Appraising Agricultural Greenhouse Gas Mitigation Potentials: Effects of Alternative Assumptions

Uwe A. Schneider*
Assistant Professor
Research Unit Sustainability and Global Change
Center for Marine and Climate Research
Hamburg University
Bundesstrasse 55
D-20146 Hamburg, Germany
schneider@dkrz.de
49-40-428386593

Research Associate
Forestry Project
International Institute of Applied Systems Analysis (IIASA)
Schlossplatz 1
A-2361Laxenburg, Austria

Bruce A. McCarl
Regents Professor
Department of Agricultural Economics
Texas A&M University
2124 TAMU
College Station, TX 77843-2124
mccarl@tamu.edu
1-979-845-1706

Working Paper FNU-81

Hamburg, Germany, July 2005

* Corresponding Author

Abstract

There is interest in society in general and in the agricultural and forestry sectors concerning a land based role in greenhouse gas mitigation reduction. Numerous studies have estimated the potential supply schedules at which agriculture and forestry could produce greenhouse gas offsets. However such studies vary widely in critical assumptions regarding economic market adjustments, allowed scope of mitigation alternatives, and region of focus. Here, we examine the effects of using different assumptions on the total emission mitigation supply curve from agriculture and forestry in the US. To do this we employ the US based Agricultural Sector and Mitigation of Greenhouse Gas Model and find that variations in such factors can have profound effects on the results. Differences between commonly employed methods shift economic mitigation potentials from –55 to +85 percent. The bias is stronger at higher carbon prices due to afforestation and energy crop plantations which reduce supply of traditional commodities. Lower carbon prices promote management changes with smaller impacts on commodity supply.

Key words: greenhouse gas emission mitigation, Agriculture, forestry, economic potential,

Appraising Agricultural Greenhouse Gas Mitigation Potentials: Effects of Alternative Assumptions

Carbon sequestration in agricultural and forest soils as well as in standing trees has received substantial attention within the policy, energy, and agriculture and forestry (AF) communities. This attention has arisen due to:

1. The widely accepted link between greenhouse gas (GHG) emissions and projected climate change (Petit et al. 1999).
2. The global dialogue over GHG emission reductions including the emergence of emission reducing agreements such as the Kyoto Protocol (Bolin 1998, Najam, Huq, and Sokona 2003).
3. Projected high-costs for GHG emission offset production in some sectors of the economy (Viguier, Babiker and Reilly, 2003) coupled with projected low costs from some agricultural sources (Richard and Stokes, 2004, Pautsch et al. 2001).
4. Co-benefits of GHG emission reduction activities with other AF-related societal goals like soil conservation, pollution control, improved water quality (Lal et al. 2004) and farm income support (Schneider and McCarl, 2003, Schneider and McCarl, 2005), and
5. Emergence of GHG offset markets (Johnson and Heinen, 2004, Hasselknippe, 2003).

This interest is beginning to stimulate policy action. In the U.S. bills have been introduced into Congress and discussions are being held in both environmental and agricultural agencies regarding policy and/or program design. Many factors need to be considered in formulating appropriate GHG emission reduction policy and programs. Substantial literature is emerging regarding soil science and forest management aspects of and potential for carbon sequestration (Lal 1998, Marland et al., 2004, Johnson and Curtis 2001). However, depending on the appraisals' scope and methods, the true competitive potential may be much smaller than estimated through the appraisal (McCarl and Schneider 2001). Thus, the political interest may often be founded in engineering based estimates of per hectare net GHG emission estimates times an estimate of the applicable acreage without regard to the cost of generating such emissions or any market implementation issues (Lal 1998, Dendoncker et al. 2004, Neufeldt 2005). In this paper we will explore the impact of methodological differences on the magnitude of the GHG emission mitigation potential in the AF sectors of the US.

Agriculture and Forestry GHG Emission Reduction: Concepts

Before comparing various methods and assumptions for the estimation of emission mitigation potential, let us briefly review the mechanisms through which AF can participate. Following the arguments in McCarl and Schneider (1999, 2000), AF may mitigate GHG emissions by

- creating or expanding sinks to enhance terrestrial absorption of atmospheric GHGs (carbon sequestration);
- reducing emissions generated during AF operations; and
- providing products such as biofuel feedstocks that ultimately substitute for GHG emission intensive products and thereby displace emissions.

Each of these options will be discussed below.

Carbon Sequestration

Atmospheric CO2 (CO_2) buildup is the most prevalent GHG (Schlesinger 2001; North 2001). Terrestrial carbon sequestration offers a possible way of reducing atmospheric CO_2 concentrations. CO_2 is exchanged continuously between the terrestrial biosphere and the atmosphere. Chlorophyllic plants absorb it through photosynthesis and use the contained carbon to build organic matter. Thus, carbon directly accumulates as plants grow. At the end of plant life, most of the organic carbon is quickly released to the atmosphere through oxidization, microbial decomposition and/or combustion. However, some of the carbon enters other terrestrial pools (humus, wood products, etc.).

Scientists estimate that about 80 percent of global carbon is stored in soils or forests (IPCC 2000) and that a substantial proportion of the carbon originally contained in soils and forests has been released due to past AF activities and deforestation. Collectively, these facts imply that there is substantial potential for AF activities to sequester carbon (Lal et al. 1998).

There are two fundamental physical processes through which carbon sequestration can be enhanced: increasing the amount of carbon accumulated in soils or trees and decreasing microbial decomposition and combustion (Paustian et al. 2001). Management actions that increase carbon inputs to soils and trees include expansion of forested areas, delay of the time of forest harvest, increase in forest growth rates through enhanced silvicultural practices, adoption agricultural practices that minimize soil disturbance and erosion, increasing retention of crop or logging residue, and maximization of water- and nutrient-use efficiency of crop production.

Emission Reductions

The IPCC (1996) estimates that on a global basis, agriculture emits about 50 percent of all Methane (CH_4), 70 percent of all nitrous oxide (N2O), and 20 percent of all CO2. Methane is emitted in AF through enteric fermentation of ruminant animals, anaerobic livestock manure decomposition, rice cultivation, and termites. Possible abatement strategies include altering crop choice, livestock herd size, livestock feeding and rearing practices, and manure management. N_2O emissions arise from manure, legumes, and fertilizer use and can be abated by reducing livestock herd size and changing crop mixes and fertilization practices. CO_2 is emitted from fossil fuel usage, oxidization of soil organic matter, deforestation, and biomass decomposition or burning. Emissions can be reduced by decreasing fossil fuel use; changing the allocation of land among crops, pasture, grass lands, and forests; increasing forest harvest intervals; improving crop residue management; and restoring degraded land. Forest management practices that reduce emissions include diminished deforestation or logging, protection of forest reserves, and improved disturbance management with respect to fire and pest outbreaks.

The relative magnitude of these emission sources varies substantially across countries, with the greatest differences occurring between developing and developed countries. Deforestation and land degradation mainly occur in developing countries while developed countries slightly increase their forest base (FAO 1997). Developed country agriculture generally uses more capital-intensive production systems[1], resulting in higher fossil-fuel-based emissions.

Product Substitution

AF biomass products may replace fossil fuel intensive products such as electrical power and liquid fuels. The use of biomass energy mitigates CO2 emissions because most of the carbon released at combustion time is recycled carbon. Kline, Hargrove, and Vanderlan (1998), for example, estimate that only 5 percent of the carbon emitted through poplar-fed electrical power

---

[1] Aggregate estimates of tractor inventory show developed countries using about three times as many tractors as developing countries on an agricultural area that is 40 percent smaller (FAO 1999)

plants pertains to fossil fuels. The remaining 95 percent pertains to carbon photosynthetically absorbed from the atmosphere during biomass growth. Use of pure fossil fuel products, on the other hand, increases atmospheric CO2 concentrations by 100 percent of the contained CO2 plus emissions related to extraction and processing of these fuels.

Forestry products also can be used as substitutes for fossil-fuel-intensive steel and concrete in construction (Marland and Schlamadinger 1997, Brown 1999, and Brown et al. 1996 elaborate on this point). Finally, there may be gains from substituting cotton and other fibers for petroleum-based synthetics.

GHG Emission Mitigation Potential: Appropriate Appraisal Scope

Emission mitigation efforts may be complimentary (profitable) or competitive (costly) with traditional agricultural and forest business. However, in a world where for a long time emissions have not imposed a direct cost to businesses, it is safe to assume that the majority of truly complimentary options have already been adopted voluntarily and evolved into common business strategies while the majority of truly competitive options have been idle. For example, while many farmers have employed intensive tillage methods which led to lower soil organic matter levels, they have prevented soil organic carbon levels from becoming too low and used humus-increasing measures such as manure applications or cover crops to reap the benefits of higher soil productivities. Consequently, the mitigation options “left to implement” are generally those which for economic reasons have not been adopted in the past. This implies that appraisals of realistic AF-generated mitigation potentials should incorporate the cost of mitigation. Particularly, we believe that an appropriate appraisal should entail four important economic matters. These include

- factors that would cause an AF producer to adopt a strategy,
- regional scope and market feedbacks
- competition across alternative strategies, and
- multi-gas trade-offs.

A brief discussion of these matters follows below.

Factors Causing Strategy Adoption by Agricultural and Forestry Producers

While policymakers and others may desire certain AF GHG offset practices, the farm or forest operator ultimately controls the practices employed. Farmers and foresters adopt those practices that maximize their well-being. Well-being, however, is complex involving many dimensions, such as

- practice profitability,
- risk exposure,
- time availability of resources required to use the practice,
- amount of training and/or learning required to employ the practice,
- willingness to adopt the degree of management required to employ the practice,
- consistency of the practice with existing machinery,
- willingness and ability to invest in new machinery required to employ the practice,
- desire for environmental stewardship coupled with the environmental attributes of practice, and
- necessity to perform in compliance with imposed regulations.

Some practices currently used by farmers and foresters are desirable from a GHG emission mitigation point of view. In such cases, the operator has judged the practice superior to other alternatives, even in the absence of adoption incentives. However, in other cases the desired practices are not used. To convince farmers to adopt such practices, regulations or incentives are needed. The incentives may be a mixture of direct instruments (such as carbon-related payments) and indirect instruments (such as sequestration shortfall insurance, investment subsidies, and training programs).

