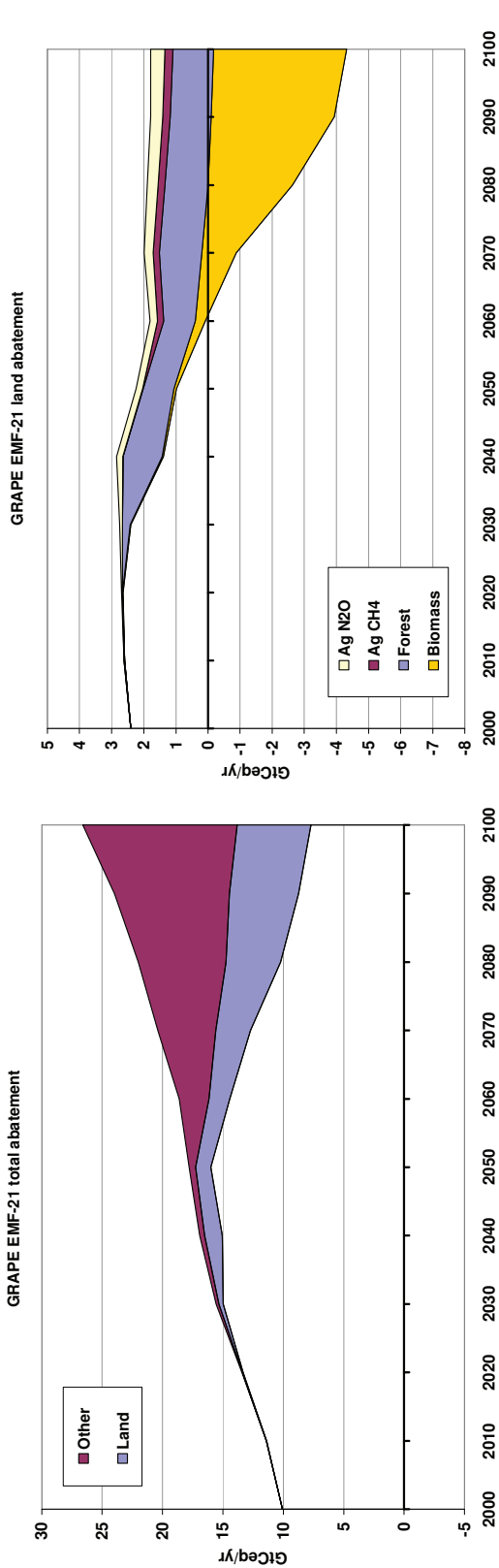


Figure 3: Annual emissions reductions for the IMAGE 2.2 model from EMF-21. Stabilization with target 4.5 W/m² in 2100 with multigas and sinks mitigation.

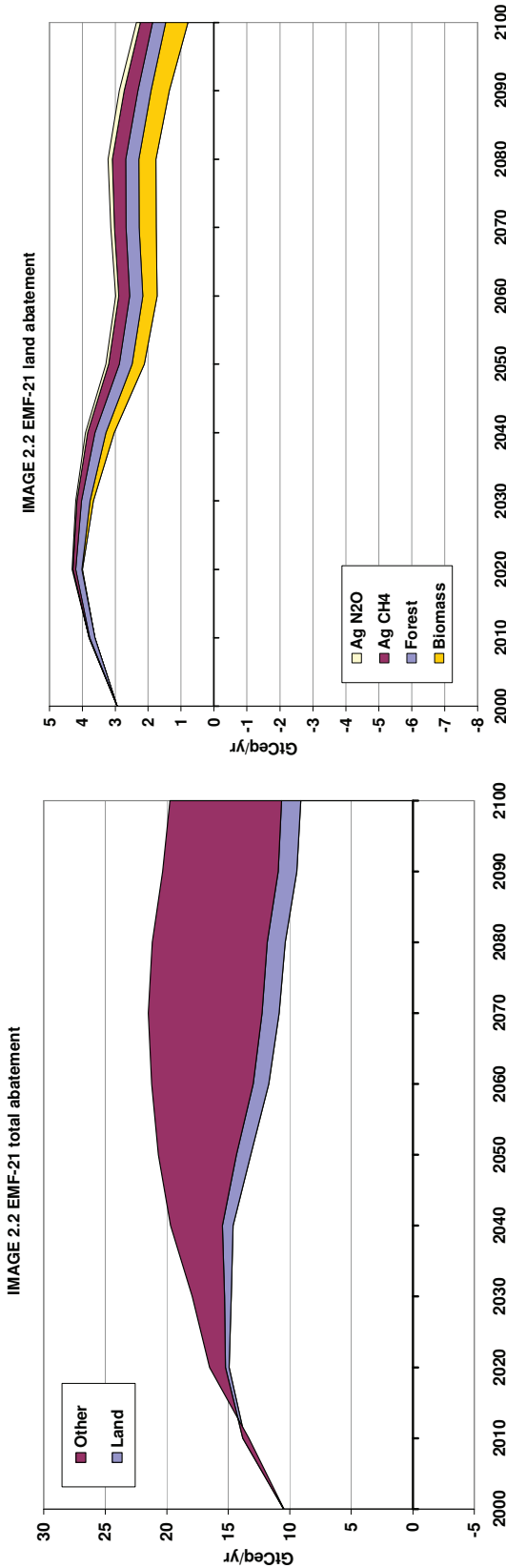


Figure 4: Annual emissions reductions for the GTEM model from EMF-21. Stabilization with target 4.5 W/m^2 in 2100 with multigas and sinks mitigation. (GTEM scenarios ran through 2050.)

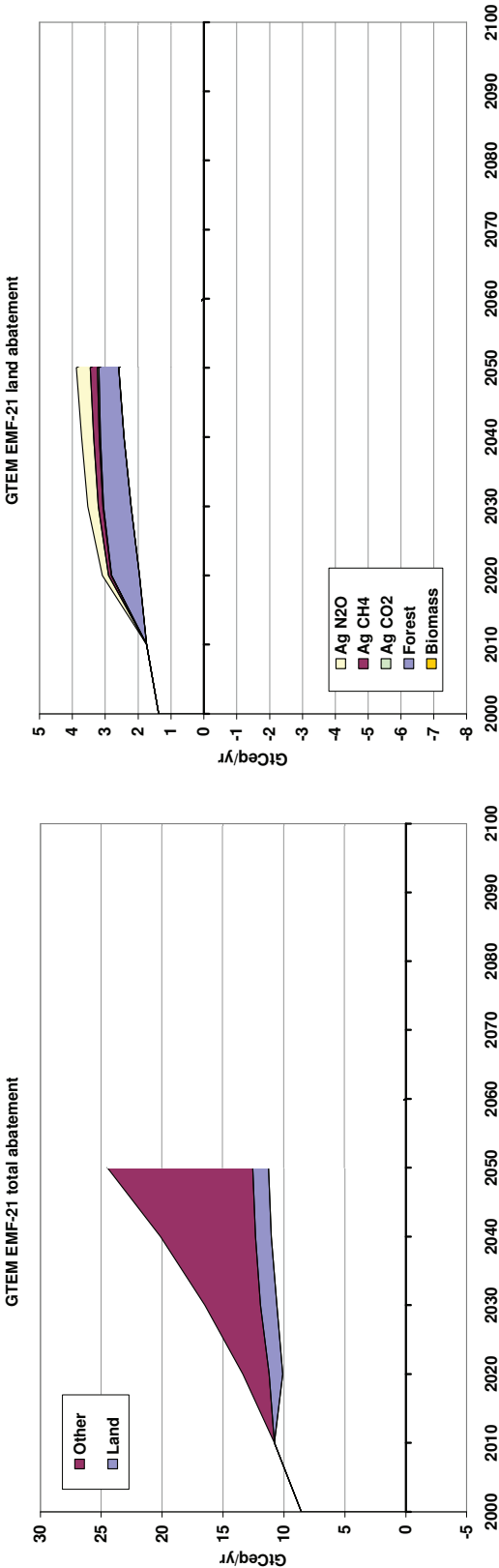


Figure 5: Annual emissions reductions for the MESSAGE model from EMF-21. Stabilization with target 4.5 W/m^2 in 2100 with multigas and sinks mitigation.

