Bio-electricity and land use in the Future Agricultural Resources Model (FARM)

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Abstract Bio-electricity is an important technology for Energy Modeling Forum (EMF-27) mitigation scenarios, especially with the possibility of negative carbon dioxide emissions when combined with carbon dioxide capture and storage (CCS). With a strong economic foundation, and broad coverage of economic activity, computable general equilibrium models have proven useful for analysis of alternative climate change policies. However, embedding energy technologies in a general equilibrium model is a challenge, especially for a negative emissions technology with joint products of electricity and carbon dioxide storage. We provide a careful implementation of bio-electricity with CCS in a general equilibrium context, and apply it to selected EMF-27 mitigation scenarios through 2100. Representing bio-electricity and its land requirements requires consideration of competing land uses, including crops, pasture, and forests. Land requirements for bio-electricity start at 200 kilohectares per terawatt-hour declining to approximately 70 kilohectares per terwatt-hour by year 2100 in scenarios with high bioenergy potential.

Abbreviations

AgMIP	Agricultural Model Inter-comparison and Improvement Project
CCS	Carbon dioxide capture and storage
CES	Constant elasticity of substitution
CGE	Computable general equilibrium

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EMF   Energy Modeling Forum
EV   Equivalent variation
FARM   Future Agricultural Resources Model
FAO   Food and Agriculture Organization of the United Nations
GTAP   Global Trade Analysis Project
IEA   International Energy Agency
kha   Kilohectare
SAM   Social accounting matrix
SSP   Shared Socio-economic Pathway
TWh   Terawatt-hour

1 Introduction

With a strong economic foundation, and broad coverage of economic activity, computable general equilibrium (CGE) models have proven useful for analysis of alternative climate change policies. However, mitigation scenarios specified for the Energy Modeling Forum global model inter-comparison study (EMF-27) present a challenge for economists working with a CGE model. First, the time horizon extends beyond 2050, increasing the speculative nature of productivity assumptions for energy and agriculture. Second, the stringency of mitigation scenarios, even the 550 ppm scenarios, requires an emphasis on substitution of new production technologies instead of the usual substitution across inputs to a production function. Third, the possibility of bio-electricity combined with carbon dioxide capture and storage (CCS) creates a technology with the potential for negative carbon dioxide emissions, but the economics of this technology are unlike any other mitigation technology, with joint products of electricity and net carbon sequestration.

   In this paper, we explore the economics of alternative mitigation technologies using the Future Agricultural Resources Model (FARM), a global CGE model with particular focus on agriculture, forestry and energy sectors. The FARM model is configured for EMF-27 with 15 world regions and a time horizon of 2004 through 2104 in 5-year time steps.[1] Land use can shift among crops, pasture, and forests in response to the demand side factors of population and income growth, the supply side factor of agricultural productivity growth, and policies such as a greenhouse gas cap-and-trade. Bio-electricity using solid biomass provides a link between energy and agricultural systems, affecting markets for energy, agricultural products, and land. In developing FARM, we emphasize a balanced approach to energy, agriculture and land use. FARM model development is driven primarily by requirements of model inter-comparison studies organized by the Stanford Energy Modeling Forum and the Agricultural Model Inter-comparison and Improvement Project (AgMIP).

   We address the following questions:

- How does the availability of bio-electricity and CCS affect net carbon dioxide emissions from electricity generation?
- How does the cost of mitigation, measured as equivalent variation, vary across regions and mitigation scenarios?
- What factors determine the amount of land used to grow biomass for electricity generation?

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[1] Model output is interpolated to 10-year time steps, starting in 2010, for submission to the EMF-27 data base.