Consider for example the adoption of no-till farming as opposed to conventional moldboard plowing. Discussions with farmers (see Bennett 1999) reveal reservations about the adoption of no-till due to factors such as

- potential yield losses due to slower warming of untilled soils during cool spring planting seasons;
- potential yield reductions due to other factors;
- potential cost increases, particularly for weed and insect control;
- need to acquire new expensive equipment;
- critical reliance on the effectiveness of chemical weed control compounds and the need for continued efficacy of weed control;
- learning time to effectively employ the practice; and
- willingness on behalf of older farmers to switch practices.

All of these factors affect the magnitude of the financial incentives required to stimulate adoption. A lower bound on the needed incentive could be calculated as the foregone net income due to average yield loss (note yield gains are possible) plus the net value of any cost change. In developing efficient policies, however, incentives above and beyond lost income may be needed to overcome other barriers to adoption. Pautsch et al. (2001), for example, indicate that nominally profitable practices may not always result in full adoption.

Regional scope and market feedbacks

Economic potential can be appraised at the field, farm, regional, or sector level. Farm-level assessments examine the incentives needed to induce participation on individual farms or relatively detailed farm type classes (Pautsch et al. 2001, de Cara and Jayet 2000). However, such appraisal results are typically based on assumed exogenous and fixed prices and thus may be misleading. The following calculation will illustrate why AF GHG mitigation efforts might substantially impact market prices for traditional AF commodities. U.S. cropland amounts to approximately 325 million acres (132 million hectares). The literature suggests an annual maximum potential for agricultural carbon sinks of around one and a half tons of carbon per acre of cropland through afforestation (Newell and Stavins 2000). Food will still need to be produced so it is inconceivable that more than half of the acreage could convert. As a result, the total annual agricultural-cropland-based contribution to carbon storage may be bounded at about 250 million metric tons. The annual U.S. provisions if it complied with the Kyoto Protocol would be in the neighborhood of 600-700 million metric tons. If a strong GHG emission mitigation program diverted almost half of US cropland, that would imply similar reductions in crop production, leading to higher market prices. Higher market prices for traditional AF commodities would raise the opportunity cost of mitigation strategies and thus make AF mitigation more expensive the more cropland is involved. To account for these complex interactions, a sector-level approach that simultaneously analyzes mitigation impacts and impacts on the traditional agricultural sector is needed.

Competition Across Alternative Strategies

The potential of certain AF GHG emission mitigation strategies is not independent of the level of other strategies. For example, the more cropland farmers allocate to biofuels, the less cropland is available for establishing permanent forests or adopting GHG emission friendly tillage practices. Complementary relationships also emerge; farmers may supply corn for ethanol processing and at the same time sequester soil carbon through minimum tillage and offset emissions by reducing fossil fuel usage. Thus, simultaneous consideration of potential strategies rather than independent appraisal would appear to be appropriate.

Multiple Gas Trade-offs

AF enterprises contribute to emissions of multiple GHGs. A crop-livestock farm releases CO2 when combusting the fuel necessary to operate field machinery, emits N2O through fertilizer applications, releases CH4 through enteric fermentation from ruminant animals or as a manure by-product, but possibly augments the soil carbon stock by using reduced tillage. Trade-offs between these emissions may occur if, for example, more fertilizer is needed under reduced tillage or if usage of growth hormones for animals alters the required acreage to produce feed.

Multiple gases can be considered using the global warming potential (GWP) concept. The GWP compares the radiative force of the various GHGs relative to CO2 over a given time (IPCC 1996). The one-hundred-year GWP for CO2 equals 1. Higher values for CH4 (23) and N2O (298) reflect a greater per ton heat-trapping ability. Thus, multiplying an emission quantity by the GWP forms a “carbon equivalent” measure after factoring in an adjustment for the molecular weight of carbon in CO2.

Mitigation Potential: Empirical Findings

Now we turn our attention to empirical estimates of mitigation potential. Numerous appraisals have estimated the GHG emission mitigation potential from agriculture and forestry in recent years (Richards and Stokes 2004, McCarl and Schneider 2000). The estimated mitigation potentials however differ considerably between appraisals. These differences may partially be due to different data but they are also due to different methods related to market design, strategy scope, regional scope, and emission reduction incentives. Large methodological differences have several negative consequences. First, they lead to different results and thus increase the uncertainty of mitigation potentials. Second, they make comparisons across different studies difficult. Third, they adversely influence policy decisions who give equal weight to many different studies. Here, we want to alleviate some of these drawbacks and facilitate the interpretation and comparison of different AF mitigation appraisals.

We will use the Agricultural Sector and Mitigation of Greenhouse Gas (ASMGHG) model of the United States (Schneider 2000). This model features many of the characteristics advocated above but does not fully account for the disincentives that are not profit related. Previously, the model has been used to compute the competitive economic potential of major AF strategies in the US at various incentive levels (McCarl and Schneider 2001). In this study, we will extent the analysis and examine how the emission potential changes as different appraisal specifications are used related to strategy interactions, interregional trade, and market feedbacks. Because the alternative assumptions are examined with the same model, a consistent data set is implied.

The Agricultural Sector and Mitigation of Greenhouse Gas Model[2]

The ASMGHG model is an expansion of the U.S. Agricultural Sector Model (ASM) (Chang et al. 1992, Chen and McCarl 2000). It is a mathematical programming based, price-endogenous sector model of the agricultural sector, modified to include GHG emission accounting by Schneider (2000). ASMGHG also includes data on forestry production based on the FASOM model (Alig, Adams, and McCarl 1998). ASMGHG depicts production, consumption, and international trade in 63 U.S. regions for 22 traditional and 3 perennial energy crops, 29 animal products, 6 forest products and more than 60 processed agricultural products. Management choices include tillage, irrigation, fertilization, manure treatment, and animal feeding alternatives.

Environmental accounts include levels of net GHG emission for CO2, CH4, and N2O; surface, subsurface, and groundwater pollution for nitrogen and phosphorous; and soil erosion. ASMGHG simulates the market and trade equilibrium in agricultural markets of the United States and major foreign trading partners. Domestic and foreign supply and demand conditions are considered, as are regional production conditions and resource endowments. The market equilibrium reveals commodity and factor prices, levels of domestic production, export and import quantities, GHG emission management strategy adoption, resource usage, and environmental impacts.

Alternative Assumptions

Appraisals of agriculture and forestry based GHG emission mitigation potentials encompass interdisciplinary research involving many natural scientists but also many economists. Market

---

[2] The Appendix provides details on the mathematical structure of ASMGHG and the scope of portrayed AF producer choices, regions, mitigation strategies, and other environmental accounts.

feedbacks tend to be ignored by natural scientists and some economists who use detailed farm level models with constant commodity prices. To address alternative market design assumptions, we use alternative specifications of ASMGHG's objective function and producer constraints. Four cases are distinguished. The first case represents the basic ASMGHG setup, where commodity prices are endogenous and crop and livestock producers are able to alter crop and animal choices as well as their management. Second, we portray price-exogenous appraisals by modifying ASMGHG's objective function. In particular, all downward sloping demand functions are converted to infinitely elastic, (horizontal) demand functions. Similarly, all upward-sloping factor supply functions are replaced by perfectly elastic (horizontal) supply functions. Moreover, export and import quantities are fixed as well.

A third market design specification represents appraisals with constant prices, constant crop shares, constant livestock numbers, and constant trade volumes. This type of appraisal is frequently called budgeting. It resembles GIS based geographic appraisals, where economic potentials are computed as so-called cost landscapes. To implement this market design, we modified the ASMGHG's objective function as in case two. In addition, we imposed regional crop area and livestock constraints, which forced the total crop area and the animal population to stay at the level of the base solution. Thus, possible producer adaptations were limited to management changes involving tillage, fertilization, irrigation, livestock manure treatment, and feed diet changes. Fourth, we setup a market design case, where prices are endogenous as in case one but crop acres and livestock numbers are fixed as in case three. This design represents appraisals where market price adjustments are considered but only one or few crops are included in the model.

Another important difference between existing appraisals of mitigation potentials concerns the scope of considered strategies. Frequently, only one or a subset of all strategies is assessed (Faaij et al. 1998, de Cara, Houzé, and Jayet 2005). One reason may be that researchers or whole research teams are sometimes exclusively devoted to particular options, i.e. certain energy crop options, agricultural tillage systems, forest management alternatives, or non-CO_2 opportunities. Such appraisals neglect competitive or complimentary effects with other strategies. To address this issue, we design five alternative scenarios were we only permit particular strategies to be eligible for a combined tax/subsidy policy. First we made all greenhouse gas accounts eligible (see Appendix for a list). In turn we specified scenarios where the policy affects only a) fossil fuel emissions and biofuel offsets, b) sequestration from afforestation, c) sequestration from soil carbon changes through either tillage or land-use changes, and d) N2O and CH4 emissions.

Existing appraisals reveal also a large variation in regional scope. Some studies portray only a relatively small region in the first place (Neufeldt 2005). Others consider several countries or the whole globe but their estimates are simple summations of many independent country or sub-country appraisals (Makundi and Sathaye 2003). Very few studies appraise multinational or global potentials with individual regions assessed simultaneously (Reilly et al. 1999). The first two approaches are likely to overstate mitigation potentials due to emission leakage. Emission intensive activities are exported out of the small appraisal regions. To emulate the effects of different regional scopes, we consider 10 major regions in US (see Appendix). For each of the 10 regions, we construct models that reflect policy being active only in one macro-region at a time. As basic setup, we impose the carbon price simultaneously on all regions in ASMGHG.

Finally, different mitigation incentives are implemented by specifying 32 different carbon price levels ranging from \$0 to \$500 per metric ton of carbon equivalent (mtce). These carbon prices are imposed on different greenhouse gas accounts depending on the chosen assumption about the strategy and region scope. For N2O and CH4 emissions when eligible, the carbon price was inflated by the 100-year global warming factor of those gases relative to CO2 divided by the conversion rate from carbon to CO2 (3.667). The use of several carbon prices is a common approach in the literature to address the uncertainty of future carbon prices and to trace out an emission reduction supply curve. In the context of this study, we employ a wide range of carbon prices also to find out whether the impacts of regionality, strategy, and market assumptions differ across different incentive levels.

