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Competitiveness of terrestrial greenhouse gas offsets: are they a bridge to the future?

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Abstract Activities to reduce net greenhouse gas emissions by biological soil or forest carbon sequestration predominantly utilize currently known, readily implementable technologies. Many other greenhouse gas emission reduction options require future technological development or must wait for turnover of capital stock. Carbon sequestration options in soils and forests, while ready to go now, generally have a finite life, allowing use until other strategies are developed. This paper reports on an investigation of the competitiveness of biological carbon sequestration from a dynamic and multiple strategy viewpoint. Key factors affecting the competitiveness of terrestrial mitigation options are land availability and cost effectiveness relative to other options including CO_2 capture and storage, energy efficiency improvements, fuel switching, and non-CO_2 greenhouse gas emission reductions. The analysis results show that, at lower CO_2 prices and in the near term, soil carbon and other agricultural/forestry options can be important bridges to the future, initially providing a substantial portion of attainable reductions in net greenhouse gas emissions, but with a limited role in later years. At higher CO_2 prices, afforestation and biofuels are more dominant among terrestrial options to offset greenhouse gas emissions. But in the longer run, allowing for capital stock turnover, options to reduce greenhouse gas emissions from the energy system and biofuels provide an increasing share of potential reductions in total US greenhouse gas emissions.

1 Introduction

More than 170 countries have ratified the United Nations Framework Convention on Climate Change (United Nations 1992) that has an objective of stabilizing greenhouse gas (GHG) concentrations in the atmosphere "at a level that would prevent dangerous anthropogenic interference with the climate system."

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Stabilization of atmospheric GHG concentrations will require a pervasive effort to reduce net GHG emissions (which we will hereafter call mitigation) and some mitigation options may be initially expensive. This has caused a search for low-cost options and has introduced the possibility of mitigation through agricultural and forestry (AF) management. In particular, AF options provide an opportunity to increase the amount of carbon stored over time in soils and above-ground biomass.

Most of the emissions reduction burden in the United States is likely to fall outside of AF because over 90% of anthropogenic GHG emissions come from energy transformation, transport, heating/cooling/lighting, and industrial activity. However, mitigation in the energy supply and demand sectors can require substantial capital investment, perhaps not occurring until after facilities using current technologies become obsolete, and will take time to achieve, thus arising over a longer term future. On the other hand, a number of well known and currently implementable AF technologies can reduce net GHG emissions. These involve reductions in net GHG emissions by

- Changing tillage,
- Altering land uses,
- Better managing livestock herds,
- Altering crop mix and fertilization practices, and
- Expanding production of biofuels,

among other practices. See McCarl and Schneider (2000, 2001) for discussion.

While currently available, a number of these possibilities have finite lifetimes, i.e. sequestration in agricultural soils and forests accumulates carbon until the associated ecosystems come into carbon equilibrium (West and Post 2002).

The current availability of AF GHG mitigation strategies, using known technology but with limited duration, coupled with the longer-term nature of non-agricultural GHG strategies, raises several questions:

- Can AF provide a short-term bridge to a longer-term reduced-emissions future?, and
- How significant of a contribution could AF make in the face of non-agricultural mitigation possibilities?

This paper addresses these questions, in part focusing on the intertemporal role of AF sequestration and other possibilities in comparison to non-agricultural options. Related work by McCarl and Schneider (2001), Lee (2002) and Lee et al. (2005) provides an intertemporal comparison of mitigation limited to AF actions but does not simultaneously consider options in the more general economy. In this investigation, we concentrate on soil carbon sequestration, afforestation, forest management, and biofuel offsets simultaneously with GHG mitigation options in the broader economy including fuel switching, energy efficiency improvements, reductions in emissions of non-CO_2 GHGs, and CO_2 capture and storage.

2 A bridge to the future?

An important phrase in the paper title is *bridge to the future*, and refers to important dynamic considerations involved with both the AF and energy sector mitigation alternatives that we are considering.

AF carbon sequestration will only contribute carbon sequestration increments for a finite time period. West and Post (2002) provide evidence that shows agricultural soil options have at most 20-year implications in the case of reduced tillage intensity and 50 years in land use change. Similarly, Birdsey (1996) and Birdsey and Lewis (2003) among others show that carbon sequestration in standing forests exhibits a diminishing rate of uptake that reaches a carbon equilibrium and ceases uptake after a longer (80 years for southern softwood forests) but still finite time period. Furthermore, if the sequestering practices are reversed, much of the carbon can volatize, depending on the new land use activity. Consequently, one might question whether pursuit of agricultural sequestration related strategies is desirable.

However, the story is not only an AF one. In the energy sector, many of the strategies require turnover of capital stock or substantial capital investment for implementation. In particular, suppose we consider introduction of AF feedstocks as inputs to electrical generation. Such an introduction can only occur if there are facilities to use the feedstocks. This depends on the rate at which new power plants are built that can accommodate such feedstocks or the rate of retrofit of existing power plants to accommodate such feedstocks. The need for new plants is a function of obsolescence of existing plants and the growth in demand for electricity, meaning the potential grows over time. Power plant retrofits are expensive and will not occur instantaneously. Market penetration potential is also a function of energy and GHG offset prices. Collectively these forces mean that market penetration potential likely grows into the future relative to today.

Similar stories could be told for many energy-sector GHG mitigation possibilities. Strategies such as fuel switching or CO_2 capture and storage require a substantial degree of research and development that will take time. Thus the concept regarding the AF-energy interface is: Can the limited duration AF sequestration mitigation activities provide a bridge into a future when a much fuller suite of energy sector mitigation alternatives become available? This question has been posed in various places including Marland (2001), McCarl and Schneider (2001), and Lecocq and Chomitz (2001). We investigate this question further below.