Table 1 FARM scenario matrix

	Default	"All Good"	Single technology sensitivities				Conventional vs. Renewable	
Technology dimension								
Energy Intensity	Ref	Low	Ref	Ref	Ref	Ref	Ref	Low
CCS	On	On	Off	On	On	On	On	Off
Nuclear	On	On	On	Off	On	On	On	Off
Wind and Solar	Adv	Adv	Adv	Adv	Cons	Adv	Cons	Adv
Bioenergy potential	High	High	High	High	High	Low	Low	High
Policy Dimension								
Reference	G01	G02				G05	G06	G07
550 ppm CO_2-eq	G17	G18	G19			G22	G23	G24
Fragmented Policy	G28							

The 12 scenarios submitted by the FARM modeling team are a subset of all EMF-27 scenarios. We did not report results for the nuclear and wind/solar sensitivity scenarios

We provide a description of EMF-27 scenarios in Section 2 of this paper, including the specific assumptions used to implement the scenarios in FARM. In Section 3 we describe the economic framework of the FARM model. Selected output on emissions, CO_2 prices, and economic cost across EMF-27 scenarios is provided in Section 4. In Section 5 we describe our implementation of CCS with electricity generation, including bio-electricity. In Section 6 we describe the implications of bioelectricity for land use. Section 7 concludes the paper.

2 Overview of scenarios

We reported results for 12 scenarios to the EMF-27 database: five reference scenarios and the seven policy scenarios. Each policy scenario is paired with a corresponding reference scenario.[2] The top section of Table 1 describes assumptions for each scenario across five groups of technologies. Shaded boxes represent optimistic technology assumptions; scenarios G02 and G18 are labeled "all good" with optimistic assumptions for all five technology groups.

Table 2 provides specifics about technologies in the FARM model. Table 3 describes implementation of EMF-27 policy scenarios that were run using FARM.

3 Economic framework

The FARM model is a dynamic-recursive CGE model used to project behavior of global energy and agricultural systems, and the response of these systems to alternative environmental policies. The model is dynamic in that it has an aggregate capital stock for each world region that is updated each time step through investment and depreciation. The model has no forward-looking behavior, but a representative consumer in each region sets aside a fixed fraction of income for investment in future capital. A large system of nonlinear equations is solved each time period, and each equation is paired with an unknown variable. Market

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[2] Policy scenario G19 is paired with reference scenario G01.

Table 2 FARM technology characteristics

	Optimistic	Pessimistic
Energy Intensity	**Low energy intensity:** Global final energy demand is lower than in the pessimistic scenario by approximately 25 % in 2050 and 40 % in 2100.	**Reference energy intensity:** Roughly reflects historical decline of final energy per unit of GDP, with a global average decline of 1.2 % per year.
CO_2 Capture and Storage (CCS)	**On:** CCS is available at a break-even cost of $50 per tCO_2 for all electricity generating technologies that emit CO_2, including bio-electricity.	**Off:** No implementation of CCS.
Nuclear	**On:** Nuclear energy is fully available.	**Off:** Nuclear is phased out after 2010.
Wind and Solar Power	**Advanced:** Capital cost per kW declines by 2.5 % per year.	**Conservative:** Capital cost per kW declines by 1 % per year.
Bioenergy Potential	**High:** Biomass crop yield increases by 1 % per year.	**Low:** Biomass crop yield is constant over time.

Technology assumptions apply to all world regions

clearing equations are paired with prices of commodities and primary factors of production. Zero-profit (efficiency) conditions are paired with activity levels for each production process. Expenditure must equal revenue for a representative consumer in each world region. In policy scenarios, constraints on CO_2 emissions are paired with an unknown CO_2 price; the emissions constraints may or may not be binding. If not binding, the CO_2 price is held at a minimum level of $1 per metric ton of CO_2.

The FARM base year is 2004, the base year of the GTAP 7 data set distributed by the Global Trade Analysis Project at Purdue University (Hertel 1997). GTAP 7 provides social accounting matrices (SAMs) for 112 world regions and 57 production sectors. We used tools for using GTAP data in the GAMS programming language provided by Rutherford (2010). For the EMF-27 study, we first aggregated GTAP 7 data to 15 world regions and 38 production sectors. The 15 world regions were constructed specifically for EMF-27 reporting: United States, Japan, Western European Union (15 countries), Eastern European Union (12 countries), other OECD countries (as of 1990), Russian Federation, other former Soviet Union and reforming economies, China, India, Indonesia, other Asia, Middle East and North Africa, sub-Saharan Africa, Brazil, and other Latin America.