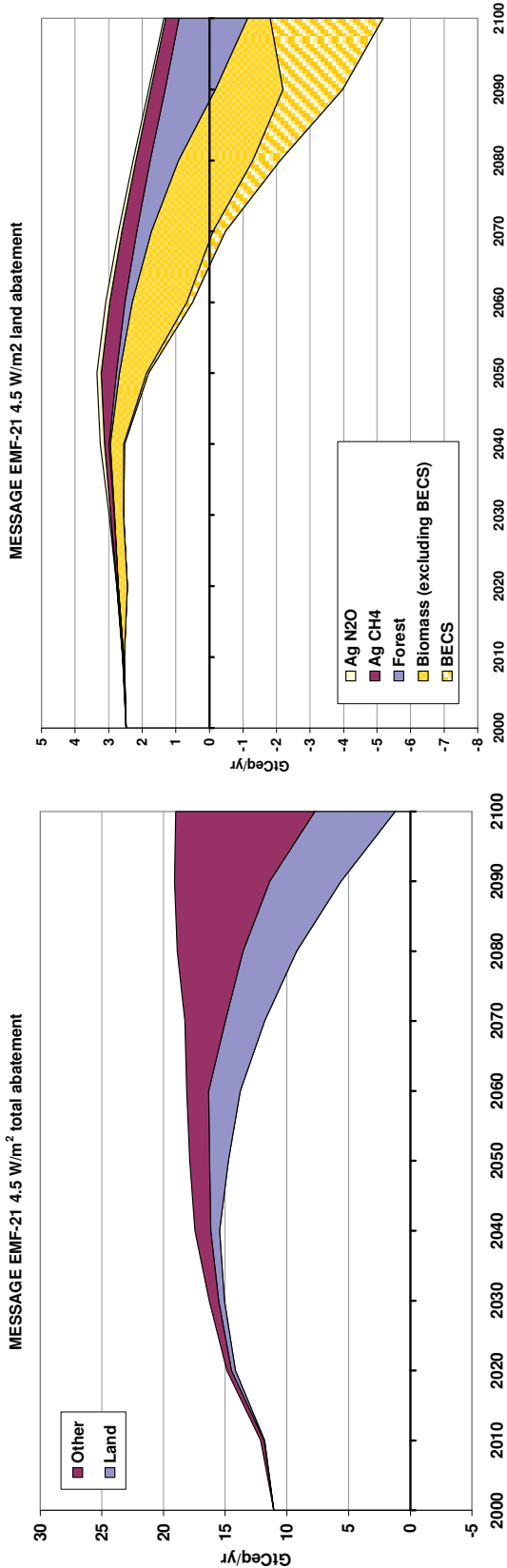


Table 2: Global land-based mitigation's share of total emissions reductions for various stabilization scenarios by radiative forcing target in 2100

4.5 W/m2																							
IMAGE-EMF21*				MESSAGE-EMF21**				GRAPE-EMF21				MESSAGE-A2r			GTEM-EMF21								
2000-2030		2000-2050		2000-2100		2000-2030		2000-2050		2000-2100		2000-2030		2000-2050		2000-2100		2000-2030		2000-2050		2000-2100	
Forest	Mitigation source			CO2			17%	9%	5%	0%	2%	8%	25%	55%	15%	1%	4%	20%	11%				
	CO2			6%	5%	4%	7%	9%	5%	0%	2%	-1%	0%	2%	6%	4%	2%	2%					
	CH4			1%	1%	1%	3%	4%	1%	13%	3%	4%	3%	1%	3%	2%	5%	4%					
	N2O			na	na	na	25%	23%	19%	12%	4%	19%	6%	5%	7%	nm	nm						
Biomass	Fuel substitution			na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na				
	Energy with CCS (BECS)			na	na	na	0%	1%	10%	nm	nm	nm	0%	1%	7%	nm	nm						
	Total			2%	4%	5%	26%	24%	29%	12%	4%	19%	6%	6%	14%	nm	nm						
	Share of total abatement (all GHGs)			26%	19%	15%	37%	40%	44%	59%	72%	40%	16%	14%	21%	29%	18%						
Land totals	Share of total abatement (all GHGs)			-7.4	-24.5	-94.4	-6.0	-23.2	-222.8	-2.5	-24.9	-208.6	-9.4	-31.2	-307.5	-18.0	-43.9						
	Share (all GHGs)			74%	81%	85%	63%	60%	56%	41%	28%	60%	84%	86%	79%	71%	82%						

450 CO2eq, ppmv (~2.9 W/m²)																	
IMAGE2.3				IMAGE2.3				IMAGE2.3				MESSAGE-EMF21					
2000-2030		2000-2050		2000-2100		2000-2030		2000-2050		2000-2100		2000-2030		2000-2050		2000-2100	
Forest	Mitigation source			CO2			16%	8%	5%	11%	6%	4%	7%	4%	3%	5%	11%
	CO2			7%	6%	4%	6%	5%	3%	5%	4%	3%	12%	8%	8%	1%	
	CH4			4%	3%	2%	3%	2%	1%	3%	2%	1%	5%	3%	3%	1%	
	N2O			na	na	na	na	na	na	na	na	na	12%	13%	7%		
Biomass	Fuel substitution			na	na	na	na	na	na	na	na	na	na	na	na	na	na
	Energy with CCS (BECS)			na	na	na	na	na	na	na	na	na	1%	2%	12%	2%	
	Total			4%	11%	18%	7%	13%	14%	9%	14%	13%	12%	15%	19%		
	Share of total abatement (all GHGs)			31%	29%	29%	28%	26%	23%	23%	24%	22%	32%	31%	35%		
Land totals	Share of total abatement (all GHGs)			-7.6	-33.0	-200.8	-10.1	-46.4	-217.8	-14.6	-62.9	-254.6	-17.5	-54.8	-343.4		
	Share (all GHGs)			60%	71%	71%	72%	74%	77%	77%	76%	78%	68%	69%	65%		

Notes:

* The IMAGE EMF-21 forest results represent carbon gains from the planting of additional forest plantations. They do not include deforestation carbon losses induced by bioenergy crop expansion. These carbon losses are accounted for under forestry for the scenarios from the other models. See section 3.5 for the net changes in the forest carbon stock associated with the IMAGE EMF-21 scenario.

*** Results based on the 4.5 W/m² MESSAGE scenario from the sensitivity analysis of Rao and Riahi (2006) that used the DIMA model.

The GTEM scenarios ran through 2050 and the GTEM land mitigation totals include fossil fuel CO₂ emissions reductions in agriculture.

The GRAPE model projected an increase in CH₄ emissions in 2020.

na = data not available

When modeled, biomass mitigation is found to be an extremely important mitigation option, with GRAPE and MESSAGE projecting biomass as the heavily dominant land abatement strategy over the century, leading to 4 GtCeq abatement in 2100 from both scenarios, for cumulative abatement of 100 and 147 GtCeq by 2100 respectively. Alternatively, the IMAGE EMF-21 results project 0.7 GtCeq in 2100 for cumulative abatement of 31 GtCeq by 2100. The more recent IMAGE results from version 2.3 of the model (van Vuuren *et al.*, 2007) project substantially more biomass abatement for achieving a similar concentration stabilization target of 650 CO₂eq ppm (2.8 GtCeq abatement in 2100, for cumulative abatement of 129 GtCeq by 2100). See Section 3.4 below for additional discussion of the biomass results.

In general, the stabilization scenarios support the perspective that agriculture (excluding biomass) and forestry mitigation options are part of a cost effective near-term abatement strategy. These options make positive abatement contributions of 2 to 15 GtCeq (10 to 44 per cent) of cumulative abatement from 2000-2030 (Table 2). Both agriculture and forestry mitigation contribute throughout the century; however, some scenarios project that forest sequestration will have its largest relative mitigation role in the initial decades, while others suggest that the role of forest sequestration will peak in the middle of the century and continue to contribute a substantial share through 2100. Meanwhile, the overall mitigation share of agricultural abatement of rice and livestock methane (enteric and manure) and soil nitrous oxide is projected to be modest throughout the time horizon, with some suggestion of increased relative importance in early decades.

While land-based mitigation strategies can make a substantial contribution to the cost effective stabilization portfolio, all the

scenarios illustrate the simple fact that, for long-term stabilization, fossil fuel emissions must be addressed. This point is reinforced further by recalling that biomass mitigation—liquid and solid—is substituting for fossil fuels.

3.2 A brief note on baselines

While a detailed baseline comparison is not within the scope of this analysis, it is important to note that there are clear base year and baseline emissions differences across studies, both in total and from the land activities—agriculture and forestry. Recall that the upper boundary of the coloured areas in Figures 2 – 5 represents the baseline emissions. Some of the studies suggest that baseline total emissions will increase over the century (GRAPE, Figure 2; MESSAGE, Figure 5; GTEM's trajectory suggests this as well, Figure 4), while others suggest that total carbon equivalent emissions will rise until mid-century and then level-off or decline over the remainder of the century (IMAGE 2.2, Figure 3). Underlying these baseline emissions differences are different population, economic growth, and technological change projections and therefore different emissions generation processes and economic opportunities. In addition, differences in land-use net emissions baselines can also be attributed to differences in the agricultural emission sources considered and differences in the definitions of forests and deforestation assumptions. For instance, agricultural emission sources vary across the scenarios, with livestock methane, rice paddy methane, and crop soil nitrous oxide emissions consistently represented. However, the handling of biomass burning and fossil fuel combustion emissions varies, and only the IMAGE model accounts for agricultural soil carbon fluxes. Also, GTEM considers carbon fluxes from managed forests, while the other scenarios include fluxes from both managed and unmanaged forests, and GTEM assumes less early and cumulative deforestation over time and more

deforestation in later years than the other scenarios.

There is some agreement across models that baseline *land* emissions will rise early in the century and then decline. The general pattern is consistent with storylines of increasing and then decreasing deforestation pressure as population growth diminishes, agricultural productivity improves, and demands for pasture land decline. However, the chronological timing of the apex varies across the models, as does the maximum emissions level over the century (e.g., IMAGE results peak at over 4 GtCeq in 2020, while GRAPE results peak at just less than 3 GtCeq in 2040).