Combining 32 carbon price levels, 4 market and producer adjustment designs, 5 strategy scope options, and 11 regional specifications yields 7040 potential ASMGHG runs that would require about half a year of computing time on a standard computer. To make our analysis less computer time demanding, we solve ASMGHG only for a subset of the above combinations. Particularly, we investigate the following combinations of assumptions:

- Regionally independent appraisals with simultaneous strategy implementation and full producer and market price adjustments,
- Regionally independent appraisals with individual strategy implementation and full producer and market price adjustments,

- National appraisals with simultaneous strategy implementation for all four producer and market adjustment options,
- National appraisals with independent strategy implementation and full producer and price adjustment,
- National appraisals with independent strategy implementation, full producer adjustment but constant market prices
- National appraisals with simultaneous strategy implementation and ignorance of all costs, and
- National appraisals with independent strategy implementation and ignorance of all costs.

Measuring the Magnitude and Bias of Alternative Appraisals

To empirically illustrate the effect of different GHG mitigation appraisal specifications, we focus on the national estimates of total mitigation potential in the US. Our first exercise is to distinguish economic and technical potentials. This is shown in Figure 1. There are two technical potentials estimates represented by vertical lines. These estimates are obtained by changing ASMGHG's objective function from welfare maximization to a pure maximization of GHG mitigation. Mitigation costs and carbon prices do not enter the model and therefore do not affect the computed potential. The competitive economic potential is far less than the technical potential. Even at a relatively high carbon price of $100/mtce, it amounts only to about 50 percent of the simultaneous technical potential. The competitive potential is also substantially lower than the geographic potential, where price effects and strategy interactions have been ignored. The highest overstatement is given however by the sum of independent technical potentials. The overstatement results from a combination of cost negligence and permission to use land several times for options which are mutually exclusive in reality.

The impact of different market and producer adjustment specifications is illustrated in Table 1 and Figure 2. The line labeled "endogenous acres and prices" represents our reference mitigation function where the fully endogenous ASMGHG version is used to compute the economic potential of AF in the US. This reference function takes into account agricultural market adjustments as well as full adaptations for crop and livestock producers. All three alternative specifications show substantial deviations from the reference function. Particularly, the assumption of constant prices leads to large overstatements of the economic potential.

Restricted adaptation on the other hand underestimates the economic potential. Moreover, deviations are generally larger at higher mitigation incentive levels.

The direction and magnitude of the estimated deviations can be understood by reviewing the nature of the multi strategy equilibrium as discussed in McCarl and Schneider 2001. Therein we found that at small incentive levels strategies are pursued which are close to existing cropping practices and land allocations, i.e. adoption of reduced or zero tillage, and which exhibit relatively small GHG emission mitigation rates. At higher incentives, strategies are pursued that yield higher rates of GHG emission mitigation but generally involve a strong deviation from traditional production practices. Namely afforestation and perennial energy crop plantations displace traditional crops and reduce the possible area for tillage based soil carbon sequestration. Further, at lower incentive levels, all market specifications give similar results because market adjustments are relatively minor. At higher incentive levels, the assumption of constant commodity prices understates the rising opportunity cost for the diversion of traditional cropland to energy crop plantation or forests. In other words, the more traditional cropland shrinks, the more increase prices and revenues for traditional commodities lowering incentives for further cropland conversions.

The assumption of constant crop acreage leads to the opposite effect because deviations from the current crop mix are prohibited and, more importantly, energy plantation and afforestation options are excluded. A combination of constant prices and restricted adaptation (case labeled: "constant prices and acres") introduces both a positive and a negative bias. While in our analysis the two opposite bias cancel at an incentive level of about $100 per mtce, one should be aware that this effect is purely spurious should not be used to recommend the underlying simple appraisal method.

Next, we examine the impact of different appraisal scopes regarding mitigation strategy and regions (Figure 3). As before, we use the fully endogenous ASMGHG with all regions and all strategies as reference function. This function is labeled "comb. regions, comb. strategies" and is computed based on 32 ASMGHG solutions for 32 different mitigation incentives. The second line "indv. regions, comb. strategies" uses information from 320 ASMGHG solutions representing specifications of 32 incentive levels and 10 regional models. Basically, at each incentive level, ASMGHG is solved 10 times, each time imposing the mitigation policy in a different US macro region. The national economic potential is then computed as sum of the 10 independently obtained regional economic potentials. Figure 3 shows that this method substantially overstates the reference potential. Differences reflect the interregional emission leakage within the US, which occurs especially at higher carbon prices because high mitigation incentives promote afforestation and energy crop plantations. For example, at a carbon price of $100 per mtce, the sum of independently computed regional potentials exceeds the simultaneous potential by about one third. At carbon prices below $50 per mtce, the difference is smaller (Table 1).

The third line in Figure 3 ("comb. regions, indv. strategies ") uses information from 96 ASMGHG solutions representing specifications of 32 incentive levels and 4 independent strategy appraisals as described in the previous section. The bias from summing independently obtained strategy potentials versus appraising all strategies simultaneously reaches considerable overstatements at high carbon prices. Overstatements result primarily from the ignored resource competition between different AF mitigation strategies. Simply speaking, land diverted to perennial energy grasses cannot be used for afforestation. This obvious fact is violated by summing independent strategy potentials. However, the sum of independent strategy potentials can also understate the joint mitigation potential if two strategies are complementary rather than competitive. For example, the adoption of zero tillage does not only sequester soil carbon but may also result in less fossil fuel use because the energy intensive plowing operation is cut out. Thus, zero tillage may result in higher economic potentials under appraisals that consider both fossil fuel reductions and soil carbon sequestration. Similarly, reduced nitrogen fertilization reduces both embodied carbon emissions and N2O emissions on the field. More generally, complementary GHG mitigation strategies in AF relate to crop management changes. The underestimation from ignoring complementary relationships is however minor in comparison to the overestimation from ignoring competitive relationships. For carbon prices at or below $50 per mtce, mitigation is primarily due to management changes but the economic potentials between joint and independent appraisals are fairly close.

Finally, the line labeled "indv. regions, indv. strategies" represents the sum of independent regional and independent mitigation strategy appraisals and uses information from 1280 ASMGHG solutions (32 carbon prices times 10 macro regions times 4 strategy classes). The resulting economic potential bias is highest especially for high carbon prices with high strategy competition and high leakage potential.

Concluding Remarks

Agriculture and forestry can mitigate a substantial quantity of greenhouse gases through source emission reductions, biofuel offsets, and carbon sequestration via growing trees, land use change, or tillage change. Numerous studies have tried to quantify the emission abatement potentials of these options. Wide differences have been revealed between technical and economic potential estimates with the latter being substantially lower. This study shows that estimates of economic potentials may also differ greatly among themselves depending on the scope of the associated appraisal. Assumptions about producer adaptations, market adjustments, strategy competition, multi-GHG trade-offs, and the regional scope of the appraisal can considerably affect the magnitude of the estimated economic potential.

Our findings can be summarized into a set of major points. First, when comparing economic potential estimates from different studies, one should carefully examine the underlying assumptions particularly in terms of market price response, regionality and scope of allowed mitigation alternatives. The few assessments cited in this study already illustrate diversity in such factors within appraisal methods.

Second, market feedbacks are important whenever GHG mitigation strategies notably alter commodity supply. This is the case for perennial energy plantations and afforestation. It is also true for crops that are primarily produced as input for biorefineries. Tillage changes, on the other hand, have a very small impact on commodity supply. Thus, market feedbacks are important when examining relatively strict GHG policies because perennial energy plantations and afforestation need relatively large incentives to become attractive to AF producers. Small GHG mitigation incentives, i.e. below $50 per mtce, favor reduced tillage options and are not likely to affect commodity prices a lot. The omission of market price adjustments overstates the economic potential of strategies, which reduce traditional commodity supply. Alternatively, if a mitigation strategy would increase traditional commodity supply, then omission of market price adjustments could also understate the economic potential. Perhaps a long-lasting adoption of zero tillage might lead to increased yields after a decade because enhanced soil organic matter increases a soil's productivity and fertility. Current data, however, do not support strong positive yield impacts from reduced tillage.

Third, economic potential estimates strongly depend on the degree to which the appraisal allows for AF producer adaptation. As shown by McCarl and Schneider (2001), the economic potential of carbon offsets from perennial energy crops is much higher when competing strategies such as carbon sequestration are prohibited rather than simultaneously allowed. This study shows that the bias from limited adaptation for the total economic potential across AF strategies can be positive or negative. A negative bias, i.e. an understatement of the total economic potential occurs because fewer options reduce the adaptability and flexibility of AF producers and thus virtually increase the cost of mitigation. However, if the total economic potential is appraised as the sum of different individual strategy assessments, it can lead to a large positive bias. This overstatement is due to neglected strategy competition resulting in multiple allocations of the same land to different strategies, which in reality are mutually exclusive. Thus, when examining the strategy scope of an appraisal, one should not only verify the number of included strategies but also check whether different strategies were assessed jointly or independently.

Fourth, many appraisals differ in regional scope. Limited regional representation in appraisals with endogenous prices and trade volumes leads to an overstatement of the economic potential because emission intensive production can be exported causing emission leakage. Regional appraisals may be appropriate if the represented mitigation policy is indeed implemented at regional level and emission leakage is a real consequence. On the other hand, if sub-national appraisals were used to assess a national policy, the estimated economic emission mitigation potentials will be truly overstated. This issue is particularly relevant for ASMGHG. While our economic potentials for the AF sectors in the US are derived from a nationwide policy implementation, other countries were left unregulated[3]. A unilateral mitigation policy in the US is, however, almost opposite to current political realities.

Finally, we need to address the issue of methodological feasibility and limitations. Currently, there is no “one does it all model” that can appropriately appraise the true economic greenhouse gas emission mitigation potential from the AF sectors. The ASMGHG model used here is no exception. Limitations include the absence of detailed AF production possibilities in foreign countries, the absence of non-agricultural sectors of the economy, and the coarse regional and technological resolution of AF production possibilities in the US relative to detailed regional farm level models, which integrate often millions of observed farm data points. Limitations arise because of computational and data deficiencies. On one hand, current computers are not able to simulate globally active mitigation policies with a high regional and technological resolution. On the other hand, data deficiencies and intellectual property rights practically restrict the opportunity for building a “one does it all” model. However, while an integrated single model

---

[3] This assumptions is relaxed in Lee et al.

may be infeasible for some time to come, an appropriately linked suit of different appraisals may be an efficient second best solution. For example, several regional farm level appraisals could provide regional abatement functions accounting for profit and non-profit aspects as well as heterogeneous soil, climate, and management conditions. These aggregated farm level response functions could be integrated in agricultural sector models such as ASMGHG. In turn, ASMGHG or similar models could estimate and provide sector level response functions for global, multi-sector general computable equilibrium and/or Earth system models. The findings of this paper demonstrate that such an approach would be by far better than a simple adding up of regionally independent appraisals of individual mitigation strategies.