The 38 production sectors retain all GTAP information related to primary agriculture, food processing, energy transformation, energy-intensive industries, and transportation. Further data processing expands the number of production sectors: the single electricity production sector in GTAP is expanded to nine electricity generating technologies; household transportation is removed from final demand to create a new production sector; and household energy consumption is removed from final demand to create a new energy services sector. All production sectors are represented by a constant-elasticity-of-substitution (CES) nest. Further background on the FARM model can be found in Sands et al. (2013).

All scenarios use the same population projections, the United Nations medium scenario through 2100 (United Nations 2011). Labor productivity parameters in FARM were adjusted to align GDP in all regions to growth rates in scenario 2 of the Shared Socio-economic Pathways (SSP2).[3] Kriegler et al. (2012) provide discussion on the motivation for using SSPs. GDP alignment was done for FARM reference scenario G01, and the calibrated labor

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[3] The SSP data are available for download at https://secure.iiasa.ac.at/web-apps/ene/SspDb

Table 3 FARM policy assumptions

Policy	Description
Reference	No climate policy.
550 ppm CO$_2$-eq	Global CO$_2$ fossil fuel and industry (FF&I) emissions budget of approximately 1300 GtCO$_2$ from 2005 to 2050, and approximately 1850 GtCO$_2$ from 2005 to 2100.
Fragmented Policy	Each world region is placed in one of three groups.
	Group I has a cap of 50 % emissions reductions in 2050 relative to 2005. After 2050, emissions caps are reduced by 2 % per year. Group I consists mainly of OECD countries.
	Group II has a cap less stringent cap than Group I and includes developing countries that are not major energy exporters.
	Group III consists of energy exporting regions that have little incentive to participate in a global climate policy regime. Emissions are unconstrained through 2100.

Emissions rights are not traded between world regions. A common CO$_2$ price is imposed on all regions that have a common emissions budget

productivity parameters were applied to all other FARM reference and mitigation scenarios. With this alignment, GDP-per-capita grows in all world regions with partial convergence across regions over time. The ratio of GDP-per-capita, between the richest and poorest world regions, falls from 72 in year 2004 to 4.3 in 2104.[4]

4 General results

Global CO$_2$ emissions across reference scenarios are clustered into two groups depending on the assumption about energy intensity. Scenario G01 uses reference energy intensity, with global CO$_2$ emissions reaching 64 GtCO$_2$ by 2050 and 74 GtCO$_2$ by 2100. The emissions paths in scenarios G05 and G06 are similar. In contrast, scenario G02 is constructed with low energy intensity: global CO$_2$ emissions peak in 2060 at about 45 GtCO$_2$ and decline to 39 GtCO$_2$ by 2100. The emissions path for scenario G07 is slightly higher with emissions peaking at approximately 47 GtCO$_2$. Therefore, the assumption on energy intensity is the primary determinant of emissions across reference scenarios. All 550 ppm mitigation scenarios share the same time path of global CO$_2$ emissions, but emissions paths vary somewhat for individual regions across mitigation scenarios.

Figure 1 provides the time path of CO$_2$ prices for six 550 ppm mitigation scenarios, which span a wide range of prices. The label for each scenario includes its paired reference scenario in parentheses. The wide range is driven primarily by the availability of CCS and variation in reference scenario emissions. The highest CO$_2$ prices are from scenario G19, with no CCS and high reference emissions. The lowest CO$_2$ prices are from scenario G18, with CCS available and low reference emissions. In scenarios that allow CCS, it is available to electricity generation technologies that use fossil fuels or biomass.