One way to evaluate the mitigation effects of baselines is for a single model to consider alternative baselines in achieving a given stabilization target. The 4.5 W/m² stabilization scenarios from Rao and Riahi (2006) and Riahi *et al.* (2007) provide such an opportunity. Rao and Riahi use a SRES B2 reference (Figure 5) and Riahi *et al.* use, among other things, a revised SRES A2 reference (see Grubler *et al.*, 2007) (Figure 6). Please note that, the scale of the y-axis in the left-hand panel of Figure 6 is different from that in the other figures. With greater population growth, food demand, and greater reliance on coal, more baseline total and land emissions are generated in the revised A2 reference and, therefore, more mitigation is required from all the conventional technologies (land and non-land) characteristic of A2 (Figure 6). Overall, the 4.5 W/m² target is more stringent for the A2 baseline, and therefore more expensive. Almost all of the additional land related mitigation in Figure 6 (relative to Figure 5) is achieved through biomass strategies, primarily with larger-scale early adoption of biomass energy combined with carbon capture and storage.

A comparison of Figures 5 and 6 also illustrates the importance of constraints on

biomass potential as well as baselines in general and their potential influence on projected land outcomes. Biomass GHG mitigation increases with the A2 baseline relative to the B2 baseline. However, biomass is not able to maintain its relative role as annual abatement in the Other sectors grows more quickly than the growth in annual biomass abatement. This result illustrates, in part, the limits—both ecological and economic—to biomass mitigation.

3.3 Alternative stabilization targets

How might land mitigation's role change with tighter stabilization targets? In addition to the 4.5 W/m² scenarios from Rao and Riahi (2006) (Figure 5), we were also able to assemble land results for the 3.0 W/m² in 2100 stabilization scenario in Rao and Riahi (2006) (Figure 7), and for each of the 650, 550, and 450 ppm CO₂-equivalent in 2100 (~4.5, 3.7, and 2.9 W/m²) stabilization scenarios in van Vuuren *et al.* (2007) (Figure 8).⁸ Note that instead of left and right panels, Figure 8 has top and bottom panels, where the total mitigation figures are in the top panels and the corresponding land mitigation projections are in the bottom panels. As expected, the more stringent stabilization targets require greater overall abatement (with greater mitigation expenditures) throughout the century from both the land and non-land using activities, with forestry and biomass providing almost all of the additional land based abatement. For example, land mitigation jumps from 6 to 9 GtCeq in 2100 in the MESSAGE scenarios when the target tightens from 4.5 to 3 W/m² with increases in forest and biomass mitigation of approximately 1 and 2 GtCeq. However, while all of the land strategies contribute increased abatement in the first half of the century, agriculture's *share* of total land abatement increases in the MESSAGE scenarios, primarily from

⁸ Radiative forcing levels in 2100. The scenarios below 4.5 W/m² stabilize after 2100.

Figure 6: Emissions reductions for the MESSAGE model with revised A2 baseline (Riahi *et al.*, 2007). Stabilization with target 4.5 W/m² in 2100 with multigas and sinks mitigation. (Note: the scale of the y-axis in the left-hand panel is different from the other figures.)

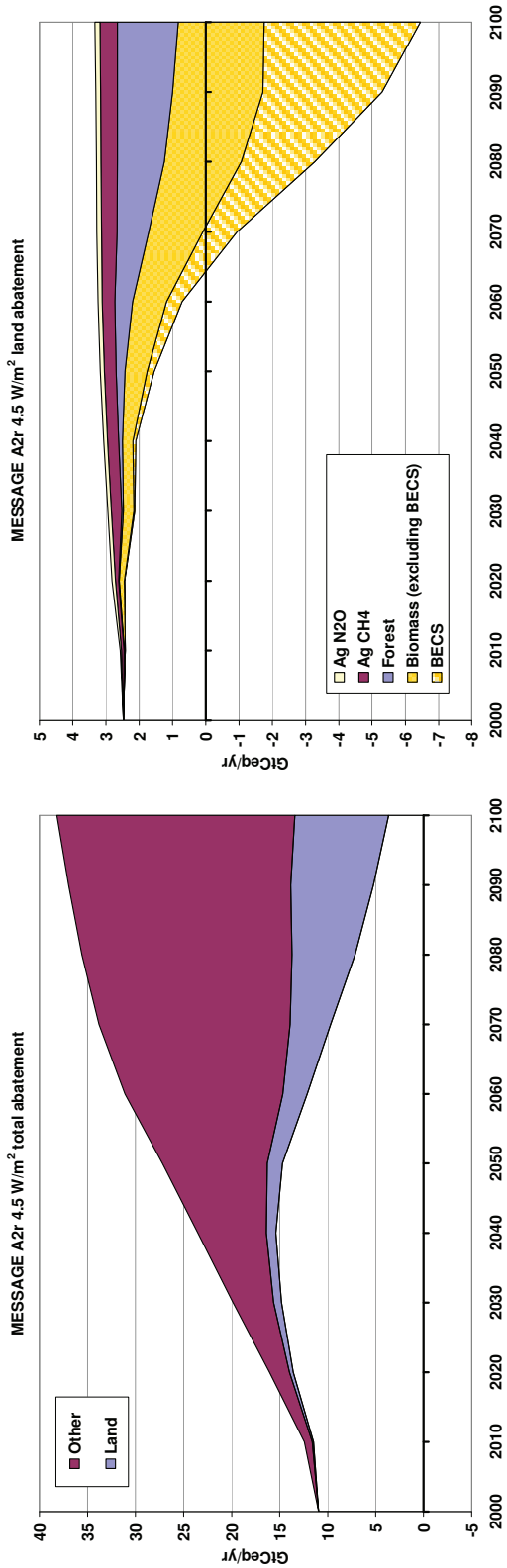


Figure 7: Emissions reductions for the MESSAGE model from EMF-21 (Rao and Riahi, 2006). Stabilization with target 3.0 W/m² in 2100 with multigas and sinks mitigation.

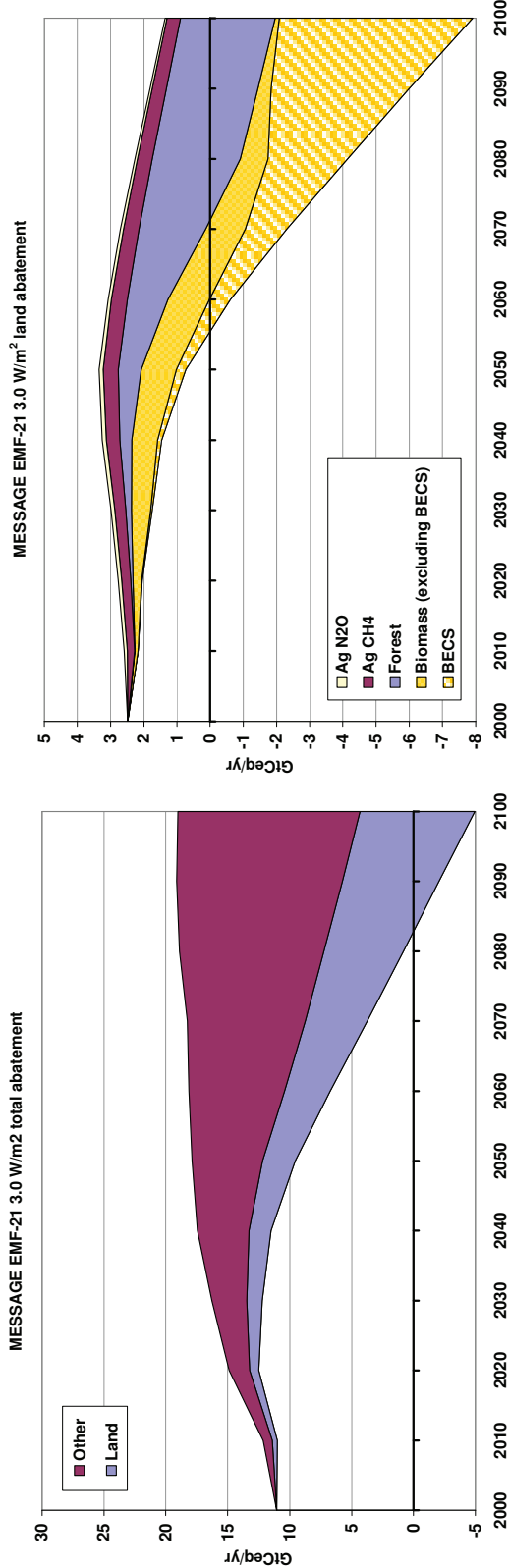
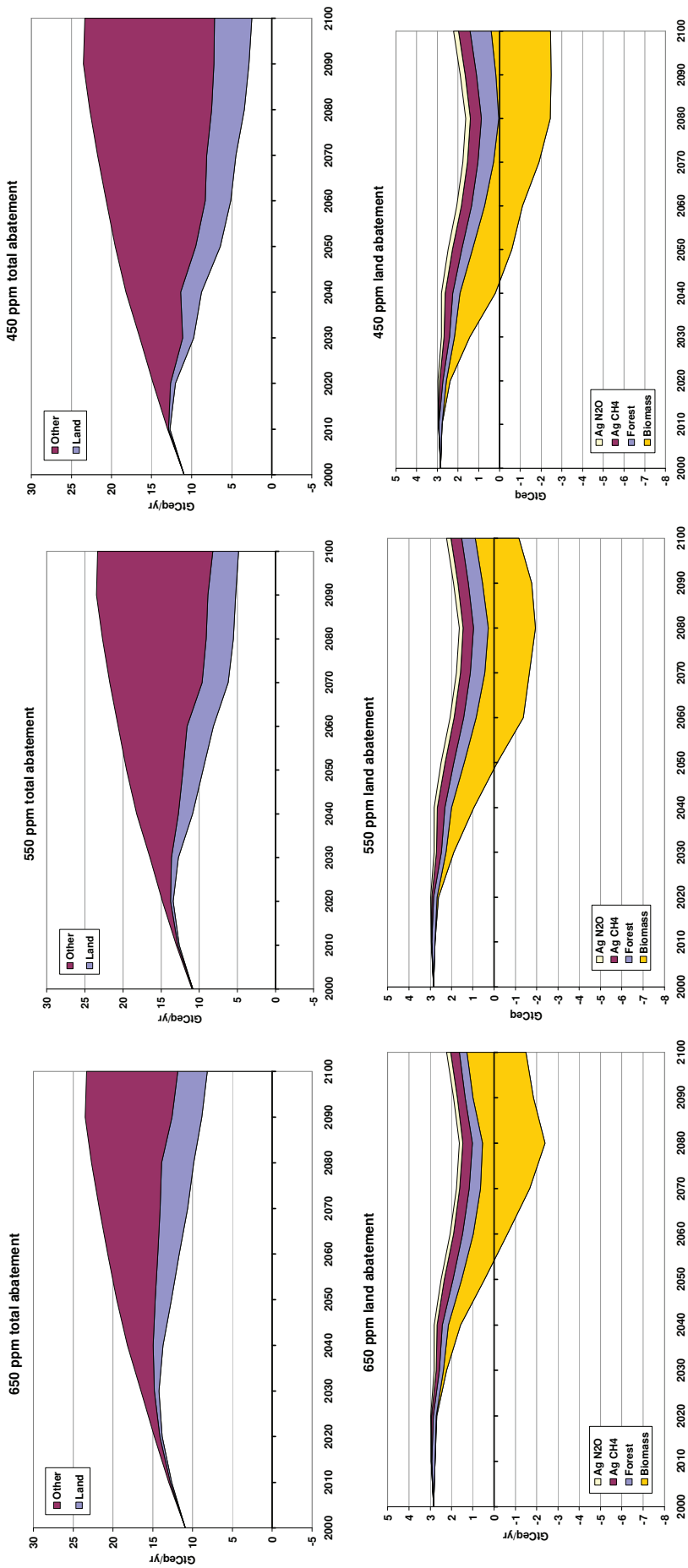