References

Alig, R.J., D.M.Adams, and B.A. McCarl. 1998. “Impacts of Incorporating Land Exchanges Between Forestry and Agriculture in Sector Models.” *Journal of Agricultural and Applied Economics* 30(2): 389-401.

Bennett, J.F. 1999. “Commentary on Marland, G., B.A. McCarl, and U.A. Schneider, Soil Carbon: Policy and Economics.” In *Carbon Sequestration in Soils: Science, Monitoring, and Beyond*, edited by N.J. Rosenberg, R.C. Izaurralde, and E.L. Malone, pp. 168-170. Proceedings of the St. Michaelis Workshop*,* St. Michaels, MD, December 3-5, 1998.

Bolin, B. 1998. “The Kyoto Negotiations on Climate Change: A Science Perspective.” *Science* 279(16 January 1998): 330-331

Brown, S., J. Sathaye, M. Cannell, and P. Kauppi. 1996. “Management of Forests for Mitigation of Greenhouse Gas Emissions,” chap. 24 in *Climate Change 1995—Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*, edited by R.T. Watson, M.C. Zinyowera, and R.H. Moss. Cambridge and New York: Cambridge University Press.

Brown, S.J. 1999. “Opportunities for Mitigating Carbon Emissions through Forestry Activities.” Report prepared for the World Bank, Winrock International, Arlington, VA, March.

Chang, C.C., B.A. McCarl, J.W. Mjelde, and J.W. Richardson. 1992. “Sectoral Implications of Farm Program Modifications.” *American Journal of Agricultural Economics* 74: 38-49.

Chen, C.C. 1999. “Development and Application of a Linked Global Trade-Detailed U.S. Agricultural Sector Analysis System.” PhD Dissertation, Texas A&M University, May 1999.

Chen, C.C. and B.A. McCarl. 2000. "The Value of ENSO Information to Agriculture: Consideration of Event Strength and Trade," *Journal of Agricultural and Resource Economics* 25 (2, 2000): 368-385.

Dantzig, G.B. and P. Wolfe. 1961. "The Decomposition Algorithm for Linear Programs." *Econometrica* 29(1961):767-778. – Appendix Reference

De Cara S. and P.A. Jayet. 2000. "Emissions Of Greenhouse Gases from Agriculture: The Heterogeneity Of Abatement Costs In France" *Europ. Rev. Agr. Econ.* 27(3, 2000):281-303.

De Cara, S., Houzé, M. and Jayet, P.-A. (2005). "Emissions of methane and nitrous oxide from agriculture in Europe: A spatial assessment of sources and abatement costs". *Environmental and Resource Economics* (forthcoming).

Dendoncker, N., B. Van Wesemael, M.D.A. Rounsevell, C. Roelandt, S. Lettens. 2004. “Belgium’s CO2 mitigation potential under improved cropland management.” *Agriculture, Ecosystems and Environment* 103 (2004): 101–116

Faaij, A., I. Steetskamp, A. van Wijk and W. Turkenburg. 1998. “Exploration of the land potential for the production of biomass for energy in the Netherlands.” *Biomass and Bioenergy* 14, (5-6, 1998): 439-456

Food and Agriculture Organization of the United Nations (FAO). 1997. "*State of the World's Forests 1997*." p. 16. Rome, Italy.

Food and Agriculture Organization of the United Nations (FAO). 1999. FAOSTAT. Statistics database. http://apps.fao.org (accessed June 2001).

Hasselknippe, H. 2003. "Systems for carbon trading: an overview." *Climate Policy* 3 (2, 2003):43-57

Intergovernmental Panel on Climate Change (IPCC). 1996. *Climate Change 1995—Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses,* edited by R.T. Watson, M.C. Zinyowera, and R.H. Moss. Cambridge and New York: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). 2000. *Land Use, Land-Use Change, and Forestry*. Cambridge and New York: Cambridge University Press.

Johnson, D.W. and P.S. Curtis "Effects of forest management on soil C and N storage: meta analysis" *Forest Ecology and Management* 140 (2-3, 15 January 2001): Pages 227-238

Johnson, E. and R. Heinen. 2004."Carbon trading: time for industry involvement." *Environment International* 30 (2, 2004): 279-288

Kline, D., T. Hargrove, and C. Vanderlan. 1998. "The Treatment of Biomass Fuels in Carbon Emissions Trading Systems." Prepared for the Center for Clean Air Policy's Greenhouse Gas Emissions Trading Braintrust, Washington, D.C., March. http://www.ccap.org/pdf/biopub.pdf.

Lal, R., Griffin, M., J. Apt, L. Lave, and M.G. Morgan. (2004) "Managing Soil Carbon." *Science* 304(2004): 393

Lal, R., J.M. Kimble, R.F. Follett, and C.V. Cole (1998). *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect*, pp. 128, Chelsea, MI: Sleeping Bear Press Inc.

Lee, H.C., B.A. McCarl, U.A. Schneider, and C.C. Chen. "Leakage and Comparative Advantage Implications of Agricultural Participation in Greenhouse Gas Emission Mitigation." Forthcoming *Mitigation and Adaptation Strategies for Global Change*

Makundi, W.R. and J.A. Sathaye. 2004. "GHG Mitigation Potential and Cost in Tropical Forestry – Relative Role for Agroforestry." *Environment, Development and Sustainability* 6(2004): 235–260.

Marland, G., and B. Schlamadinger. 1997. "Forests for Carbon Sequestration or Fossil Fuel Substitution A Sensitivity Analysis." *Biomass and Bioenergy* 13(1997): 389-97

Marland, G., C.T. Garten Jr., W.M. Post, and T.O. West. 2004. "Studies on enhancing carbon sequestration in soils." *Energy* 29(2004): 1643–1650

McCarl, B. A. 1982 “Cropping Activities in Agricultural Sector Models: A Methodological Proposal.” *American Journal of Agricultural Economics* 4. 64:768-772. – Appendix Reference

McCarl, B. A. and T. H. Spreen. 1980. "Price Endogenous Mathematical Programming as a Tool for Sector Analysis." *Amer. J. Agr. Econ*. 62(1980):87-102. – Appendix Reference

McCarl, B.A. and U.A. Schneider. 2001. "Greenhouse Gas Mitigation in U.S. Agriculture and Forestry." *Science* (5551, 2001):2481-2482

McCarl, B.A., and U.A. Schneider. 1999. “Curbing Greenhouse Gases: Agriculture’s Role.” *Choices*, First Quarter, pp. 9-12.

McCarl, B.A., and U.A. Schneider. 2000. “Agriculture’s Role in a Greenhouse Gas Emission Mitigation World: An Economic Perspective.” *Review of Agricultural Economics* 22: 134-59.

Najam, A., S. Huq, and Y. Sokona. 2003. “Climate negotiations beyond Kyoto: developing countries concerns and interests.” *Climate Policy* 3(3, 2003): 221-231

Neufeldt, H. 2005 “Carbon stocks and sequestration potentials of agricultural soils in the federal state of Baden-Württemberg, SW Germany.” *J. Plant Nutr. Soil Sci* 168(2005): 202-211.

Newell, R.G., and R.N. Stavins. 2000. “Climate Change and Forest Sinks: Factors Affecting the Costs of Carbon Sequestration.” *Journal of Environmental Economics and Management* 40(3): 211-35.

North, G. 2001. “Climate Change Over the Next Century.” In *Global Climate Change: The Science, Economics, and Politics*. Edited by James M. Griffin. University of Chicago Press, Chicago.

Önal, H. and B. A. McCarl. 1989. “Aggregation of heterogeneous firms in mathematical programming models.” *European Review of Agricultural Economics* 4 (16, 1989):499-513. – Appendix Reference

Önal, H. and B. A. McCarl. 1991. “Exact aggregation in mathematical programming sector models.” *Canadian Journal of Agricultural Economics* 2(39, 1991): 319-334. – Appendix Reference

Paustian, K., Babcock, B., Kling, C., Hatfield, J.L., Lal, R., McCarl, B., Post, W., Mosier, A.R., Rice, C., & Robertson, G. (2001). Agricultural mitigation of greenhouse gases: Science and policy options. National Conference On Carbon Sequestration. Available on the World Wide Web: http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/4C2.pdf

Pautsch, G. R., L. A. Kurkalova, B. Babcock, and C. L. Kling. 2001. “The Efficiency of Sequestering Carbon in Agricultural Soils.” *Contemporary Economic Policy* 19(2001): 123–134.

Petit, J.R., J. Jouzel, D. Raynaud et al. 1999. “Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica.” *Nature* 399(1999): 429-436.

Reilly, J., R. Prinn, J. Harnisch, J. Fitzmaurice, H. Jacoby, D. Kicklighter, J. Melillo, P. Stone, A. Sokolov, and C. Wang. 1999. “Multi-gas assessment of the Kyoto Protocol.” *Nature* 401(07 Oct 1999): 549-555

Richards, K.R. and C. Stokes. 2004. “A Review of Forest Carbon Sequestration Cost Studies: A Dozen Years of Research.” *Climatic Change* 63(2004): 1–48.

Schlesinger, W. 2001. “The Carbon Cycle: Human Perturbations and Potential Management Options.” In *Global Climate Change: The Science, Economics, and Politics*. Edited by James M. Griffin. University of Chicago Press, Chicago.

Schneider, U.A. 2000. “Agricultural Sector Analysis on Greenhouse Gas Emission Mitigation in the U.S.” PhD Dissertation, Department of Agricultural Economics, Texas A&M University.

Schneider, U.A. and B.A. McCarl. 2003. "Economic Potential of Biomass Based Fuels for Greenhouse Gas Emission Mitigation." *Environmental and Resource Economics*. 24(4): 291-312, April 2003.