In general, the CO$_2$ price is not a good indicator of policy cost. Equivalent variation (EV) is the preferred cost measure in CGE models, as it is based on the utility function of a representative consumer in each world region. However, for an individual country and an economically efficient mitigation policy such as cap-and-trade, the CO$_2$ price provides a ranking of policy scenarios similar to that of EV.

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[4] Income comparisons in the base year of 2004 are calculated using market exchange rates.
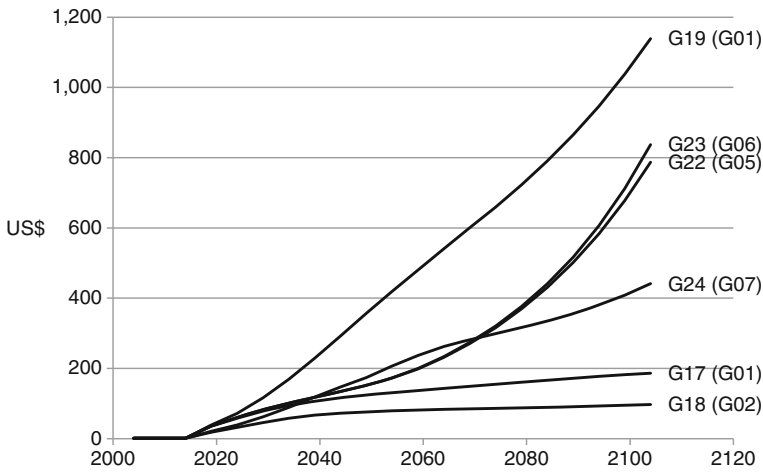
Fig. 1 CO_2 prices across 550 ppm mitigation scenarios (US$ per metric ton) with the corresponding reference scenarios in parentheses

When comparing cost across countries, the same CO_2 price can be associated with wide variation in policy cost. This is seen in Fig. 2, with the cost of a mitigation policy expressed as equivalent variation divided by GDP. In scenario G17, the CO_2 price is the same across all countries but the ratio of EV to GDP is much higher in energy-exporting regions (Group III) than OECD countries (Group I). In developing countries that are not major energy exporters (Group II), the EV to GDP ratio is between that of Group I and Group III.