Figure 8: Emissions reductions for the IMAGE 2.3 model from van Vuuren *et al.* (2007). Stabilization with targets 650, 550, and 450 ppm CO₂ equivalent concentrations in 2100 (~ 4.5, 3.7, 2.9 W/m²) with multigas and sinks mitigation.



increased agricultural CH₄ abatement while in the second half of the century, forestry assumes a larger share of overall land mitigation. Conversely, as the target is tightened with the IMAGE 2.3 model, biomass abatement assumes an increasing share of the growing total land abatement pie with essentially no change in agricultural abatement and very little increase in the level of forest abatement. In the IMAGE scenarios, agriculture and forestry mitigation are being adopted at lower cost levels and then exhausted as the target tightens. This result may change when avoided deforestation is incorporated into the model in the future. In terms of overall abatement, the scenarios suggest that land's share of cumulative abatement could fall with tighter stabilization targets in the first half of the century and over the entire century (Table 2). This implies an increasing reliance on non-land sector emissions mitigation as the least expensive mitigation measures are exhausted.

3.4 More about biomass mitigation

The GRAPE, MESSAGE, and IMAGE 2.3 results suggest that biomass could play a substantial role in stabilization, especially as a negative emissions strategy that combines biomass with CO₂ capture and storage (BECS). Across scenarios, absolute emissions reductions from biomass are projected to grow slowly in the first half of the decade and then rapidly in the second half as new biomass processing and mitigation technologies become available (Figure 9). Across the 4.5 W/m² (and 650 CO₂eq ppm) stabilization scenarios presented in this report we find cumulative biomass mitigation of 31 to 204 GtCeq over the century. The low end of the range is from the IMAGE 2.2 model, which considers a more limited set of biomass pathways.⁹ The high end of the range is

from the revised A2 high emissions MESSAGE scenario. Therefore, a more refined range for biomass mitigation potential over the century for 4.5 W/m² (650 ppm CO₂eq) might be 100 to 147 GtCeq. And, the entire range slides up to 151 to 184 GtCeq for the more stringent stabilization target (3.0 W/m² and 450 ppm CO₂eq).

Demands for bioenergy in the GRAPE, MESSAGE, and IMAGE 2.3 models include both solid and liquid feedstocks for electric power and end use sectors (transportation, buildings, industry, and non energy uses). Figure 9b presents the amount of commercial biomass primary energy utilized in the various IMAGE and MESSAGE stabilization scenarios. For example, in 2050, biomass energy could provide 12 to 38 EJ of energy above the baseline for a 2100 stabilization target of 4 to 5 W/m² and 30 to 128 EJ for targets less than 3.25 W/m². The IMAGE EMF21 and version 2.3 results for these target ranges (13 to 38 and 128 EJ) represent 2 to 5 and 20 per cent of total primary energy in 2050 respectively. Over the century and across the scenarios, additional bio-energy associated with mitigation cost-effectively provides 0.5 to 9.5 PJ of energy (as much as 15 per cent of total primary energy). While more disaggregated biomass results were not available from the IMAGE 2.3 scenarios,¹⁰ the cost-effective timing pattern of the biomass alternatives is similar to that of the MESSAGE model (Figure 10). When BECS

abandoned lands; constrains bio-energy substitution opportunities to natural gas and oil, thereby biasing biomass use towards transportation; and, does not include bioenergy from residues. On the other hand, IMAGE 2.3 is able to utilize natural grasslands and savannah as well as abandoned lands (see Hoogwijk et al., 2005); substitute bio-energy generally as a liquid or solid energy feedstock, thereby producing greater electricity use; and, include bio-energy from residues.

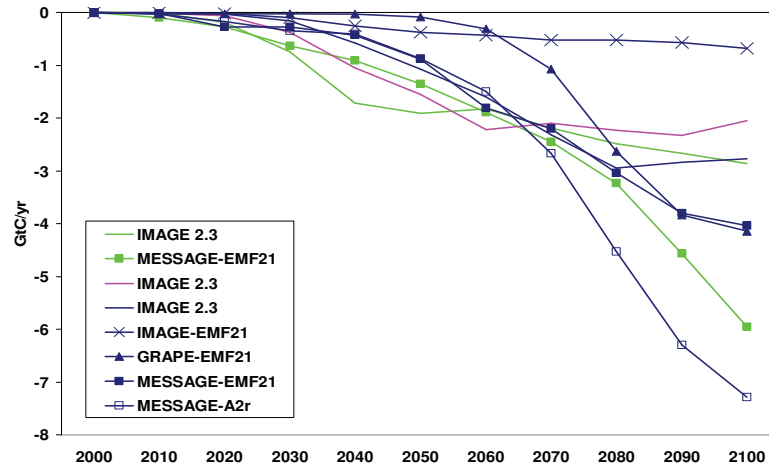
¹⁰ IMAGE 2.3 includes a BECS mitigation option; however, the disaggregated BECS results were not available.

⁹ The IMAGE 2.2 (EMF-21) and IMAGE 2.3 models have very different bio-energy opportunities. IMAGE 2.2 limits land supply for biomass production to

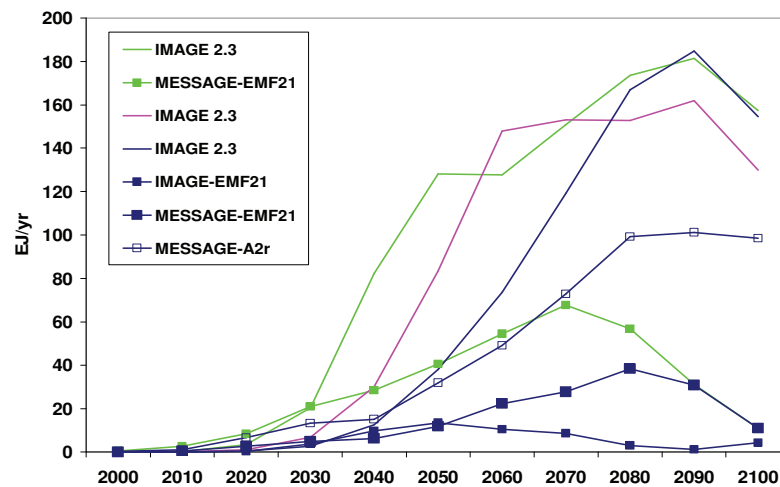
is not available as a mitigation strategy, electric power is projected to dominate