3 Methodology for assessment

Analysis of questions of the scope posed above requires a comprehensive analytical approach. Detailed AF production possibilities must be squared up against large-scale energy sector technological possibilities as they emerge over time. This implies the use of a modeling system that simultaneously deals with detailed AF production possibilities as they evolve over time while depicting future energy sector possibilities. The model structure should also reveal the competitive potential and availability over time of the full suite of greenhouse gas mitigation options in the face of incentives to reduce net greenhouse gas emissions.

No single model was available to us, or to our knowledge even exists, that could simulate all of the relevant activities and processes needed to address these questions. Therefore, we integrate two economic models: the GHG version of the Forest and Agricultural Sector Optimizing Model (FASOMGHG – Lee 2002; Adams et al. 1996, 2005), that provides a detailed representation of the US AF sectors along with a depiction of the GHG mitigation possibilities; and the US implementation of the Second Generation Model (SGM – Edmonds et al. 2004; Sands 2004), an economy-wide computable general equilibrium model that embodies energy and other non-AF GHG mitigation possibilities.

Our analysis is limited to the US, as the capabilities provided by FASOMGHG are not yet available for the globe. We concentrate on the activities that affect GHG mitigation: terrestrial C sequestration, biofuel offsets, non-CO_2 GHG emission reduction, energy efficiency and technology substitution, and CO_2 capture and storage (CCS) from electricity generation.

3.1 FASOMGHG overview

Analysis of US AF greenhouse gas mitigation options is done using the Forest and Agricultural Sector Optimizing Model (Adams et al. 2005) updated to the GHG version (FASOMGHG; Lee 2002; Adams et al. 2005). FASOMGHG combines component models of agricultural crop and livestock production, livestock feeding, agricultural processing, log production, forest processing, carbon sequestration, CO_2/non-CO_2 GHG gas emissions, wood product markets, agricultural markets, GHG payments, and land use to systematically capture the rich mix of biophysical and economic processes that determine the technical, economic, and environmental implications of policy changes, climate change, and/or GHG mitigation opportunities.

Operationally, FASOMGHG is a multiperiod, intertemporal, price-endogenous, mathematical programming model depicting land transfers and other resource allocations between and within the AF sectors in the US. The model solution portrays simultaneous market equilibrium over an extended time, typically 70 to 100 years on a decadal basis. Economically, the assumptions behind this market equilibrium are that producers are maximizing profits in choosing a land use while consumers minimize costs in choosing their consumption bundle. In the case of selection of net GHG mitigating activities this assumes that producers would only use mitigating activities if the returns to those activities were higher to some other use of the bundle of land, labor, water and other resources that would be employed. This in turn leads to a comparison of returns to the mitigating strategies including GHG payments with the opportunity cost of the land when producing conventional agricultural activities without necessarily enhancing GHG mitigation. The market simulation reflects higher and higher commodity prices if land is diverted out of agriculture and makes a gap between technical and economic potential for mitigation. The results from FASOMGHG yield a dynamic simulation of prices, production, management, consumption, GHG effects, and other environmental and economic indicators within AF, under the scenario depicted in the model data.

FASOMGHG's key endogenous variables include:

- Commodity and factor prices,
- Production, consumption, export and import quantities,
- Land use allocations between sectors,
- Management strategy adoption,
- Resource use,
- Economic welfare measures,
  - Producer and consumer surplus,
  - Transfer payments,
  - Net welfare effects,
- Environmental impact indicators,
  - GHG emission/absorption of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), and
  - Surface, subsurface, and groundwater pollution for nitrogen, phosphorous, and soil erosion.

The basic conceptual framework of FASOMGHG is presented in Fig. 1. Land, water, labor, national inputs (fertilizer, capital, etc.), and other resources are used by forest, crop (including biofuels feedstock), and livestock production. Some primary commodities move directly to markets while others move to processing making secondary commodities, direct feeding, or are blended into feeds. In turn, then the primary, secondary, biofuel feedstock, and blended feeds go to domestic demand, biofuels production, exports, or livestock feeding. In addition, imports enter the market place. If there is an incentive to reduce GHG emissions through a positive CO_2 price, then reductions in net GHG emissions can be thought of as another product demanded from the agricultural and forestry system.

Forest GHG accounting in FASOMGHG concentrates on carbon sequestered and is based on forest service practices in FORCARB as recently discussed in Smith et al. (2003, 2004). Sequestration accounting encompasses carbon in standing trees, forest soils, forest understories and floors including woody debris, and wood products both in use and in landfills. The sequestration accounting involves both increases and reductions in stocks, with increases entered when land moves into forest uses, trees grow, and products are placed in long-lasting uses or landfills. Reductions arise when timber stands are harvested, land is migrated to agriculture or development, and products decay in their current uses. Product accounting is based on forest service practices developed by Skog et al. (2004).

On the agricultural side, the main features of GHG accounting are those listed in Table 1. Again, there is coverage of emissions, sequestration, and offsets. Agricultural emissions from crop and livestock production arise principally from:

- Fossil fuel use,
- Nitrogen fertilization usage,
- Rice production,
- Enteric fermentation, and
- Manure management,

all of which can be lessened to some degree through management. In FASOMGHG, data describing baseline emissions are based on data from the USDA National Resource Inventory (NRI) and Agricultural Resource Management (ARMS) farm surveys, IPCC good practice guidelines (IPCC 2002) and assumptions in the EPA greenhouse gas inventory (US EPA 2003).

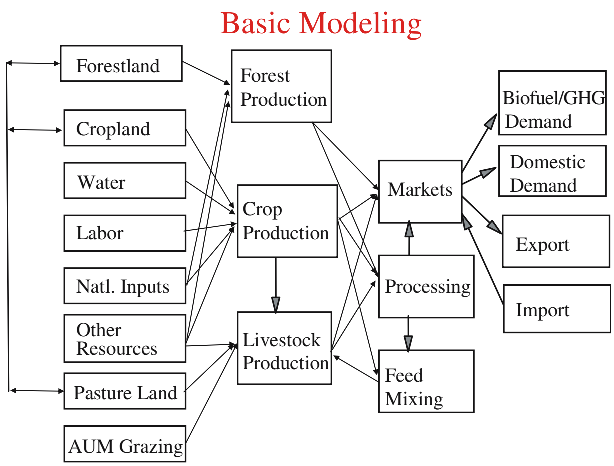


Fig. 1 FASOMGHG model structure.