Policy costs in Fragmented Policy scenario G28 do not diverge as much between world regions, but the reduction in global CO_2 emissions is much less than in mitigation scenario G17. For Group I, the corresponding 2050 CO_2 prices are $126 (G17) and $114 (G28), which is consistent with the decline in welfare cost from G17 to G28. For Group II, the corresponding 2050 CO_2 prices are $126 (G17) and $33 (G28).
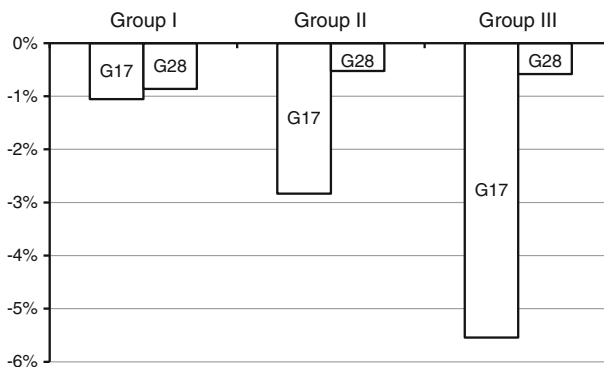
Fig. 2 Equivalent variation expressed as percent of GDP in year 2050, for mitigation scenarios G17 and G28. Group I regions: USA, Japan, European Union (EU-27), other OECD (as of 1990). Group II regions: China, India, Indonesia, other Asia, Brazil, other Latin America, sub-Saharan Africa. Group III regions: Russian Federation, other Reforming Economies, Middle East, North Africa
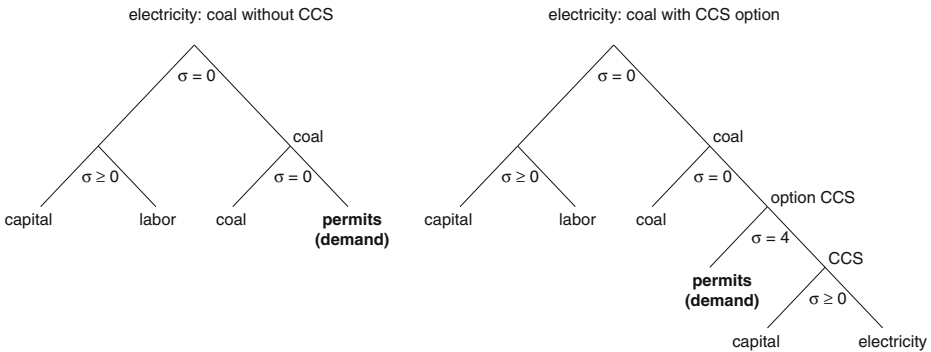
Fig. 3 Nesting structure for electricity generation from coal
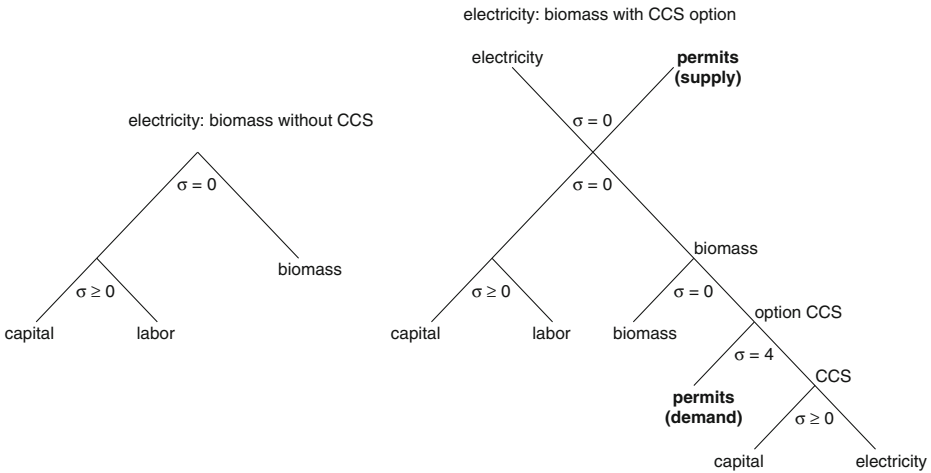
5 Electricity generation and CCS

This section describes implementation of CCS with electricity generation in the FARM model. We employ a CES nesting structure that can be used with or without CCS. Each electricity generating technology can switch CCS on or off as a function of the CO_2 price.

The economics of fossil fuels and CCS are described graphically in Fig. 3. CCS is a stand-alone production technology that can be used by any fossil electricity generation technology. The nest on the left side of Fig. 3 applies to any fossil generating technology without CCS. In this example, coal is the fuel and the ratio of electricity generated to coal energy input is fixed through the zero rate of substitution in the top level of the nest. The ratio of coal to the quantity of CO_2 emission permits is also fixed, with the cost of permits varying directly with the CO_2 price.

The right side of Fig. 2, a generalization of the left side nest, can turn the CCS option on or off depending on the CO_2 price. Instead of purchasing CO_2 permits directly, activities that generate electricity from fossil fuel purchase permits indirectly through an economic switch (option CCS) that buys permits if the CO_2 price is below the cost of CCS, and buys CCS otherwise. If the CO_2 price is equal to the break-even cost of CCS, then purchases are split equally between permits and CCS. The economic switch is a CES function with a high elasticity of substitution, equal to 4 in this case. The benchmark (base year) price of CO_2 permits is $1 per metric ton as demand would be undefined if the permit price were zero. The primary motivation for this nesting structure is that it can be further generalized to apply to bio-electricity with CCS.[5] Fossil-electricity technologies in FARM use the right side nest of Fig. 3, as this nest includes the left side as a special case when CO_2 prices are low.