Figure 9: Biomass mitigation associated with various 2100 stabilization targets – (a) Annual GHG emissions mitigated (GtC/yr), (b) Annual biomass primary energy above baseline (EJ/yr)

(a)

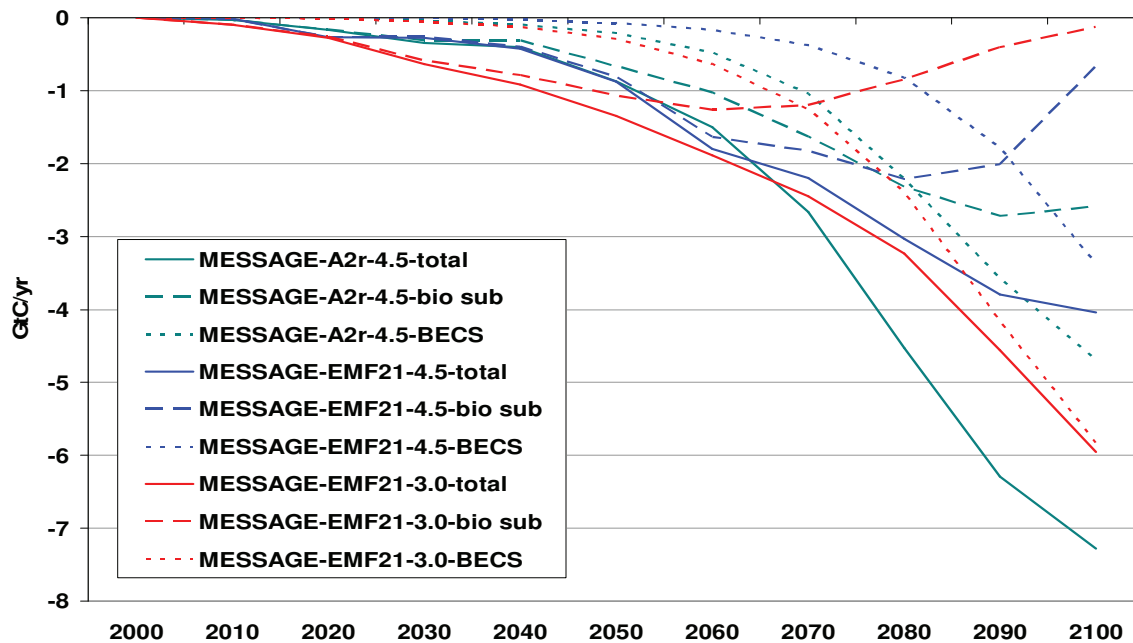


(b)



Notes: The color of the line indicates the 2100 stabilization target modeled: green < 3.25 W/m² (< 420 CO₂ concentration, < 510 CO₂eq concentration), pink 3.25 – 4 (420 – 490, 510 – 590), and dark blue 4 – 5 (490 – 570, 590 – 710). The IMAGE-EMF21 and IMAGE 2.3 forest results are net of deforestation carbon losses induced by bioenergy crop extensification. These carbon losses are accounted for under forestry by the other scenarios. Biomass energy data for GRAPE was not available.

Figure 10: Decomposition of MESSAGE biomass emissions abatement



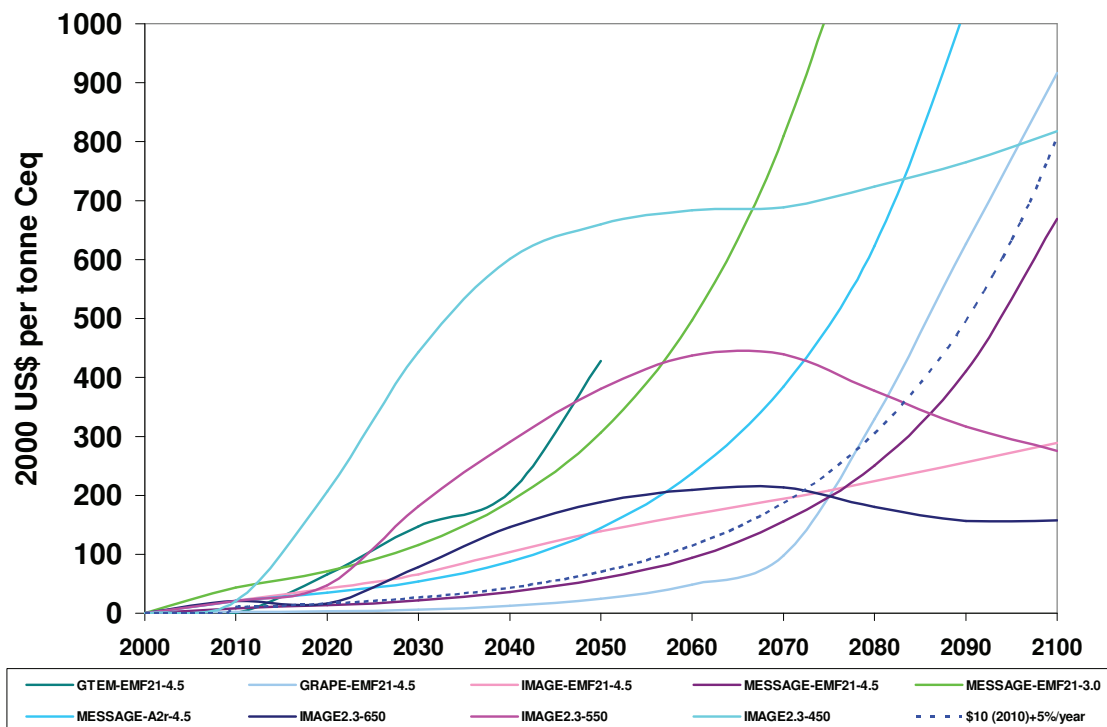
biomass demand in the initial decades and, in general, with less stringent stabilization targets. Later in the decade and for more stringent targets, transportation is projected to dominate biomass use. With BECS available, biomass mitigation shifts to the power sector to take advantage of the net negative emissions from the combined abatement option. The viability of the carbon dioxide capture and storage technology is typically assumed to increase over the century, which explains the rapid growth in BECS and the shift away from non-energy biomass late in the century (Figure 10). The cost-effective shift towards BECS occurs earlier with a tighter stabilization target or greater baseline emissions.

3.5 Comparing stabilization and sectoral results

As noted previously, many of the integrated assessment models currently rely on economic land sectoral models, especially global forestry models, for modeling land sector emissions and mitigation activities and costs. Generally, integrated assessment

and climate economic models either implement mitigation response curves generated by the sectoral model (e.g., Jakeman and Fisher, 2006), iterate with the land sector models (e.g., Sands and Leimbach, 2003; Rao and Riahi, 2006), or calibrate model responses to sectoral modeling results (Hertel *et al.*, 2006). Therefore, it is natural to ask what long term mitigation do the sectoral land economic models independently project? The sectoral models use exogenous carbon price paths to simulate different climate policies and assumptions, where the starting point and rate of increase are determined by factors such as the aggressiveness of the abatement policy, abatement option and cost assumptions, and the social discount rate (Sohngen and Sedjo, 2006). Figure 11 plots the carbon price paths inferred from many of the stabilization scenarios discussed in this report (solid lines). These are the inferred carbon equivalent price trajectories that would have produced mitigation results identical to that produced for stabilization at the specified target. Figure 11 also plots one of the carbon price paths analyzed by two

Figure 11: Carbon price paths (stabilization denoted with solid lines, hypothetical denoted by the dashed line)



recent global forestry sectoral mitigation studies—\$10/tonne C starting in 2010 that rises 5% per year (dashed line; Sohngen and Sedjo, 2006; Sathaye *et al.*, 2006). The stabilization results show that, in general, rising carbon prices are consistent with the cost-effective pathways.¹¹

Table 3 compares the forest mitigation outcomes from stabilization scenarios that have a carbon price trajectory similar to the \$10/tC in 2010 + 5%/yr used by Sohngen and Sedjo and Sathaye *et al.* Two sets of IMAGE results are presented in Table 3. The first represents the carbon gains from the planting of additional forest plantations in the cost-effective portfolio. The second represents the net changes in the forest carbon stock from multiple forces, including

additional plantations, changes in CO₂ fertilization forest growth responses, and biomass induced deforestation. The former is more directly comparable to the other scenarios in Table 3. These IMAGE results and the results from the other models are discussed in the next few paragraphs. The IMAGE net forest carbon stock change results are discussed further below.

Rising carbon prices will provide incentives for additional forest area, longer rotations, and more intensive management to increase carbon storage. Consistent with our previous discussion, Table 3 shows that the vast majority of forest mitigation is projected to occur in the second half of the century. Table 3 also shows that tropical regions in most cases assume a larger share of global forest sequestration mitigation than temperate regions. Sohngen and Sedjo and Sathaye *et al.* project that tropical forest mitigation activities are expected to be heavily dominated by land use change

¹¹ The quickly rising and peaking shape of the IMAGE 2.3 carbon price pathways is a result of allowing concentrations to overshoot (exceed) the stabilization before stabilization. The other scenarios do not allow overshoot.

activities (reduced deforestation and afforestation), while land management activities (increasing inputs, changing rotation length, adjusting age or species composition) are expected to be slightly more than half of the mitigation in temperate regions. The current stabilization scenarios include more limited and aggregated forestry GHG abatement technologies that do not distinguish the detailed responses seen in the sectoral models.