Schneider, U.A. and B.A. McCarl. 2005. "Implications of a Carbon-Based Energy Tax for U.S. Agriculture.” *Agricultural and Resource Economics Review* 34(2, 2005) ****1–14

Viguier, L.L. M.H. Babiker, and J.M. Reilly. 2003 “The costs of the Kyoto Protocol in the European Union.” *Energy Policy* 31 (5, 2003): 459-481

Table 1 **Impact of Alternative ASMGHG Appraisal Assumptions on GHG Mitigation Potential from US Agriculture and Forestry**

	Appraisal Assumptions							
Prices	Endog.	Const.	Endog.	Endog.	Endog.	Const.	Endog.	Const.
Regions	Simult.	Indep.	Indep.	Simult.	Indep.	Simult.	Simult.	Simult.
Strategies	Simul.	Indep.	Simult.	Indep.	Indep.	Simul.	Simult.	Simult.
Adaptation	Full	Full	Full	Full	Full	Mangmt.	Mangmt.	Full
Carbon Tax $/mtce	Potential C-Econ mmtce	Bias Relative to Competitive Economic Potential (C-Econ Column)						
		Geogr %	I-Regs %	I-Strats %	I-RgStr %	Budget %	Fx-Acr %	Fx-Price %
5	27	-26.9	6.5	-0.2	-4.2	-2.1	-19.8	-17.2
10	50	-10.9	13.4	-4.1	3.4	16.4	-9.0	-2.8
15	71	-22.8	1.0	-4.8	-13.2	-2.6	-22.8	1.0
20	80	-9.7	22.0	-4.6	7.1	3.2	-12.7	0.7
25	95	-15.1	17.5	0.0	9.7	4.0	-18.8	-4.6
30	103	-7.8	22.5	3.2	15.5	9.6	-18.4	4.0
35	115	-6.2	21.8	6.3	17.4	13.1	-19.8	13.4
40	125	-3.2	22.8	5.2	16.7	15.2	-23.2	17.8
45	137	7.4	29.8	6.2	25.6	13.9	-26.7	34.5
50	171	-2.3	20.4	-0.2	25.1	10.2	-37.5	21.4
60	204	10.2	21.9	13.1	28.1	13.8	-41.7	39.3
70	240	14.8	20.5	27.4	31.7	4.2	-44.5	41.0
80	259	30.0	20.6	28.0	39.9	-0.1	-44.4	49.3
90	273	49.7	28.8	38.7	46.9	-1.4	-44.0	56.2
100	284	62.9	36.4	42.3	49.0	-1.7	-44.1	64.1
125	335	72.2	33.8	44.0	42.0	-12.0	-48.9	57.2
150	359	76.1	31.0	39.4	46.3	-15.5	-49.5	51.7
175	381	75.4	31.2	42.5	55.4	-17.7	-51.3	48.7
200	399	73.0	34.0	41.7	60.8	-20.5	-53.1	44.7
225	405	80.8	35.9	47.9	66.0	-21.1	-53.0	46.2
250	409	84.6	36.7	48.6	66.5	-21.6	-52.8	47.0
275	413	85.5	36.9	48.9	66.1	-22.3	-52.9	46.4
300	418	85.5	37.0	48.4	66.0	-23.1	-52.9	45.2
325	423	85.7	37.2	48.0	66.2	-23.9	-53.1	44.0
350	428	85.3	40.0	47.5	67.5	-24.7	-53.3	42.9
375	431	84.8	41.5	47.2	70.5	-25.2	-53.2	41.9
400	435	83.4	44.3	46.8	69.4	-25.9	-53.4	40.6
425	442	81.3	48.7	45.5	67.9	-26.8	-53.7	39.9
450	449	78.5	50.6	43.7	68.2	-27.9	-54.3	38.1
475	457	75.3	53.4	42.4	67.8	-28.9	-54.6	35.8
500	460	74.5	56.8	42.2	67.1	-29.3	-54.3	35.0

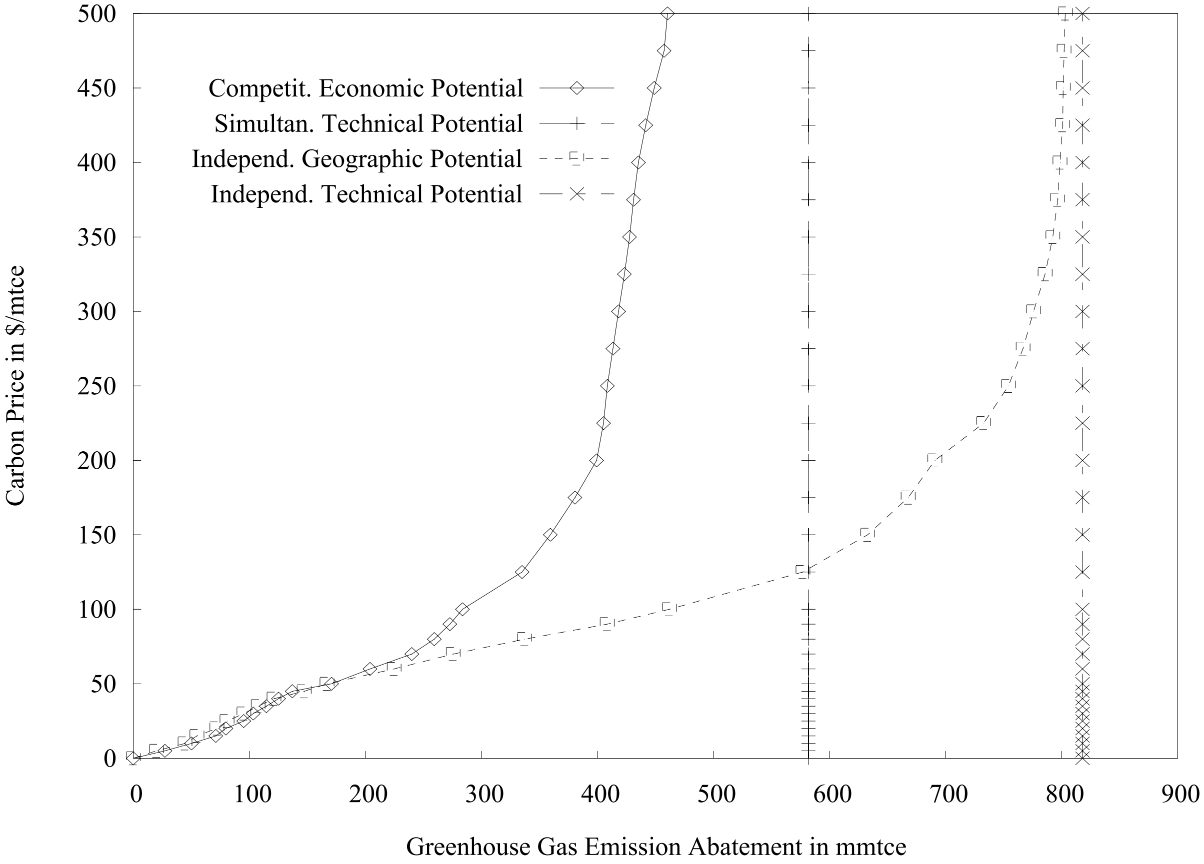

Figure 1 **Economic impacts on potential on greenhouse gas emission mitigation potential from the AF in the US**

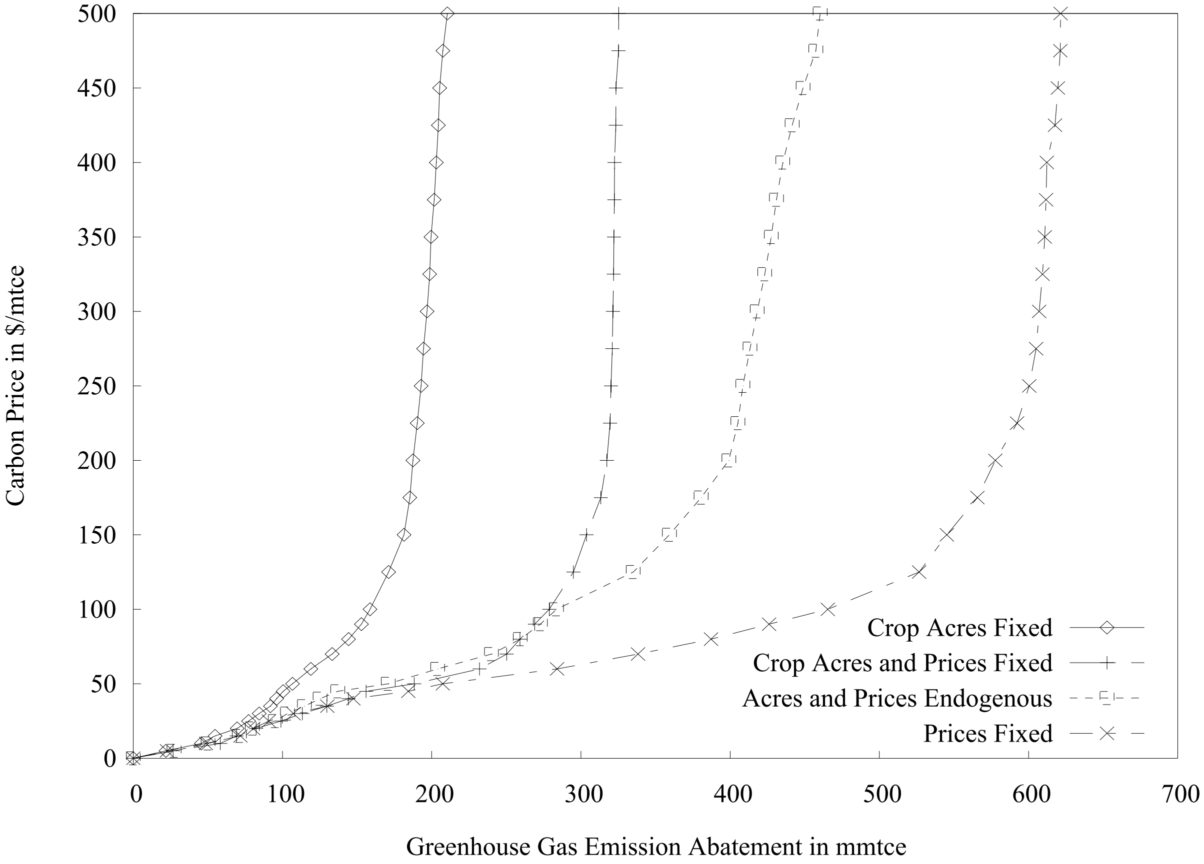

Figure 2 **Market scope impacts on the national economic potential for greenhouse gas emission mitigation in the US through AF.**