Figure 4 provides nesting structures for bio-electricity, a technology that combusts biomass to raise steam for electricity generation. However, there are important differences in the bio-electricity nests relative to the coal-electricity nests in Fig. 3. First, CO_2 emissions from biomass combustion in the left nest of Fig. 4 are not taxed: these emissions represent CO_2 that was recently removed from the atmosphere through photosynthesis. Second, the generalized nesting structure on the right side of Fig. 4 was designed to operate as the left nest at low CO_2 prices, but provide an opportunity for negative CO_2 emissions when CO_2 prices are above the break-even price for CCS.

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[5] The idea of using a floor of $1 per t$CO_2$ comes from Hyman et al. (2002) in the context of non-CO_2 greenhouse gas abatement in a CGE model.

Fig. 4 Nesting structure for electricity generation from biomass

The generalized nesting structure in Fig. 4 can simultaneously demand from, and supply permits to, a CO_2 market.[6] Supply of permits is made possible as one of two joint products: electricity and CO_2 permits. Permit supply and demand are calculated as the quantity of CO_2 emitted by combustion of biomass. With low CO_2 prices, supply and demand for permits exactly cancel, providing the same behavior as the simple bio-electricity nest.

At CO_2 prices greater than the break-even price for CCS, this production process switches from buying permits to buying CCS, as this is the less-expensive option. However, this process continues to supply CO_2 permits based on the carbon content of the biomass combusted. However, supply of permits comes at a cost, as electricity used by the CCS process offsets some of the bio-electricity generated. Revenue from permit supply acts as a subsidy for bio-electricity, allowing land for biomass production to expand relative to other land uses.

The mechanics of simultaneous permit supply and demand for bio-electricity are illustrated in Fig. 5 for mitigation scenario G18. In early years, before 2020, the CO_2 price is very low and the option-CCS switch buys permits as if CO_2 emitted by biomass combustion were taxed as a fossil fuel. This is offset by permit supply so that net permit supply is zero at low CO_2 prices. The net supply of permits is the sum of permit demand and (negative) permit supply.

Permit demand in Fig. 5 would go to zero at high CO_2 prices if the CO_2 capture rate was 100 % for bio-electricity. We use a capture rate of 90 % for bio-electricity, so there will always be demand for permits to cover the 10 % of emissions not captured.[7]

Negative emissions of the size in Fig. 5 can result in very large payments to producers of bio-electricity. For example, 2.0 $GtCO_2$ at $100 per tCO_2 is $200 billion paid globally, which ultimately ends up as payments to owners of primary factors of production, especially land. Revenue from sale of permits is distributed as a lump sum to the representative consumer in each region. If payments to bio-electricity exceed revenue from sale of permits, then the representative consumer's income declines.[8]

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[6] A fixed-coefficient constant-elasticity-of-transformation (CET) nest is used to represent joint products of electricity and CO_2 permits in Fig. 4.

[7] We use a CO_2 capture rate of 95 % for fossil-generated electricity.

[8] We do not use permit revenue to offset other tax rates in the economy.
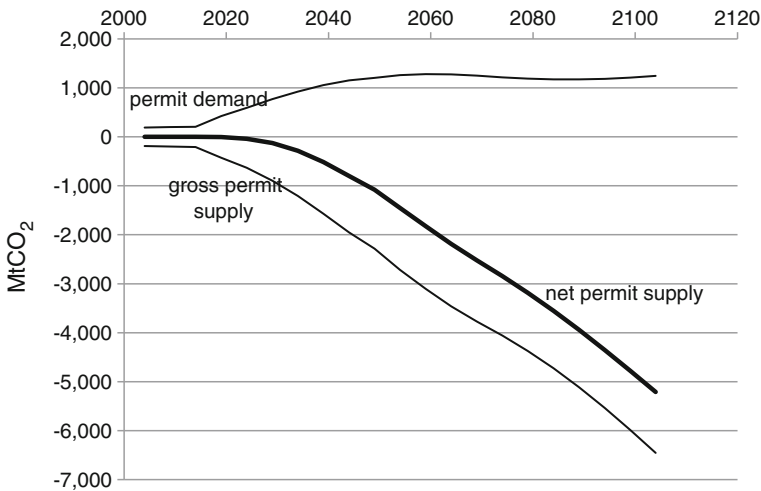
Fig. 5 Negative CO_2 emissions from bio-electricity with CCS in global mitigation scenario G18