The sectoral models, in particular, Sohngen and Sedjo, suggest substantially more mitigation than the stabilization scenarios in the second half of the century. A number of factors contribute to this deviation from the integrated assessment model results. First and foremost, Sohngen and Sedjo account for expected changes in future timber and carbon prices, which none of the integrated assessment models are currently capable of doing (they instead implicitly assume that current and future prices are the same). Therefore, a low carbon price that is expected to increase rapidly in the future results in a postponement of additional sequestration actions in Sohngen and Sedjo until the price (benefit) of sequestration is greater. Endogenously modeling the future forest biophysical and economic implications in current decisions will be a significant future challenge for integrated assessment models. Conversely, the integrated assessment models may be producing a somewhat more muted forest sequestration response given the following: (i) their explicit consideration of cost competitive mitigation alternatives in other sectors and across regions, and, in some cases, in land use (e.g., biomass); (ii) their more limited set of forest related abatement options, with all integrated assessment models modeling afforestation strategies, but only some considering avoided deforestation, and none modeling forest management options at this point; (iii) sequential land allocation rules employed by some integrated assessment models

(including those in Table 3), that satisfy population food and feed demand growth requirements first, and (iv) climate feedbacks in integrated assessment models that can lead to terrestrial carbon losses relative to the baseline.¹²

The IMAGE net forest carbon stock change results in Table 3 provide a dramatic illustration of the potential implications and importance of counterbalancing effects. Despite the planting of additional forest plantations in the IMAGE scenario, net tropical forest carbon stocks decline relative to the baseline due to deforestation induced by bioenergy crop extensification, as well as reduced CO₂ fertilization effects that affect forest carbon uptake, especially tropical forests, and decrease crop productivity, where the later effect induces greater expansion of food crops onto fallow lands; thereby, displacing stored carbon. Future modeling will want to explore these biophysical and economic interactions and their implications for forest mitigation.

4 Conclusion

This report collected and synthesized land GHG mitigation results from the EMF-21 and recent climate stabilization studies in order to assess the role of land in long-term climate stabilization. We found that land based mitigation—agriculture, forestry, and biomass liquid and solid energy substitutes—are a part of the cost-effective portfolio of mitigation strategies for long-term climate stabilization because they are less expensive than some non-land based mitigation options. Agriculture, forestry, and

¹² Also worthy of note is that the MESSAGE-EMF21 results from Rao and Riahi (2006) limited the potential for additional forest carbon to 50% of that estimated with the DIMA model by Rokityanskiy *et al.* (2007). Rao and Riahi (p. 195) note that this adjustment was made to account for market imperfections and infrastructure barriers. While the level of the adjustment is somewhat arbitrary, the other models (sectoral and integrated assessment) do not make this kind of adjustment.

Table 3: Cumulative forest carbon gained above baseline from long-term global forestry and stabilization scenarios (GtC)

		\$10 (2010) + 5% per year		
		2020	2050	2100
Sathaye et al. (2006)	World	na	24.9	96.5
	Temperate	na	6.9	32.4
	Tropics	na	15.0	66.0
Sohngen and Sedjo (2006) <i>original baseline</i>	World	0.0	6.2	146.6
	Temperate	0.9	2.2	56.7
	Tropics	-0.9	4.0	89.9
Sohngen and Sedjo (2006) <i>accelerated deforestation baseline</i>	World	0.4	4.1	132.9
	Temperate	0.3	3.3	58.0
	Tropics	0.2	0.8	75.0
		Stabilisation at 4.5 W/m² by 2100		
		2020	2050	2100
GRAPE-EMF21	World	-0.2	19.2	79.6
	Temperate	0.0	2.7	12.3
	Tropics	-0.1	16.5	67.3
MESSAGE-EMF21*	World	0.0	0.9	41.6
	Temperate	0.0	0.0	6.4
	Tropics	0.0	0.9	35.2
IMAGE-EMF21 <i>additional sinks uptake only</i>	World	2.4	11.3	31.1
	Temperate	2.1	9.1	24.8
	Tropics	0.3	2.2	6.3
IMAGE-EMF21 <i>change in net forest carbon stock</i>	World	-6.1	-3.7	2.8
	Temperate	3.9	8.7	21.4
	Tropics	-10.0	-12.4	-18.5

Notes:

* Results based on the 4.5 W/m² MESSAGE scenario from the sensitivity analysis of Rao and Riahi (2006) that used the DIMA forestry model.

Tropics: Central America, South America, Sub-Saharan Africa, South Asia, Southeast Asia

Temperate: North America, Western and Central Europe, Former Soviet Union, East Asia, Oceania, Japan

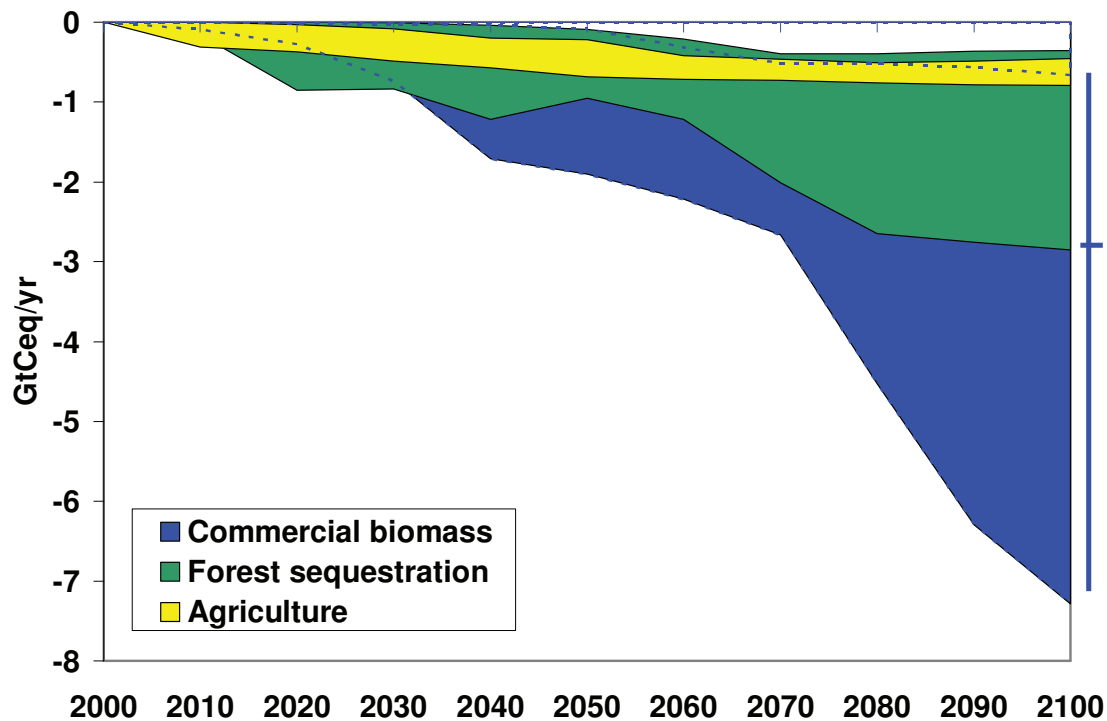
na = data not available

biomass can cost-effectively contribute throughout the century with annual abatement increasing per year. Agriculture and forestry assume larger shares of annual abatement in the near term, while biomass, especially BECS, assumes a significant mitigation role in the second half of the century (Figure 12). Cumulatively, agriculture is projected to account for a smaller, though potentially strategically significant, share of the total abatement required for stabilization relative to forestry and biomass. Biomass, in particular, may have a substantial abatement role and

therefore a large effect on the total mitigation cost of stabilization.

We also evaluated land's mitigation role with alternative baselines and other stabilization targets. Cost-effective land related abatement increases with higher emitting baselines and more stringent stabilization targets. However, despite increased absolute abatement levels, lands share of annual and cumulative total abatement declines while the abatement share of non-land mitigation activities increases.

Figure 12: Annual abatement ranges for commercial biomass, forestry, and agriculture across the stabilization studies considered



Note: The blue vertical line to the right of the graph indicates the range for commercial biomass abatement in 2100, with the horizontal line demarking the median. The dashed blue lines trace out the boundaries of the commercial biomass range.

Overall, land-based mitigation options offer significant potential and could help reduce the cost of stabilization. However, substantial fossil fuel emissions reductions will still be required for stabilization at the stabilization levels considered here. Land-based biomass could be an important fossil fuel substitution technology, which combined with carbon dioxide capture and storage, would become even more appealing. There are however still significant questions about the implications of large scale commercial biomass and the regulatory acceptability of carbon dioxide capture and storage.

There are substantial uncertainties. There is little agreement about the magnitudes of abatement. Across all the stabilization scenarios considered in this report, land contributed 94 to 343 GtCeq cumulatively across the century (approximately 15 to 40

percent of total abatement), 10 to 37 GtCeq of abatement from agricultural methane sources, 7 to 20 GtCeq from agricultural nitrous oxide sources, 31 to 113 GtCeq from forestry, and 31 to 204 GtCeq from biomass.