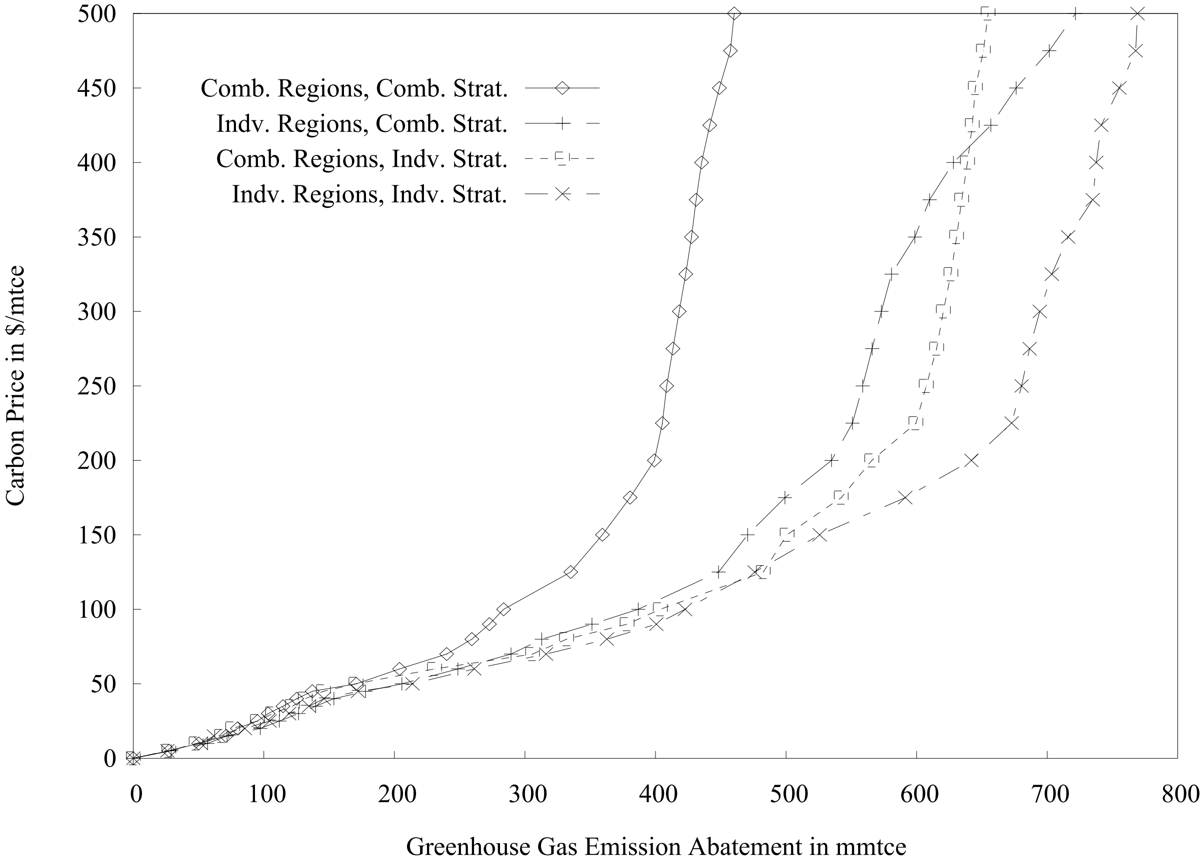

Figure 3 **Impact of different region and strategy scope on greenhouse gas emission mitigation potential from the AF in the US.**

Appendix

Appendix 1 Details on the Mathematical Structure of ASMGHG

This section documents the essential structure of the U.S. agricultural sector and mitigation of greenhouse gas (ASMGHG) model. Here, we focus on the general model structure, which is not affected by data updates or model expansion toward greater detail. Data and a GAMS version of a regionally aggregated ASMGHG version are available on the Internet. The aggregated model can be used to examine and verify the model structure and data and to qualitatively replicate the results presented in this article. In representing ASMGHG's mathematical structure, we will use summation notation because it corresponds very closely to the ASMGHG computer code.

ASMGHG is designed to emulate U.S. agricultural decision-making along with the impacts of agricultural decisions on agricultural markets, the environment, and international trade. To accomplish this objective, ASMGHG portrays the following key components: natural and human resource endowments, agricultural factor (input) markets, primary and processed commodity (output) markets, available agricultural technologies, and agricultural policies. Because of data requirements and computing feasibilities, sector models cannot provide the same level of detail as do farm level or regional models. Therefore, ASMGHG depicts only representative crop and livestock enterprises in 63 aggregated U.S. production regions rather than individual farms characteristics. International markets and trade relationships are portrayed in 28 international regions.

Agricultural technologies in the U.S. are represented through Leontief production functions specifying fixed quantities of multiple inputs and multiple outputs. Producers can choose among several alternative production technologies. Specifically, alternative crop production functions arise from combinations of 3 tillage alternatives (conventional tillage, conservation tillage, and zero tillage), 2 irrigation alternatives (irrigation, dryland), 4 alternative conservation measures (none, contour plowing, strip cropping, terracing), and 3 nitrogen fertilization alternatives (current levels, a 15 percent reduction, and a 30 percent reduction) specific to each U.S. region, land, and crop type[4]. Alternative livestock production functions reflect different production intensities, various manure treatment schemes, alternative diets, and pasture management for 11 animal production categories and 63 U.S. regions. Processing functions identify first or higher level processing opportunities carried out by producers.

ASMGHG is setup as mathematical programming model and contains more than 20,000 individual variables and more than 5,000 individual equations. These equations and variables are not entered individually but as indexed blocks. All agricultural production activities are specified as endogenous variables and denoted here by capital letters. In particular, the variable block CROP denotes crop management variables, LUTR = land use transformation, LIVE = livestock raising, PROC = processing, and INPS = production factor (input) supply variables. Additional variable blocks reflect the dissemination of agricultural products with DOMD = U.S. domestic demand, TRAD = U.S. interregional and international trade, FRXS = foreign region excess supply, FRXD = foreign region excess demand, EMIT = Emissions, and SEQU = Emission reduction or sequestration variables. WELF denotes total agricultural welfare from both U.S. and

---

[4] We use representative crop production budgets for 63 U.S. regions, 20 crops (cotton, corn, soybeans, 4 wheat types, sorghum, rice, barley, oats, silage, hay, sugar cane, sugar beets, potatoes, tomatoes, oranges, grapefruits), 6 land classes (low erodible cropland, medium erodible cropland, highly erodible cropland, other cropland, pasture, and forest)

foreign agricultural markets. With the exception of WELF, all variables are restricted be nonnegative.

ASMGHG consists of an objective function, which maximizes total agricultural welfare (WELF) and a set of constraining equations, which define a convex feasibility region for all variables. Feasible variable levels for all depicted agricultural activities range from zero to an upper bound, which is determined by resource limits, supply and demand balances, trade balances, and crop rotation constraints[5]. Solving ASMGHG involves the task of finding the "optimal" level for all endogenous variables subject to compliance with all constraining equations. By means of ASMGHG's objective function, optimal levels of all endogenous variables are those levels which maximize agricultural sector based welfare, which is computed as the sum of total consumers surplus, producers surplus, and governmental net payments to the agricultural sector minus the total cost of production, transportation, and processing. Basic economic theory demonstrates that maximization of the sum of consumers' plus producers' surplus yields the competitive market equilibrium as reviewed by McCarl and Spreen (1980). Thus, the optimal variable levels can be interpreted as equilibrium levels for agricultural activities under given economic, political, and technological conditions.

To facilitate understanding of the ASMGHG structure, we will start with the description of the set of constraining equations and subsequently explain the objective function. Small letters represent matrix coefficients and right hand side values. Demand and supply functions are denoted in italic small letters. Equations, variables, variable coefficients, and right hand sight variables may have subscripts indicating indices with index c denoting the set of crops, f = production factors with exogenous prices (subset of index w), g = greenhouse gas accounts, h = processing alternatives, i = livestock management alternatives, j = crop management alternatives, k = animal production type, l = land transformation alternatives, m = international region (subset of index r), n = natural or human resource types (subset of index w), r = all regions, s = soil classes (subset of index n), t = years, u = U.S. region (subset of index r), w = all production factors, and y = primary and processed agricultural commodities. A list of individual set elements is available on the Internet or from the authors.

Supply and demand balance equations for agricultural commodities form an important constraint set in ASMGHG, which link agricultural activities to output markets. Specifically, the total amount of commodities disseminated in a U.S. region through domestic consumption (DOMD), processing (PROC), and exports (TRAD[6]) cannot exceed the total amount of commodities supplied through crop production (CROP), livestock raising (LIVE), or imports (TRAD). Equation block (1) shows the set of commodity supply and demand balance equations employed in ASMGHG. Note that equation block (1) is indexed over U.S. regions and commodities. Thus, the total number of individual equations equals the product of 63 U.S. regions times the 54 primary agricultural commodities.

$$\textbf{(1)}\quad \begin{array}{l} -\sum\limits_{c,s,j}\left(a^{CROP}_{u,c,s,j,y}\cdot CROP_{u,c,s,j}\right)-\sum\limits_{k,i}\left(a^{LIVE}_{u,k,i,y}\cdot LIVE_{u,k,i}\right)-\sum\limits_{r}TRAD_{r,u,y} \\ \qquad +DOMD_{u,y}+\sum\limits_{h}\left(a^{PROC}_{u,h,y}\cdot PROC_{u,h}\right)+\sum\limits_{r}TRAD_{u,r,y}\le 0 \end{array}\quad \textbf{for all u and y}$$

---

[5] Crop rotation constraints force the maximum attainable level of an agricultural activity such as wheat production to be equal or below a certain fraction of physically available cropland.

[6] While the first index of the USSH and TRAD variables denotes the exporting region or country, the second denotes the importing region or country.