CCS with electricity generation, especially with bio-electricity, provides opportunities for electrification of transportation and building end-uses (Williams et al. 2013) as a mitigation strategy. However, industrial processes are complex and the potential for electrification may require industry-specific approaches (e.g. Schumacher and Sands 2007).

6 Bio-electricity and land use

In each world region, land from up to six land classes is allocated to agricultural and forestry production, including five major field crops, three other crop types, biomass, pasture, and managed forests.[9] Based on data in IEA energy balances, all FARM world regions generate some electricity from biomass in 2004, the model base year. We allocate land to bio-electricity in 2004 as if the biofuel were switchgrass. A base-year land requirement of approximately 200 kilohectares (kha) per terawatt-hour (TWh) was calculated using a net energy yield of 60 GJ per hectare for switchgrass (Schmer et al. 2008) and conversion efficiency to electricity of 30 %.

The land requirement for biomass declines over time in all FARM scenarios with high bioenergy potential. Some mitigation scenarios have an optimistic assumption on land requirements (G17, G18, G19, G24), while other mitigation scenarios reflect pessimistic assumptions (G22, G23). In the optimistic scenarios, the land requirement per TWh drops from 200 kha to a range between 67 and 80 kha by year 2100. This is an improvement in land efficiency of approximately 1 % per year.

Several recent papers have suggested that increasing agricultural productivity may be an important source of greenhouse gas mitigation by reducing cropland expansion and thereby avoiding the CO_2 emissions associated with land conversion (Wise et al. 2009; Burney et al. 2010; Choi et al. 2011). Comparing productivity assumptions across studies is complicated by the various ways that productivity is measured or applied in models. Agricultural

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[9] The five field crops are wheat, rice, coarse grains, oil seeds, and sugar. The three crop types are vegetables and fruit, plant-based fibers, and other crops.
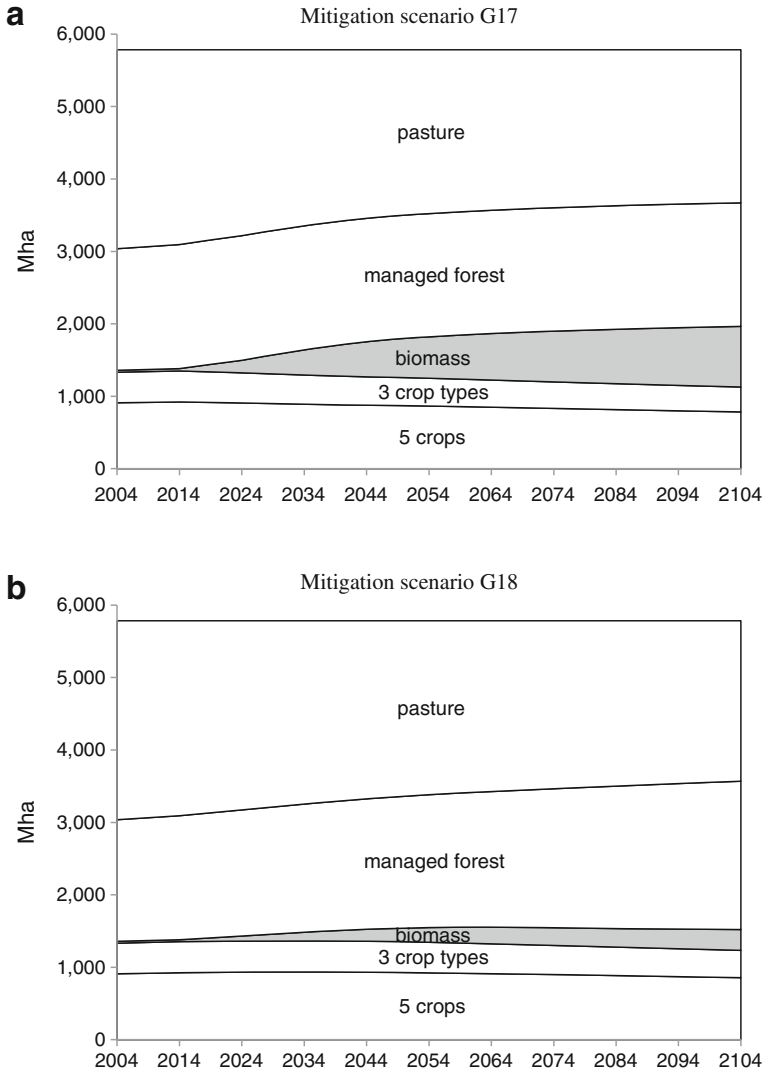
Fig. 6 Global land use in mitigation scenarios (million hectares)