Across the six 4.5 W/m^2 2100 radiative forcing stabilization scenarios, land as a whole contributed cumulative abatement of 23 to 44 GtCeq by 2050 (14 to 72% of total abatement) and 94 to 308 GtCeq by 2100 (15 to 44%). The magnitude and timing of the individual types of land related mitigation for 4.5 W/m^2 stabilization vary across scenarios, with agricultural CH_4 emissions reductions of 0.1 to 9.9 and 9.6 to 32.8 GtCeq by 2050 and 2100 respectively, agricultural N_2O emissions reductions of 1.6 to 10.8 and 70 to 19.9 GtCeq, additional forest sequestration above the baseline of 0.9 to 27.1 and 31.2 to 79.6 GtC, and

biomass emissions offsets and sequestration of 1.3 to 14.2 and 30.9 to 204.3 GtC.

Furthermore, to date, most models have only entertained exogenous or model linking approaches to incorporate land-based mitigation costs. Endogenizing land-based mitigation within a model requires that land input use and competition be explicitly modeled (discussed more below). Individually, forestry, agriculture, and biomass present unique challenges for endogenizing the cost of land mitigation. While forestry mitigation strategies are not novel, modeling forest investment behavior calls for dynamic optimization modeling capable of considering future markets (vs. recursive modeling). Econometric modeling of dynamic land allocation and land management decisions (e.g., Lubowski *et al.*, 2006; Plantinga *et al.*, 1999; Stavins, 1999) provides useful information for calibrating dynamic optimization responses of forward-looking agents, and could also provide an intermediate approach that could be more immediately applied in other dynamic programming frameworks. For agriculture, modeling of the detailed mitigation actions and technologies represented in agricultural abatement schedules requires more precise modeling of agricultural emissions sources and drivers; and, use of techniques for endogenizing costs like those employed for modeling non-CO₂ GHG mitigation for the energy and industry sectors (Hyman *et al.*, 2003) and more refined techniques that allow for input substitution away from emissions intensive inputs (Hertel *et al.*, in press-a). Finally, biomass production is a relatively new economic sector that lacks historical data, which complicates model calibration.

Refinement of the estimates of biomass abatement potential is a priority model development agenda item. Research is needed to improve the characterization of biomass' potential, including the opportunity costs of land and utilization

alternatives, processing constraints, geologic formation characterization, fertilizer use implications, and ecosystem externalities. In particular, present studies are relatively poor in representing land competition with food supply and timber production, which has a significant influence on the economic potential of bioenergy crops.

Long-run land climate modeling is rapidly evolving and many of these modeling challenges are being addressed by on-going model development. Recent developments in data and modeling techniques should be helpful (Hertel *et al.*, in press-b; Bouwman *et al.*, 2006). A central development initiative is the improvement in the dynamic modeling of regional and sub-regional land-use and land-use competition (e.g., Hertel *et al.*, in press-a). The total cost of any land-based mitigation strategy should include the opportunity costs of land, which are dynamic and regionally unique functions of changing regional bio-physical and economic circumstances. An essential part of improved land competition modeling is endogenous modeling of forest biophysical and economic dynamics. Better modeling of competition between land-uses will improve leakage estimates and help identify comparative advantages in land-related mitigation and production.

Other important issues include long-run interactions between mitigation and potential climate change impacts (e.g., fires, pests, weeds, atmospheric CO₂ fertilization, precipitation and water availability), evaluation of key baseline input sensitivities and narrowing the range of acceptable values (e.g., crop productivity in Sands and Leimbach, 2003; land supply and harvesting costs in Sohngen and Mendelsohn, 2006), and improvements in mitigation cost estimates for agriculture to address uncertainties due to the novel and detailed mitigation technologies represented and land heterogeneity, which imply data limitations and uncertainty about adoption and marginal

responses. Uncertainties about the full cost of forest conversion introduce uncertainty into the opportunity cost of land. Recent econometric work will help bound this uncertainty (e.g., Lubowski *et al.*, 2006). Furthermore, with more sophisticated land modeling, we will be better able to evaluate alternative policy instrument designs that affect land allocation within and across regions.

To facilitate the development of land modeling, the EMF-22 study (“Climate Policy Scenarios for Stabilization and in Transition”) has created a land modeling subgroup of international global modeling teams. The subgroup provides a forum for developing and exchanging data, methods, and ideas. The subgroup has met three times over the last year and half to stimulate major modeling innovations that will yield a new generation of more rigorous and structured global land use baseline and mitigation modeling and better characterizations of land’s long-run climate change and mitigation contributions (e.g.,

Hertel *et al.*, in press-b, Bouwman *et al.*, 2006).

In future analyses, we plan to pursue additional details to further refine and evaluate the characterizations of land’s potential in stabilization and more intimately explore differences across models. We will be delving into the regional acreage, energy, and production details of the utilization of land-based mitigation in existing and future stabilization scenarios.

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Appendix

Appendix

Table A: Global emissions abatement results for the stabilization studies covered by this report (GtCeq)

															2000-2030	2000-2050	2000-2100	
Model	Target	Mitigation source		2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100				
GRAPE EMF-21	4.5 W/m2	Forest Agriculture	CO2	0.00	-0.02	0.00	0.24	1.22	0.95	0.99	1.32	1.34	1.27	1.27	1.03	19.17	79.62	
			CH4	0.00	0.00	0.00	0.00	0.01	0.01	0.18	0.19	0.21	0.23	0.26	-0.05	0.11	9.59	
			N2O	0.00	0.02	0.03	0.09	0.19	0.21	0.24	0.27	0.34	0.38	0.44	0.97	4.35	19.87	
		Biomass	Fuel substitution	0.00	0.02	0.02	0.02	0.03	0.08	0.31	1.07	2.63	3.83	4.14	0.50	1.31	99.50	
			Energy with CCS (BECS)	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	
		Land total	Total	0.00	0.02	0.02	0.02	0.03	0.08	0.31	1.07	2.63	3.83	4.14	0.50	1.31	99.50	
			All GHGs	0.00	0.02	0.05	0.34	1.45	1.26	1.72	2.86	4.52	5.71	6.10	2.45	24.94	208.58	
			Non-land	All GHGs	0.00	0.01	0.04	0.23	0.41	0.54	2.45	4.79	7.26	9.53	12.80	1.70	9.70	317.97
			Total	All GHGs	0.00	0.03	0.09	0.58	1.86	1.80	4.17	7.65	11.78	15.24	18.90	4.15	34.63	526.55
IMAGE 2.2 EMF-21	4.5 W/m2	Forest Agriculture	CO2	0.00	0.16	0.19	0.26	0.33	0.39	0.40	0.40	0.40	0.40	0.40	4.78	11.38	31.16	
			CH4	0.00	0.01	0.09	0.14	0.22	0.31	0.33	0.36	0.40	0.42	0.38	1.63	6.04	24.59	
			N2O	0.00	0.01	0.01	0.04	0.06	0.09	0.11	0.11	0.14	0.14	0.11	0.37	1.62	7.68	
		Biomass	Fuel substitution	na	na	na	na	na	na	na	na	na	na	na	na	na	na	
			Energy with CCS (BECS)	na	na	na	na	na	na	na	na	na	na	na	na	na	na	
		Land total	Total	0.00	0.00	0.01	0.10	0.25	0.37	0.42	0.52	0.52	0.56	0.67	0.62	5.50	30.94	
			All GHGs	0.00	0.17	0.30	0.54	0.86	1.17	1.26	1.38	1.46	1.52	1.56	7.40	24.54	94.38	
			Non-land	All GHGs	-0.02	-0.50	1.28	2.63	4.22	6.34	8.28	9.23	9.34	9.40	9.07	20.77	107.86	547.53
			Total	All GHGs	-0.03	-0.33	1.58	3.17	5.08	7.51	9.54	10.62	10.80	10.92	10.64	28.17	132.40	641.91
GTEM EMF-21	4.5 W/m2	Forest Agriculture	CO2	0.00	0.00	0.85	0.83	0.72	0.60	nm	nm	nm	nm	nm	12.69	27.05	na	
			CO2	0.00	0.00	0.02	0.03	0.03	0.05	nm	nm	nm	nm	nm	0.30	1.02	na	
			CH4	0.00	0.00	0.09	0.14	0.17	0.22	nm	nm	nm	nm	nm	1.56	5.07	na	
			N2O	0.00	0.00	0.18	0.32	0.37	0.42	nm	nm	nm	nm	nm	3.43	10.78	na	
		Biomass	Fuel substitution	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	
			Energy with CCS (BECS)	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	
		Land total	Total	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	nm	
			All GHGs	0.00	0.00	1.14	1.32	1.29	1.28	nm	nm	nm	nm	nm	17.97	43.92	na	
			Non-land	All GHGs	0.00	0.00	2.16	4.58	7.80	11.95	nm	nm	nm	nm	nm	44.48	205.09	na
Total	All GHGs	0.00	0.00	3.30	5.90	9.09	13.23	nm	nm	nm	nm	nm	62.45	249.01	na			
MESSAGE EMF-21	4.5 W/m2	Forest Agriculture	CO2	0.00	0.00	0.00	0.01	0.04	0.09	0.21	0.44	0.84	1.50	2.04	0.08	0.94	41.59	
			CH4	0.00	0.03	0.04	0.11	0.14	0.45	0.46	0.45	0.43	0.42	0.40	1.22	5.50	27.25	
			N2O	0.00	0.01	0.01	0.05	0.12	0.12	0.11	0.09	0.08	0.07	0.06	0.48	2.55	6.95	
		Biomass	Fuel substitution	0.00	0.02	0.27	0.26	0.40	0.81	1.63	1.82	2.21	2.01	0.66	4.15	13.46	97.55	
			Energy with CCS (BECS)	0.00	0.00	0.00	0.01	0.03	0.07	0.17	0.37	0.82	1.78	3.38	0.07	0.77	49.46	
		Land total	Total	0.00	0.02	0.27	0.27	0.43	0.88	1.80	2.20	3.03	3.79	4.04	4.22	14.23	147.01	
			All GHGs	0.00	0.06	0.32	0.44	0.73	1.54	2.58	3.18	4.38	5.78	6.54	6.00	23.23	222.80	
			Non-land	All GHGs	-0.01	0.28	0.38	0.77	1.29	1.60	1.77	3.29	5.33	7.74	11.29	10.34	35.05	280.72
			Total	All GHGs	-0.01	0.33	0.70	1.21	2.02	3.15	4.35	6.47	9.70	13.52	17.83	16.34	58.28	503.52