Table 1 Agricultural mitigation strategies in FASOMGHG

Mitigation strategy	Strategy nature	GHG affected		
		CO_2	CH_4	N_2O
Biofuel production	Offset	X	X	X
Crop mix alteration	Emission, sequestration	X		X
Rice acreage reduction	Emission		X	
Crop fertilizer rate reduction	Emission	X		X
Other crop input (fuel, pesticides etc) alteration	Emission	X		
Crop tillage alteration	Sequestration	X		
Grassland conversion	Sequestration	X		
Irrigated /dry land conversion	Emission	X		X
Livestock management	Emission		X	
Livestock herd size alteration	Emission		X	X
Livestock system change	Emission		X	X
Liquid manure management	Emission		X	X

Agricultural sequestration involves the amount of carbon sequestered in agricultural soils, due principally to choice of tillage and irrigation along with changes to crop mix choice. Sequestration is also considered in terms of grasslands versus crop land or mixed usage, where crop land can be moved to pasture use or vice versa. The sequestration accounting can yield either positive or negative quantities, depending upon the direction of tillage change (conventional, low, or zero tillage) and irrigation choices, along with conversions between crop land and pasture land (grassland). Sequestration accounting will also have a negative term when land moves out of agriculture into forestry or developed use. Although in the case of forestry, the loss in agricultural carbon will typically be more than offset by gains in forest carbon. The sequestration data we use arises from runs of the CENTURY model (Parton 1996).

Commodities that are endogenous to the model can be used as feedstocks for biofuel production processes offsetting fossil fuel usage and their GHG emissions. The forms of biofuel production are:

- Usage of switchgrass, poplar, willow, wood chips (or milling residues) as inputs to electric generating power plants replacing coal usage;
- Usage of corn, switchgrass, poplar, or willow for conversion to ethanol and replacement of carbon emissions from petroleum usage.

In all these cases the GHG offset is the amount involved in burning and producing the replaced fossil fuel less the fossil fuel related emissions cost of producing the biofuel feedstock, plus associated soil carbon and production input effects. The combustion emissions from the biofuels feedstock are not counted as they are assumed to be offset by absorption of GHGs from the atmosphere by photosynthesis during plant growth. The above is a broad overview of FASOMGHG. A comprehensive documentation is available on the internet (Adams et al. 1996, 2005).

3.2 SGM overview

The Second Generation Model (SGM) is a collection of globally-defined regional computable-general-equilibrium (CGE) models with an emphasis on energy transformation, energy consumption, and greenhouse gas emissions. Regional models may be run independently or as a system with international trade in carbon emissions rights. For this analysis we use the regional model for the US.

Economic activity, energy consumption, and greenhouse gas emissions are simulated in each SGM region in five-year time steps from 1990 through 2050. The model is designed specifically to address issues associated with global change: projecting baseline GHG emissions over time; determining the way GHG emissions respond to a carbon or CO_2 price; determining the least-cost way to meet a given emissions constraint; and providing a measure of the overall cost of meeting an emissions target. SGM theory is documented in Fawcett and Sands (2005); model parameters and data are documented in Sands and Fawcett (2005). A general model overview is provided by Edmonds et al. (2004).

One of the most important features of SGM is its treatment of capital: capital stocks are industry-specific and grouped into vintages for each five-year time step. Old vintages of capital are less responsive to changes in prices than are new vintages. For example, new capital has a greater ability to adjust energy consumption per unit of output in response to changing energy or CO_2 prices than old capital. This structure means that the energy system has a lagged response to changes in prices.

Most economic sectors in SGM use a single production function for each capital vintage, but electricity is an important exception. The electricity sector is divided into subsectors that represent alternative processes for generating electricity such as gas-turbine, coal-steam, nuclear, or hydro. The SGM also includes advanced technologies for generating electricity such as natural gas combined cycle (NGCC) and coal integrated gasification combined cycle (IGCC).

A baseline GHG emissions scenario from SGM through year 2050 is presented in Fig. 2. Carbon dioxide emissions for the United States are calibrated to roughly match projections from the US Energy Information Administration (US EIA 2002) through 2025 by adjusting SGM parameters governing labor productivity and energy efficiency. These parameters are extrapolated to 2050 to extend the SGM time frame. The baseline scenario includes three types of non-CO_2 GHGs: methane, nitrous oxide, and the fluorinated GHGs (F-gases). The F-gases consist of hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6). Baseline emissions for the non-CO_2 gases in SGM are calibrated to estimates provided by the US Environmental Protection Agency (Ottinger et al. 2006).

In emissions mitigation scenarios, one can think of four large classes of mitigation options: fuel switching and improvements in energy efficiency; introduction of CO_2 capture and storage with electric generating technologies; reductions in emissions of non-CO_2 greenhouse gases; and terrestrial mitigation options including carbon sequestration and biofuel offsets. Two of these classes, non-CO_2 greenhouse gases and the terrestrial options, are handled in SGM through the introduction of exogenous marginal abatement cost curves. The non-CO_2 cost curves were developed by the US Environmental Protection Agency for a study organized by the Stanford Energy Modeling Forum (EMF-21). The terrestrial cost curves are derived from FASOMGHG. In this study, emissions of greenhouse gases are simulated in a baseline scenario and with several constant-CO_2-price experiments, with a CO_2 price in effect in 2010 and held constant thereafter.