As shown in equation block (1), agricultural commodities can be supplied in each U.S. region through crop production activities (if cropping activity $\mathrm{CROP}_{u,c,s,j} > 0$ with yield $a^{\mathrm{CROP}}_{u,c,s,j,y} > 0$), livestock production activities (if activity variable $\mathrm{LIVE}_{u,k,i} > 0$ with yield $a^{\mathrm{LIVE}}_{u,k,i,y} > 0$), shipments from other U.S. regions (from U.S. region $\tilde{u}$ to u if $\mathrm{TRAD}_{\tilde{u},u,y} > 0$), or foreign imports (from foreign region m to U.S. region u if $\mathrm{TRAD}_{m,u,y} > 0$). On the demand side, commodities can be used as an input for livestock production (if activity variable $\mathrm{LIVE}_{u,k,i} > 0$ and with usage rate $a^{\mathrm{LIVE}}_{u,k,i,y} < 0$), processed (if activity variable $\mathrm{PROC}_{u,h} > 0$ with usage rate $a^{\mathrm{PROC}}_{u,h,y} < 0$), directly sold in U.S. region u's market (if $\mathrm{DOMD}_{u,y} > 0$), shipped to other U.S. regions (if $\mathrm{TRAD}_{u,\tilde{u},y} > 0$), or exported to foreign markets (if $\mathrm{TRAD}_{u,m,y} > 0$).

The coefficients $a^{\mathrm{CROP}}_{u,c,s,j,y}$, $a^{\mathrm{LIVE}}_{u,k,i,y}$, and $a^{\mathrm{PROC}}_{u,h,y}$ are unrestricted in sign. While negative signs indicate that commodity y is an input for an activity, positive signs indicate outputs. The magnitudes of these coefficients along with their sign identify either input requirements or output yields per unit of activity. The structure of equation block (1) allows for production of multiple products and for multi level processing, where outputs of the first process become inputs to the next process. All activities in (1) can vary on a regional basis.

Supply and demand relationships are also specified for agricultural production factors linking agricultural activities to production factor markets. As shown in equation block (2), total use of production factors by cropping (CROP), livestock (LIVE), land use change (LUTR), and processing (PROC) activities must be matched by total supply of these factors (INPS) in each region.

(2)
$$\begin{aligned}\mathrm{INPS}_{u,w} &- \sum_{c,s,j} a^{\mathrm{CROP}}_{u,c,s,j,w} \cdot \mathrm{CROP}_{u,c,s,j} - \sum_{l} a^{\mathrm{LUTR}}_{u,l,w} \cdot \mathrm{LUTR}_{u,l} \\ &- \sum_{k,i} a^{\mathrm{LIVE}}_{u,k,i,w} \cdot \mathrm{LIVE}_{u,k,i} - \sum_{h} a^{\mathrm{PROC}}_{u,h,w} \cdot \mathrm{PROC}_{u,h} \le 0\end{aligned}$$
for all u and w

The most fundamental physical constraints on agricultural production arise from the use of scarce and immobile resources. Particularly, the use of agricultural land, family labor, irrigation water, and grazing units is limited by given regional endowments of these private or public resources. In ASMGHG, all agricultural activity variables (CROP, LUTR, LIVE, and PROC) have associated with them resource use coefficients ($a^{\mathrm{CROP}}_{u,c,s,j,n}$, $a^{\mathrm{LUTR}}_{u,l,n}$, $a^{\mathrm{LIVE}}_{u,k,i,n}$, $a^{\mathrm{PROC}}_{u,h,n}$), which give the quantity of resources needed for producing one unit of that variable. For example, most crop production activity variables have a land use coefficient equaling 1. However, land use coefficients are greater than 1 for some wheat production strategies, where wheat is preceded by fallow. Land use coefficients were also inflated by set aside requirements when analyzing previous features of the farm bill.

The mathematical representation of natural resource constraints in ASMGHG is straightforward and displayed in equation block (3). These equations simply force the total use of natural or human resources to be at or below given regional resource endowments $b_{u,n}$. Note that the natural and human resource index n is a subset of the production factor index w. Thus, all $\mathrm{INPS}_{u,n}$ resource supplies also fall into constraint set (2). The number of individual equations in (3) is given by the product of 63 U.S. regions times the number of relevant natural resources per region.

(3) $\mathrm{INPS}_{u,n} \le b_{u,n}$ **for all u and n**

In ASMGHG, trade activities ($\mathrm{TRAD}_{u,m,y}$, $\mathrm{TRAD}_{\tilde{m},m,y}$, $\mathrm{TRAD}_{m,u,y}$, $\mathrm{TRAD}_{m,\tilde{m},y}$) by international region of destination or origin are balanced through trade equations as shown in equation blocks (4) and (5). The equations in block (4) force a foreign region's excess demand for an agricultural commodity ($\mathrm{FRXD}_{m,y}$) to not exceed the sum of all import activities into that particular region from other international regions ($\mathrm{TRAD}_{\tilde{m},m,y}$) and from the U.S. ($\mathrm{TRAD}_{u,m,y}$). Similarly, the equations in block (5) force the sum of all commodity exports from a certain international region into other international regions ($\mathrm{TRAD}_{m,\tilde{m},y}$) and the U.S. ($\mathrm{TRAD}_{m,u,y}$) to not exceed the region's excess supply activity ($\mathrm{FRXS}_{m,y}$).

(4) $$-\sum_{u}\mathrm{TRAD}_{m,u,y}-\sum_{\tilde{m}}\mathrm{TRAD}_{m,\tilde{m},y}+\mathrm{FRXD}_{m,y}\leq 0$$ **for all m and y**

(5) $$\sum_{u}\mathrm{TRAD}_{u.m,y}+\sum_{\tilde{m}}\mathrm{TRAD}_{\tilde{m},m,y}-\mathrm{FRXS}_{m,y}\leq 0$$ **for all m and y**

The number of individual equations in blocks (4) and (5) equals the product of the number of traded commodities times the number of international regions per commodity. Because of data limitations only 8 major agricultural commodities are constraint through international trade balance equations. More details can be found in Chen (1999) and in Chen and McCarl (2000).
A fifth set of constraints addresses aggregation related aspects of farmers' decision process. These constraints force producers' cropping activities $\mathrm{CROP}_{u,c,s,j}$ to fall within a convex combination of historically observed choices $h_{u,c,t}$ [equation (6)]. Based on decomposition and economic duality theory (McCarl 1982, Onal and McCarl 1991), it is assumed that observed historical crop mixes represent rational choices subject to weekly farm resource constraints, crop rotation considerations, perceived risk, and a variety of natural conditions. In (6), the $h^{\mathrm{CMIX}}_{u,c,t}$ coefficients contain the observed crop mix levels for the past 30 years. $\mathrm{CMIX}_{u,t}$ are positive, endogenous variables indexed by historical year and region, whose level will be determined during the optimization process.

(6) $$-\sum_{t}\left(h^{\mathrm{CMIX}}_{u,c,t}\cdot\mathrm{CMIX}_{u,t}\right)+\sum_{s,j}\mathrm{CROP}_{u,c,s,j}=0$$ for all u and c

The utilization of (6) has several important implications. First, many diverse constraints faced by agricultural producers are implicitly integrated. Second, crop choice constraints impose an implicit cost for deviating from historical crop rotations. Note that the sum of the CMIX variables over time is not forced to add to unity. Therefore, only relative crop shares are restricted, allowing the total crop acreage to expand or contract. Third, crop choice constraints prevent extreme specialization by adding a substantial number of constraints in each region and mimicking what has occurred in those regions. A common problem to large linear programming (LP) models is that the number of activity variables by far exceeds the number of constraint equations. Because an optimal LP solution will always occur at an extreme point[7] of the convex feasibility region, the number of non-zero activity variables cannot exceed the number of constraints. Fourth, crop choice constraints are a consistent way of representing a large entity of small farms by one aggregate system (Dantzig and Wolfe 1961, Onal and McCarl 1989).

---

[7] Suppose we have a convex set. A point in this set is said to be an extreme point if it can not be represent as a convex combination of any two other points in this set.

Crop mix constraints are not applied to crops, which under certain policy scenarios are expected to expand far beyond the upper bound of historical relative shares. Particularly, if $E\left[\sum_{s,j} \mathrm{LAND}_{u,c,s,j} \Big/ \sum_{c,s,j} \mathrm{LAND}_{u,c,s,j}\right] > \operatorname*{Max}_{t}\left(h^{CMIX}_{u,c,t} \Big/ \sum_{c} h^{CMIX}_{u,c,t}\right)$, then these crops should not be part of the crop mix equations. In ASMGHG, the biofuel crops of switchgrass, poplar and willow fall into this category.

The mix of livestock production is constraint in a similar way as crop production [equation (7)]. Particularly, the amount of regionally produced livestock commodities is constraint to fall in a convex combination of historically observed livestock product mixes ($h^{LMIX}_{u,y,t}$). $\mathrm{LMIX}_{u,t}$ are positive, endogenous variables indexed by historical year and region, whose level will be determined during the optimization process.

(7)
$$-\sum_{t}\left(h^{LMIX}_{u,y,t} \cdot \mathrm{LMIX}_{u,t}\right) + \sum_{k,i}\left(a^{LIVE}_{u,k,i,y} \cdot \mathrm{LIVE}_{u,k,i}\right) = 0 \quad \textbf{for all u and y}$$

Agricultural land owners do not only have a choice between different crops and different crop management strategies, they can also abandon traditional crop production altogether in favor of establishing pasture or forest. Equivalently, some existing pasture or forest owners may decide to convert suitable land fractions into cropland. In ASMGHG, land use conversions are portrayed by a set of endogenous variables LUTR. As shown in (8), certain land conversion can be restricted to a maximum transfer $d_{u,l}$, whose magnitude was determined by GIS data on land suitability. If $d_{u,l} = 0$, then constraint (8) is not enforced. In such a case, land use transformations would only be constraint through constraint set (3).

(8)
$$\mathrm{LUTR}_{u,l} \le d_{u,l}\Big|_{d_{u,l} \ge 0} \quad \textbf{for all u and l}$$

The assessment of environmental impacts from agricultural production as well as political opportunities to mitigate negative impacts is a major application area for ASMGHG. To facilitate this task, ASMGHG includes environmental impact accounting equations as shown in (9) and (10). For each land management ($\mathrm{CROP}_{u,c,s,j}$ and $\mathrm{LUTR}_{u,l}$), livestock ($\mathrm{LIVE}_{u,k,i}$), or processing ($\mathrm{PROC}_{u,h}$) activity, environmental impact coefficients ($a^{LAND}_{u,c,s,j,g}$, $a^{LUTR}_{u,l,g}$, $a^{LIVE}_{u,k,i,g}$, $a^{PROC}_{u,h,g}$) contain the absolute or relative magnitude of those impacts per unit of activity. Negative values of greenhouse gas account coefficients, for example, indicate emission reductions. A detailed description of environmental impact categories and their data sources is available in Schneider (2000).