Note: nm = not modeled, na = not applicable

Table A – continued

Model	Target	Mitigation source		2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100	2000-2030	2000-2050	2000-2100
MESSAGE EMF-21	3.0 W/m ²	Forest Agriculture	CO ₂	0.00	0.01	0.07	0.16	0.35	0.69	1.22	2.01	2.65	2.76	2.86	1.62	9.41	113.44
			CH ₄	0.00	0.22	0.27	0.34	0.41	0.46	0.47	0.46	0.45	0.42	0.40	6.59	14.66	37.08
			N ₂ O	0.00	0.09	0.10	0.11	0.12	0.12	0.11	0.09	0.08	0.07	0.06	2.50	4.92	9.32
		Biomass	Fuel substitution	0.00	0.09	0.26	0.58	0.79	1.06	1.26	1.19	0.84	0.40	0.12	6.43	22.52	65.38
			Energy with CCS (BECS)	0.00	0.00	0.02	0.05	0.12	0.28	0.63	1.25	2.39	4.16	5.83	0.41	3.33	118.22
		Land total	Total	0.00	0.09	0.27	0.63	0.91	1.35	1.89	2.44	3.23	4.56	5.95	6.84	25.85	183.61
			All GHGs	0.00	0.42	0.71	1.25	1.80	2.62	3.69	5.01	6.41	7.81	9.27	17.55	54.85	343.45
			All GHGs	0.00	0.73	1.64	2.82	4.18	5.70	7.71	9.52	11.66	13.37	14.72	37.75	122.13	646.76
			All GHGs	0.00	1.15	2.35	4.07	5.98	8.31	11.40	14.54	18.07	21.17	23.98	55.30	176.98	990.21
		Non-land Total	All GHGs	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
			All GHGs	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MESSAGE A2r	4.5 W/m ²	Forest Agriculture	CO ₂	0.00	0.01	0.02	0.05	0.12	0.26	0.53	0.96	1.41	1.66	1.83	0.54	3.30	59.25
			CH ₄	0.00	0.09	0.10	0.30	0.33	0.35	0.38	0.47	0.49	0.51	0.53	3.34	9.94	32.77
			N ₂ O	0.00	0.03	0.10	0.11	0.12	0.12	0.13	0.14	0.14	0.14	0.15	1.92	4.25	11.11
		Biomass	Fuel substitution	0.00	0.03	0.16	0.31	0.31	0.66	1.02	1.63	2.32	2.71	2.59	3.37	11.32	104.41
			Energy with CCS (BECS)	0.00	0.00	0.01	0.03	0.09	0.21	0.47	1.04	2.21	3.58	4.69	0.27	2.40	99.92
		Land total	Total	0.00	0.03	0.17	0.34	0.40	0.87	1.50	2.67	4.53	6.29	7.28	3.64	13.73	204.33
			All GHGs	0.00	0.15	0.39	0.81	0.96	1.61	2.53	4.23	6.57	8.60	9.79	9.45	31.22	307.48
			All GHGs	0.01	0.80	2.09	4.21	7.11	10.91	16.45	19.89	21.87	23.11	24.76	49.99	196.64	1188.08
			All GHGs	0.01	0.95	2.47	5.02	8.07	12.52	18.97	24.11	28.44	31.72	34.55	59.44	227.86	1495.56
		Non-land Total	All GHGs	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
			All GHGs	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
IMAGE 2.3	650 Ceq ppm (~4.5 W/m ²)	Forest Agriculture	CO ₂	0.00	0.16	0.14	0.18	0.28	0.42	0.50	0.53	0.47	0.36	0.36	3.92	9.71	32.34
			CH ₄	0.00	0.01	0.07	0.16	0.26	0.39	0.42	0.44	0.45	0.37	0.40	1.61	6.94	27.62
			N ₂ O	0.00	0.01	0.05	0.09	0.12	0.15	0.16	0.17	0.17	0.17	0.18	0.98	3.43	11.85
		Biomass	Fuel substitution	na	na	na	na	na	na	na	na	na	na	na	na	na	na
			Energy with CCS (BECS)	na	na	na	na	na	na	na	na	na	na	na	na	na	na
		Land total	Total	0.00	0.00	0.03	0.15	0.57	1.07	1.60	2.31	2.94	2.84	2.77	1.08	12.89	129.01
			All GHGs	0.00	0.18	0.29	0.58	1.23	2.04	2.69	3.45	4.04	3.74	3.71	7.59	32.97	200.82
			All GHGs	0.02	0.18	0.68	1.65	3.24	4.85	6.29	7.65	8.80	10.91	11.45	17.03	81.89	499.86
			All GHGs	0.01	0.37	0.97	2.23	4.47	6.88	8.98	11.09	12.84	14.65	15.16	24.63	114.86	700.68
		Non-land Total	All GHGs	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
			All GHGs	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
IMAGE 2.3	550 Ceq ppm (~3.7 W/m ²)	Forest Agriculture	CO ₂	0.00	0.16	0.15	0.22	0.32	0.48	0.59	0.68	0.69	0.66	0.64	4.18	10.82	42.69
			CH ₄	0.00	0.01	0.09	0.24	0.35	0.42	0.44	0.46	0.48	0.49	0.50	2.20	8.91	32.24
			N ₂ O	0.00	0.01	0.06	0.10	0.14	0.18	0.20	0.20	0.19	0.19	0.19	1.22	4.07	13.77
		Biomass	Fuel substitution	na	na	na	na	na	na	na	na	na	na	na	na	na	na
			Energy with CCS (BECS)	na	na	na	na	na	na	na	na	na	na	na	na	na	na
		Land total	Total	0.00	0.00	0.06	0.37	1.05	1.55	2.21	2.09	2.23	2.32	2.04	2.50	22.59	129.10
			All GHGs	0.00	0.19	0.36	0.93	1.85	2.63	3.44	3.43	3.59	3.67	3.38	10.10	46.38	217.80
			All GHGs	0.09	0.18	1.03	2.80	5.44	7.38	9.06	12.09	13.60	14.60	15.11	26.58	131.94	737.91
			All GHGs	0.09	0.36	1.39	3.73	7.29	10.02	12.50	15.52	17.19	18.27	18.49	36.68	178.32	955.70
		Non-land Total	All GHGs	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
			All GHGs	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
IMAGE 2.3	450 Ceq ppm (~2.9 W/m ²)	Forest Agriculture	CO ₂	0.00	0.16	0.17	0.23	0.34	0.50	0.63	0.75	0.84	0.94	1.02	4.40	11.44	50.59
			CH ₄	0.00	0.01	0.16	0.26	0.37	0.45	0.49	0.51	0.53	0.54	0.55	3.01	10.31	35.94
			N ₂ O	0.00	0.01	0.09	0.13	0.18	0.21	0.23	0.23	0.24	0.24	0.24	1.61	5.13	16.68
		Biomass	Fuel substitution	na	na	na	na	na	na	na	na	na	na	na	na	na	na
			Energy with CCS (BECS)	na	na	na	na	na	na	na	na	na	na	na	na	na	na
		Land total	Total	0.00	0.01	0.19	0.74	1.71	1.91	1.82	2.19	2.48	2.67	2.86	5.64	36.00	151.43
			All GHGs	0.00	0.18	0.60	1.37	2.60	3.07	3.17	3.67	4.08	4.39	4.67	14.65	62.87	254.64
			All GHGs	0.00	0.11	2.17	5.35	6.81	10.03	12.37	13.60	15.20	16.24	16.18	49.51	194.55	899.74
			All GHGs	-0.01	0.29	2.77	6.72	9.41	13.11	15.53	17.27	19.29	20.63	20.85	64.16	257.42	1154.38
		Non-land Total	All GHGs	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
			All GHGs	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: nm = not modeled, na = not applicable