3.2.1 Energy efficiency and fuel switching

Improvements in energy efficiency take place through changes in demand for energy in response to changes in the relative price for energy. Consumers substitute other consumption goods for energy if the price of energy increases relative to other consumption

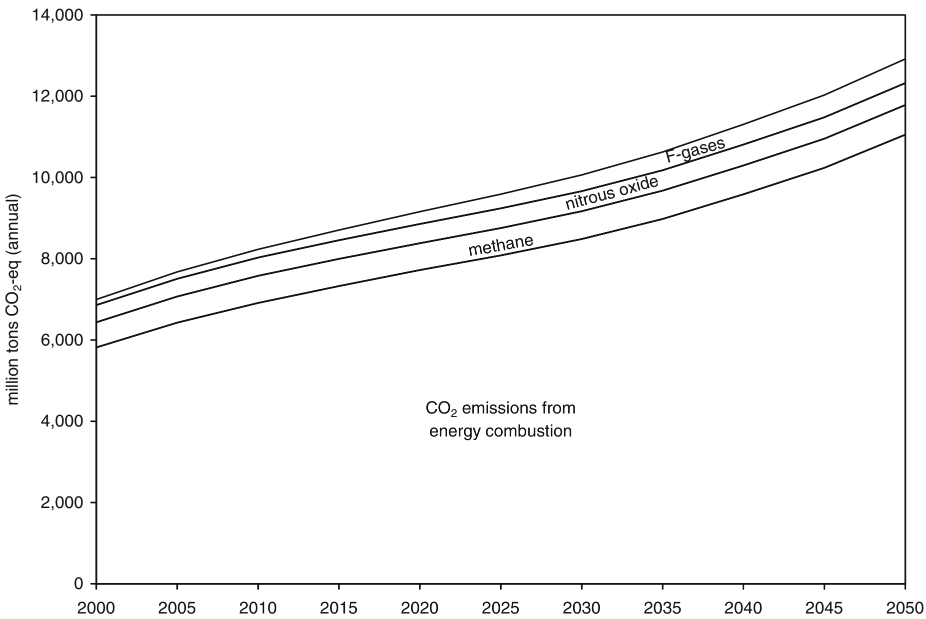


Fig. 2 Baseline GHG emissions scenario for the United States from the Second Generation Model. This scenario covers CO_2 emissions from energy combustion and emissions of three types of non-CO_2 GHGs: methane, nitrous oxide, and the fluorinated GHGs (F-gases). The F-gases consist of hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride. Emissions of non-CO_2 GHGs are weighted at their 100-year global warming potential. All results are expressed as annual emissions in metric tons of CO_2-equivalent, through the year 2050.

goods. Producers substitute other inputs for energy in production. Most SGM production sectors allow a parameterized response, through the elasticity of technical substitution, of input demand with respect to changes in the prices of inputs to production. The electricity sector in SGM is an exception: technical change takes place through shifts among specific electricity generating technologies including advanced technologies such as natural gas combined cycle and coal integrated gasification combined cycle. These generating technologies are represented in SGM using engineering parameters including the purchase price of capital, generating efficiency, fraction of hours in one year that the plant operates, and cost of operation.

3.2.2 CO_2 capture and storage

An extended set of advanced electricity generating technologies allows simulation of CO_2 capture and storage (CCS). Engineering parameters are collected for CO_2 capture technologies, including capture efficiency (percent), purchase cost of additional capital (dollars per kg CO_2 per hour), and energy penalty (kWh per kg CO_2). Estimates of the cost of CO_2 storage are also needed to complete the economic description of CCS technologies. This information allows the following technologies to be represented in SGM: pulverized coal + CCS, NGCC + CCS, and coal IGCC + CCS. Cost estimates for CCS technologies are based on David and Herzog (2000). Sands (2004) describes the operation of CCS technologies in SGM in more detail.

3.2.3 Non-CO_2 greenhouse gases

Options for reducing emissions of non-CO_2-greenhouse gases exist throughout the US economy. These options are represented by marginal abatement cost curves for a specific set of mitigation activities. We use cost curves constructed by the US Environmental Protection Agency for the Stanford Energy Modeling Forum. Although FASOMGHG generates information on options for reducing emissions for non-CO_2 greenhouse gases in AF, primarily methane and nitrous oxide, we use the EMF-21 marginal abatement cost curves for all non-CO_2 greenhouse gases. EMF-21 cost curves and assumptions are documented in DeAngelo et al. (2006), Delhotal et al. (2006), and Ottinger et al. (2006). An application of the EMF-21 cost curves to the Second Generation Model is provided in Fawcett and Sands (2006).

4 Concepts for addressing mitigation potential

When one wishes to assess the importance of a type of mitigation activity, like reliance on AF, or component strategies like soil sequestration, the potential of such activities can be considered with various types of analyses. For simplicity they can be called technical, economic, and competitive appraisals of mitigative potential.

- A technical appraisal is one that looks at a strategy in isolation, generally without consideration of implementation cost or possibly with an attached cost estimate that is independent of the volume of activity pursued. Such an estimate is typically constructed based on physical grounds and asserts something like: if all sequestration opportunities in AF of a particular nature were implemented, then the amount of activity that would occur at the continental scale is a given amount of GHG offsets. Obviously, such an estimate does not consider cost or competition for land from other mitigation options. Lal et al. (1998) present such an estimate in the case of agricultural soil carbon sequestration.
- A single-strategy economic appraisal is one that adds in the concept of implementation cost but also considers the fact that as one expands, the implementation gets placed in less suitable environments facing either higher per-unit costs or lower per-unit levels of net GHG emission reductions. Such analyses typically show an increasing schedule of marginal implementation costs as more and more is implemented. Antle et al. (2002) present such an estimate in the case of soil carbon sequestration. Note that this single-strategy economic potential estimate ignores competition for common land resources and the possible market effects of widespread mitigation activity.
- An appraisal of competitive potential considers multiple strategies simultaneously and examines how particular strategies fare in terms of the total mix of strategies. Such an appraisal typically shows one can achieve more mitigation with a wider mix than when considering a single strategy but also shows that the collective potential at a price across all strategies is usually less than the sum of their potentials when examined individually. One example is the recent EMF-21 study where consideration of non-CO2 effects in conjunction with carbon effects yields a substantially lower cost of reducing emissions to the same target (Fawcett and Sands 2006). A second example is discussed below.