productivity changes in FARM for EMF-27 are applied to the land input and all intermediate inputs (e.g. fertilizer), but not to labor or capital.[10] Agricultural productivity is set to improve at 1.0 % per year for all crops in all regions. This rate of growth is enough to keep global land used for crops relatively constant over time in all reference scenarios.

Global land use for mitigation scenarios G17 and G18 is shown in Fig. 6(a) and (b) respectively. Both mitigation scenarios have high bioenergy potential, but land used for biomass is much greater in scenario G17. In this case, biomass used for bio-electricity

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[10] Labor productivity in each FARM region is adjusted to align GDP growth rates with the SSP2 scenario. Capital productivity changes are zero for all production sectors in all regions, with two exceptions: electricity from wind and electricity from solar.

compensates for pessimistic assumptions on energy intensity, and the corresponding higher level of reference emissions. Another indication is that CO_2 prices in scenario G17 are nearly double those in scenario G18.

Land use data in Fig. 6 are consistent with the GTAP land use data base (Avetisyan et al. 2011). Land use can shift among cropland, pasture, and forest land depending on the rate of return per hectare. Land is allocated within each world region and land class by market clearing, with land rents adjusting until the land markets clear. Cropland is used for eight crop types and biomass. Pasture is used to feed ruminant animals. Forests supply roundwood and pulpwood to industry. For an overview of land allocation in GTAP-based CGE models, see Hertel et al. (2009).

7 Conclusions

Representing global carbon dioxide stabilization scenarios and the technologies that enable reductions in carbon dioxide emissions is a challenging task within a CGE framework, especially for a negative-emissions technology such as bio-electricity with CCS. The benchmark SAM is expressed in values, but we require a method to convert values to physical units for energy (joules), emissions (tCO_2), primary agriculture (tons or calories), and land use (hectares). Further, the benchmark SAM must be extended to represent energy technologies while remaining globally balanced.

The extra effort required to simulate EMF-27 scenarios using a CGE model can be justified by gaining an improved economic perspective on questions such as: What is the welfare cost of a mitigation policy? How do payments for negative emissions, to producers of bio-electricity with CCS, affect land use?

Representing bio-electricity and its land requirements requires consideration of competing land uses, including crops, pasture, and forests. Further progress in simulating land competition may require the development of new data sets with greater spatial resolution of agricultural production and land quality.

FARM presently has limited options for biomass. In particular, we would like to add biomass options for direct combustion as heat, and gasification for transportation.

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