Analysis of soil carbon sequestration based on agricultural tillage by McCarl and Schneider (2001) provides a good example of the three types of mitigation potential and how they differ. Marginal abatement cost curves for the three concepts of mitigation potential are shown in Fig. 3. Note that the technical potential estimate, drawn from Lal et al. (1998), is substantially greater than the single-strategy economic potential at all carbon prices, but that the economic potential approaches the technical potential as the carbon price increases. However, when competition is considered along with increasing carbon prices, other terrestrial mitigation options, especially afforestation and biofuel offsets, compete for the same land and reduce the land on which tillage-based sequestration can be achieved. Also, this reduced cropped area contributes to increasing market prices and causes land to be farmed more intensively. Therefore, tillage-based sequestration gains are much less than the other appraisals would indicate.

This reveals the underlying conceptual grounds for this study. Namely, widening the opportunity set of mitigation options may lower costs, but will also change ones view of the 'most important' mitigation alternatives.

5 Synchronizing the models

One way to represent a carbon policy in an economic model is by imposing an exogenous time path for a carbon or CO_2 price, which translates to an additional charge for each fossil fuel based on the fuel's carbon content. Another representation is to impose a limit on the quantity of CO_2-equivalent emissions each year and allow the economic model to determine the time path of the CO_2 price that just meets the emissions target. Yet another approach is to establish a cumulative emissions target over a range of years, consider only time paths of CO_2 price that increase by a fixed annual rate of interest, and then search for the starting price that just meets the cumulative emissions constraint.

Results from both FASOMGHG and SGM depend not only on the level of CO_2 price in a simulation year, but also on the path of CO_2 prices in preceding simulation years. Therefore, results from FASOMGHG and SGM are best compared when both models are driven by the same time path of CO_2 prices. Here we specify a limited number of time paths for an exogenous CO_2 price that are intended to provide insights on a wide range of possible carbon policies.

We cannot know all the possible time paths of the CO_2 price in advance, but two types of time paths are particularly useful: constant CO_2 prices and CO_2 prices that increase at a fixed rate per year. CO_2 prices that increase at a fixed rate over time, or a Hotelling price path (Hotelling 1931), are useful for representing a carbon policy that has a cumulative emissions target over several years. If banking of emissions rights is allowed during that

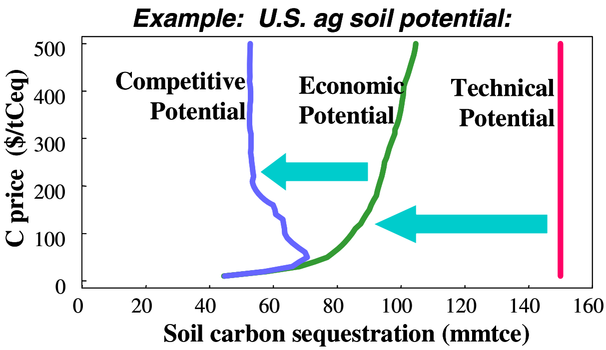
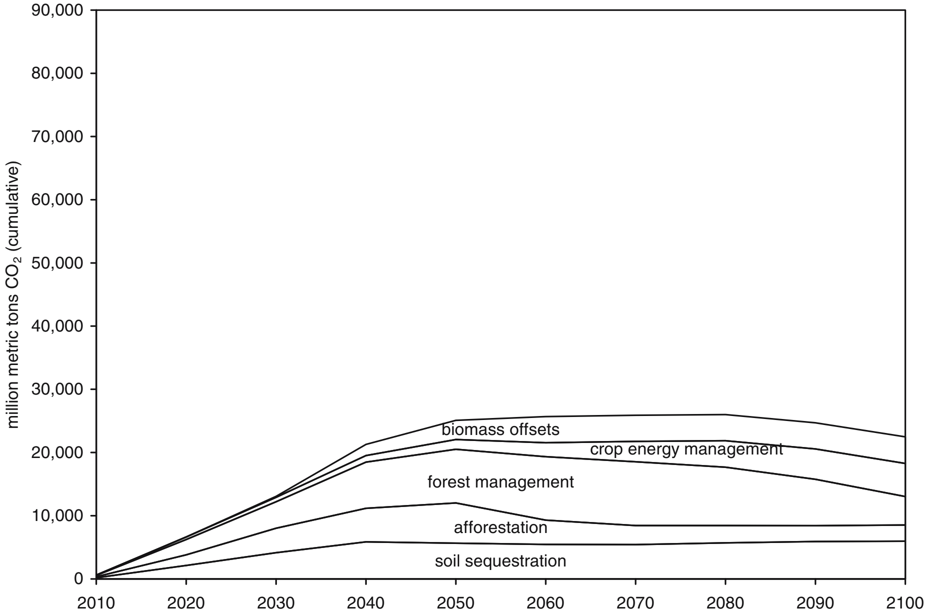
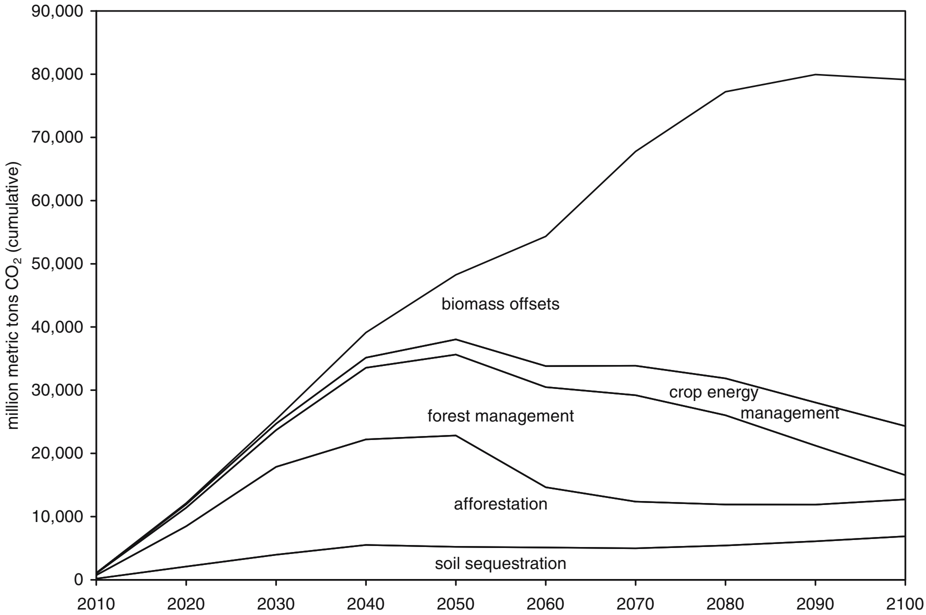


Fig. 3 Estimates of soil carbon sequestration potential under varying assumptions. Soil sequestration, in million metric tons of carbon equivalent, is at an annual rate for a typical year within the first few decades of sequestration.

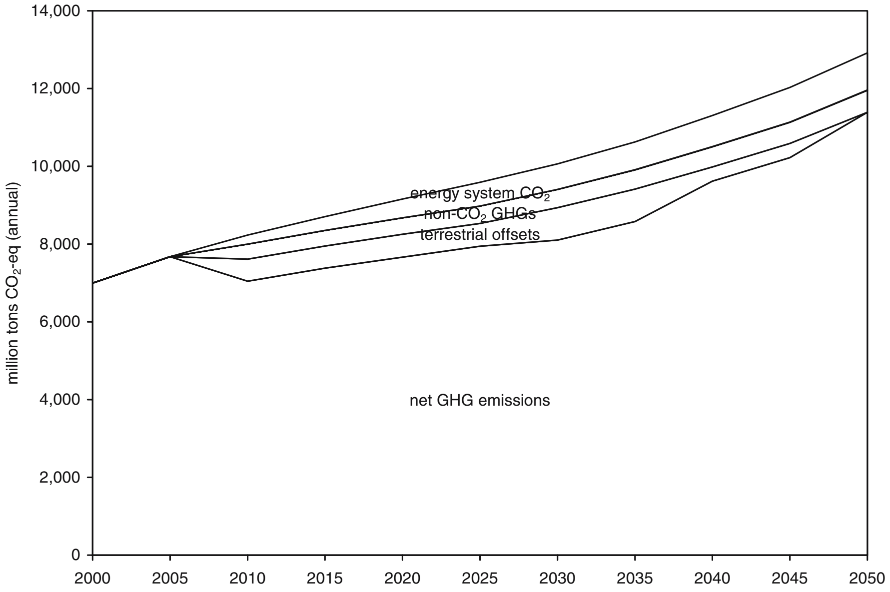


(a) CO_2 price equals \$15 per t-CO_2

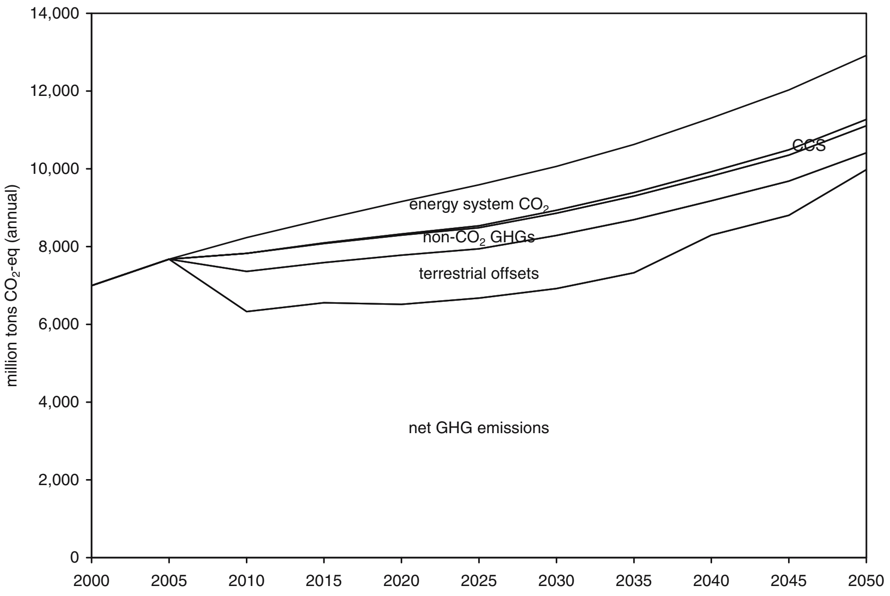


(b) CO_2 price equals \$30 per t-CO_2

Fig. 4 Cumulative emissions reductions or offsets from FASOMGHG. Five types of terrestrial GHG mitigation options were simulated in FASOMGHG at various CO_2 prices: \$5, \$15, \$30, and \$50 per metric ton of CO_2. Results are shown here for the \$15 (a) and \$30 (b) scenarios. CO_2 prices were held constant, in real dollars, during the simulation time frame. All results are presented as cumulative emissions reductions (in the case of crop energy management) or cumulative carbon sequestered, expressed as million metric tons of CO_2.

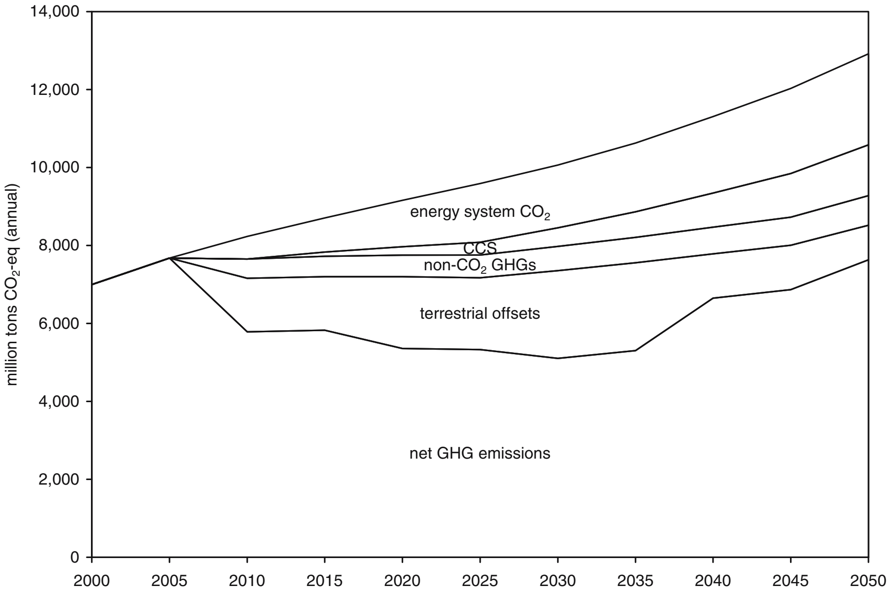


(a) CO_2 price equals $15 per t-$CO_2$



(b) CO_2 price equals $30 per t-$CO_2$

Fig. 5 Components of US GHG emissions reductions relative to US multigas baseline at CO_2 prices of $15 (a), $30 (b), and $50 (c) per metric ton of CO_2. All results are presented as annual increments in tons of CO_2-equivalent. Emissions of non-CO_2 GHGs are weighted at their 100-year global warming potential. CCS represents emissions reduction due to carbon dioxide capture and storage from electricity generation. The terrestrial offsets component is the sum of soil sequestration, afforestation, forest management, and biomass offsets from Fig. 4, converted from cumulative levels to annual increments.



(c) CO_2 price equals \$50 per t-CO_2

Fig. 5 (continued).

time period, the CO_2 price is expected to increase at the rate of interest. Constant CO_2 prices are a special case of Hotelling prices if the interest rate is zero. In the following section we provide results for carbon-constrained scenarios where an exogenous CO_2 price becomes effective in 2010 and remains constant thereafter in real dollars.

6 Results

Four constant-CO_2-price scenarios were run for FASOMGHG and SGM: \$5, \$15, \$30, and \$50 per metric ton of CO_2 equivalent. In Section 6.1, FASOMGHG results are presented as the cumulative amount of CO_2 emissions avoided, in the case of crop energy management, or as the cumulative amount of carbon sequestered for other terrestrial options. Output from FASOMGHG is presented in terms of CO_2 equivalent on a cumulative basis to better handle individual mitigation options that have positive increments in some years but negative increments in others. These results are then summed across terrestrial mitigation options, converted to an annual basis, and combined with other greenhouse gas mitigation options in Section 6.2.

6.1 Results from FASOMGHG

Figure 3 provided a marginal abatement cost curve for soil sequestration, but at an annual rate for a typical year within the first few decades of sequestration. However, it does not show the time profile of soil sequestration. A convenient way to view results from FASOMGHG is to plot the cumulative amount of carbon sequestered over time, for a given price of CO_2. Figure 4 provides plots of cumulative reductions in net greenhouse gas emissions, for prices of \$15 and \$30 per t CO_2-equivalent. In each of the plots, soil sequestration ramps up during the first few decades and then saturates. Carbon sequestered through afforestation also ramps up during the early decades, but then accumulation slows down and can fall as trees are harvested. Cumulative avoided emissions from crop energy management (selecting crop management strategies to reduce energy consumption) increases over time and with the CO_2 price as would be expected.

6.2 Combined results

Results for all greenhouse gas mitigation activities are combined in Fig. 5. Four aggregate GHG mitigation components are shown relative to a US multigas baseline: energy system CO_2, carbon dioxide capture and storage (CCS), non-CO_2 greenhouse gases, and terrestrial offsets. Energy system CO_2 covers mitigation options related to energy efficiency and fuel switching. CCS covers capture and storage from electricity generating plants. The non-CO_2 gases include methane, nitrous oxide, and the fluorinated GHGs (F-gases). Terrestrial offsets include soil sequestration, afforestation, forest management, and biomass offsets. The terrestrial option for crop energy management is excluded to avoid double counting with the energy system component.

The US multigas baseline provides a point of departure for the mitigation options in Fig. 5, shows the relative magnitudes for each mitigation component over time, and shows how the magnitude of each component compares to baseline GHG emissions. The energy system CO_2 component and the non-CO_2 GHG component represent direct annual reductions in baseline emissions. The CCS component represents a direct annual reduction in CO_2 emissions to the atmosphere. The terrestrial offsets component was constructed by first summing over four individual terrestrial options, and then converting to an annual basis. When the terrestrial options are viewed as a whole, annual increments are non-negative through 2050. However, individual terrestrial mitigation options, can have negative increments due to competition for land with biofuels (e.g., afforestation). Net GHG emissions for the United States, as shown in Fig. 5, is the residual when all four aggregate mitigation components are subtracted from the multigas baseline.

Each of the aggregate GHG mitigation components increases along with the CO_2 price. However, the energy system and CCS components are constrained by the rate that capital stocks turn over. At \$30 per t CO_2-equivalent, the CO_2 price is just high enough to provide an incentive for some CO_2 capture and storage to take place with coal integrated gasification combined cycle (IGCC) electricity generating plants. CO_2 capture and storage increases rapidly as the CO_2 price goes above \$30 and as capital stocks of existing generating plants are replaced.

7 Strategic comparison

The focus of this paper is on the terrestrial GHG mitigation options. Figure 4 provided scenarios of individual terrestrial mitigation options over time at two CO_2 prices, with the CO_2 prices held constant over time. Individual terrestrial mitigation options can have positive increments in some years, can saturate (soil sequestration), or can have negative increments (afforestation). The patterns observed in the results are primarily a function of cost, greenhouse gas offset production rate, production of existing commodities and land competition. In particular, at low CO_2 prices one observes a lot of the activity in tillage modification on agricultural soils which produces approximately the same amount of food output, is relatively low-cost but produces relatively low amounts of CO_2 offsets. As CO_2

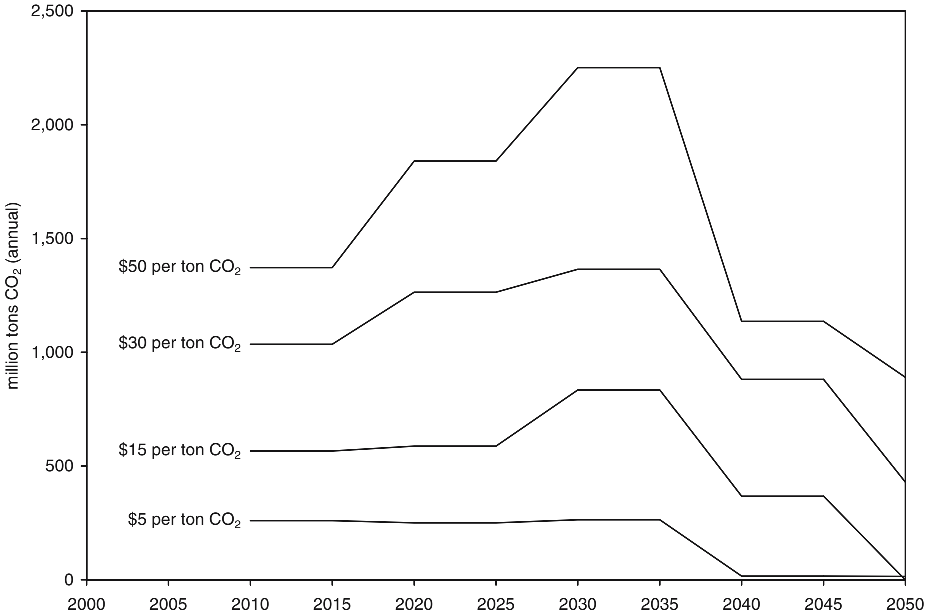


Fig. 6 Total terrestrial offset potential at four CO_2 prices: \$5, \$15, \$30, and \$50 per metric ton of CO_2. The terrestrial offsets are the sum of soil sequestration, afforestation, forest management, and biomass offsets from Fig. 4, converted from cumulative levels to annual increments.

prices get higher the model increasingly turns toward biofuels and afforestation which produce higher rates of CO_2 but also require diversion of land from existing agricultural production and thus have higher production plus opportunity costs causing them to only be truly competitive when higher CO_2 prices arise. Furthermore we observe some negative increments in technologies used at low prices due mainly to land competition for land being withdrawn for biofuels and afforestation. When viewed as a whole, the terrestrial options generally provide positive annual increments to net GHG mitigation. The terrestrial contribution is quite large in early years; its magnitude is comparable to any of the other aggregate GHG mitigation components. The contribution in later years depends mainly on biofuels, which is not limited by saturation. Figure 6 provides a summary of the terrestrial component over time at four CO_2 prices. Sustainable reductions in net GHG emissions in later years are achieved only at higher CO_2 prices that provide an incentive for biofuel production. For CO_2 prices of \$15 and higher, the terrestrial component peaks around 2030, before the sequestration options saturate.

Each of the four major classes of GHG mitigation options has its own characteristics with respect to cost, availability over time, and saturation. Options to reduce emissions of the non-CO_2 GHGs are generally less capital intensive than energy system options, as the non-CO_2 options can often be handled with retrofits to capital and need not wait for capital stocks to turn over. These options can be implemented quickly, but the long-term potential is limited relative to the energy system options. The energy system and CCS mitigation options are limited by the rate that capital stocks turn over, but have large potential in the long run and at higher CO_2 prices.

It is useful to partition the terrestrial mitigation options into two types: those that involve sequestration of carbon and therefore saturate, and biofuels which do not saturate. In early years, terrestrial sequestration options provide reductions in net greenhouse gas emissions that are comparable in magnitude to any of the other classes of GHG mitigation options, over a wide range of CO_2 prices. The biofuels option requires higher CO_2 prices than some of the terrestrial sequestration options, but is sustainable in the long term.

8 Concluding remarks

We have taken an economy-wide approach to assess the potential for terrestrial greenhouse gas mitigation options to contribute to stabilization of atmospheric greenhouse gas concentrations, by comparing major types of greenhouse gas mitigation options across the entire economy over time, finding the most cost-effective options. We find that terrestrial greenhouse gas mitigation options can provide a bridge to the future with the sequestration activities providing an important option during the first three decades then diminishing in importance as other options become more available. Greenhouse gas mitigation options with large capital requirements, such as those in the energy system, provide the bulk of mitigation in later years but are limited in early years by the turnover of capital stock. Carbon sequestration in soils and forests, and reducing emissions of non-CO_2 greenhouse gases, contribute heavily in early time periods.

Several caveats are in order. The analysis presented here assumes that all greenhouse gas mitigation options operate at the same price margin. However, real-world proposals to control greenhouse gas emissions may create two types of options: terrestrial sequestration and all other options. The quantity of terrestrial sequestration offsets allowed may be constrained and therefore exploited up to a CO_2 price below that of other options.

This analysis used exogenous CO_2 prices that were held constant over time. Constant CO_2 prices tend to favor sequestration options in the short term. Prices that rise rapidly over time provide incentives to delay mitigation activities that have a fixed cumulative contribution. If the rate of increase in the CO_2 price exceeds the interest rate, it may pay to wait for a higher price.

Also, terrestrial mitigation options in this analysis reflect current technologies. Ongoing scientific work in the US Department of Energy's program to enhance carbon sequestration in terrestrial ecosystems (CSiTE) seeks to identify methods to increase the technical, economic, and competitive potential for terrestrial carbon sequestration and for biofuels. Future analysis will be updated to reflect new results from CSiTE.

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