(9)
$$\begin{aligned} \mathrm{EMIT}_{u,g} = {} & \sum_{c,s,j}\left(a^{CROP}_{u,c,s,j,g} \cdot \mathrm{CROP}_{u,c,s,j}\right)\Big|_{a^{LAND}_{u,c,s,j,g} > 0} \\ & + \sum_{l}\left(a^{LUTR}_{u,l,g} \cdot \mathrm{LUTR}_{u,l}\right)\Big|_{a^{LUTR}_{u,l,g} > 0} \\ & + \sum_{k,i}\left(a^{LIVE}_{u,k,i,g} \cdot \mathrm{LIVE}_{u,k,i}\right)\Big|_{a^{LIVE}_{u,k,i,g} > 0} \\ & + \sum_{h}\left(a^{PROC}_{u,h,g} \cdot \mathrm{PROC}_{u,h}\right)\Big|_{a^{PROC}_{u,h,g} > 0} \end{aligned} \qquad \textbf{for all u and g}$$

(10) $$\begin{aligned}\mathrm{SEQU}_{u,g} = &\sum_{c,s,j}\left(a^{CROP}_{u,c,s,j,g}\cdot \mathrm{CROP}_{u,c,s,j}\right)\Big|_{a^{LAND}_{u,c,s,j,g}<0}\\ &+\sum_{l}\left(a^{LUTR}_{u,l,g}\cdot \mathrm{LUTR}_{u,l}\right)\Big|_{a^{LUTR}_{u,l,g}<0}\\ &+\sum_{k,i}\left(a^{LIVE}_{u,k,i,g}\cdot \mathrm{LIVE}_{u,k,i}\right)\Big|_{a^{LIVE}_{u,k,i,g}<0}\\ &+\sum_{h}\left(a^{PROC}_{u,h,g}\cdot \mathrm{PROC}_{u,h}\right)\Big|_{a^{PROC}_{u,h,g}<0}\end{aligned}$$ **for all u and g**

While the structure of equation blocks (9) and (10) can be used to account for many different environmental impacts, special focus was placed in ASMGHG on greenhouse gases. GHG emissions and emission reductions are accounted for all major sources, sinks and offsets from agricultural activities, for which data were available or could be simulated. Generally, ASMGHG considers:

- Direct carbon emissions from fossil fuel use (diesel, gasoline, natural gas, heating oil, LP gas) in tillage, harvesting, or irrigation water pumping as well as altered soil organic matter (cultivation of forested lands or grasslands),
- Indirect carbon emissions from fertilizer and pesticide manufacturing,
- Carbon savings from increases in soil organic matter (reduced tillage intensity and conversion of arable land to grassland) and from tree planting,
- Carbon offsets from biofuel production (ethanol and power plant feedstock via production of switchgrass, poplar, and willow),
- N2O emissions from fertilizer usage and livestock manure,
- CH4 emissions from enteric fermentation, livestock manure, and rice cultivation,
- CH4 savings from changes in manure and grazing management changes, and
- CH4 and N2O emission changes from biomass power plants.

All equations described so far have defined the convex feasibility region for the set of agricultural activities. Let us now turn to the objective function. The purpose of this single equation is to determine the optimal level of all endogenous variables within the convex feasibility region. Applying the McCarl and Spreen (1980) technique, we use a price-endogenous, welfare based objective function. This equation is shown in (11)[8].

The left hand side of equation (11) contains the unrestricted total agricultural welfare variable (WELF), which is to be maximized. The right hand side of equation (11) contains several major terms, which will be explained in more detail below. The first term $\sum_{u,y}\left[\int_{y} p^{DOMD}_{u,y}\left(\mathrm{DOMD}_{u,y}\right)\mathrm{d}(\cdot)\right]$ adds the sum of the areas underneath the inverse U.S. domestic demand curves over all crops, livestock products, and processed commodities. ASMGHG can employ four types of demand specifications: a) downward sloping demand curves, b) horizontal or totally elastic demand implying constant prices, c) vertical demand implying fixed demand quantities, and d) zero demand. Downward sloping demand curves are specified as constant

---

[8] In displaying the objective function, several modifications have been made to ease readability: a) the integration terms are not shown explicitly, b) farm program terms are omitted, and c) artificial variables for detecting infeasibilities are omitted. A complete representation of the objective function is available on the Internet or from the authors.

elasticity function[9]. To prevent integrals underneath a constant elasticity function and thus consumers' surplus reach infinity, we use truncated demand curves. A truncated demand curves is horizontal between zero and a small quantity ($\mathrm{DOMD}^{\mathrm{TF}}_{\mathrm{u,y}}$) and downward sloping for quantities above $\mathrm{DOMD}^{\mathrm{TF}}_{\mathrm{u,y}}$. In particular, the truncated inverse demand curve for commodity y and region u becomes $p^{DOMD}_{u,y}\left(\mathrm{DOMD}_{\mathrm{u,y}}\right) = \{\, \hat{\mathrm{p}}_{\mathrm{u,y}} \times \left(\frac{\mathrm{DOMD}^{\mathrm{TF}}_{\mathrm{u,y}}}{\mathrm{DOMD}^{\wedge}_{\mathrm{u,y}}}\right)^{1/\varepsilon_{\mathrm{u,y}}}$ for all $\mathrm{DOMD}_{\mathrm{u,y}} < \mathrm{DOMD}^{\mathrm{TF}}_{\mathrm{u,y}}$ and $\hat{\mathrm{p}}_{\mathrm{u,y}} \cdot \left(\frac{\mathrm{DOMD}_{\mathrm{u,y}}}{\mathrm{DOMD}^{\wedge}_{\mathrm{u,y}}}\right)^{1/\varepsilon_{u,y}}$ for all $\mathrm{DOMD}_{\mathrm{u,y}} \geq \mathrm{DOMD}^{\mathrm{TF}}_{\mathrm{u,y}}$ }, where $\hat{\mathrm{p}}_{\mathrm{u,y}}$ and $\mathrm{DOMD}^{\wedge}_{\mathrm{u,y}}$ denote an observed price quantity pair and $\varepsilon_{\mathrm{u,y}}$ denotes the own price elasticities of demand.

(11)

$$
\begin{aligned}
\text{Max WELF} = {} & \sum_{\mathrm{u,y}} \left[\int_{\mathrm{y}} p^{DOMD}_{u,y}\left(\mathrm{DOMD}_{\mathrm{u,y}}\right) \mathrm{d}(\cdot) \right] \\
& - \sum_{\mathrm{u,n}} \left[\int_{\mathrm{n}} p^{INPS}_{u,n}\left(\mathrm{INPS}_{\mathrm{u,n}}\right) \mathrm{d}(\cdot) \right] \\
& + \sum_{\mathrm{m,y}} \left[\int_{\mathrm{y}} p^{FRXD}_{m,y}\left(\mathrm{FRXD}_{\mathrm{m,y}}\right) \mathrm{d}(\cdot) \right] \\
& - \sum_{\mathrm{m,y}} \left[\int_{\mathrm{y}} p^{FRXS}_{m,y}\left(\mathrm{FRXS}_{\mathrm{m,y}}\right) \mathrm{d}(\cdot) \right] \\
& - \sum_{\mathrm{u,f}} \left(\mathrm{p}^{\mathrm{INPS}}_{\mathrm{u,f}} \cdot \mathrm{INPS}_{\mathrm{u,f}} \right) \\
& - \sum_{\mathrm{r,\tilde{r},y}} \left(\mathrm{p}^{\mathrm{TRAD}}_{\mathrm{r,\tilde{r},y}} \cdot \mathrm{TRAD}_{\mathrm{r,\tilde{r},y}} \right)
\end{aligned}
$$

The second right hand side term $-\sum_{\mathrm{u,n}} \left[\int_{\mathrm{n}} p^{INPS}_{u,n}\left(\mathrm{INPS}_{\mathrm{u,n}}\right) \mathrm{d}(\cdot) \right]$ subtracts the areas underneath the endogenously priced input supply curves for hired labor, water, land, and animal grazing units. Supply curves for these inputs are specified as upward sloping constant elasticity functions with $p^{INPS}_{u,y}\left(\mathrm{INPS}_{\mathrm{u,n}}\right) = \hat{\mathrm{p}}^{\mathrm{INPS}}_{\mathrm{u,n}} \times \left(\frac{\mathrm{INPS}_{\mathrm{u,n}}}{\mathrm{INPS}^{\wedge}_{\mathrm{u,n}}}\right)^{1/\varepsilon_{\mathrm{u,n}}}$. Note that the $\mathrm{INPS}_{\mathrm{u,n}}$ supply variables are constraint by physical limits in equation block (3). Thus, when the physical limit is reached, the inverse supply curve becomes effectively vertical.

The following two terms $+\sum_{\mathrm{m,y}} \left[\int_{\mathrm{y}} p^{FRXD}_{m,y}\left(\mathrm{FRXD}_{\mathrm{m,y}}\right) \mathrm{d}(\cdot) \right]$ and $-\sum_{\mathrm{m,y}} \left[\int_{\mathrm{y}} p^{FRXS}_{m,y}\left(\mathrm{FRXS}_{\mathrm{m,y}}\right) \mathrm{d}(\cdot) \right]$ account for the areas underneath the foreign inverse excess demand curves minus the areas

---

[9] The GAMS version of ASMGHG contains a nonlinear and a stepwise linear representation of constant elasticity supply and demand functions both of which can be used.

underneath the foreign inverse excess supply curves. Together these two terms define the total trade based Marshallian consumer plus producer surplus economic of foreign regions.

Finally, the terms $-\sum_{u,f}\left(p^{INPS}_{u,f}\cdot INPS_{u,f}\right)$ and $\sum_{r,\tilde{r},y}\left(p^{TRAD}_{r,\tilde{r},y}\cdot TRAD_{r,\tilde{r},y}\right)$ subtract the costs of exogenously priced production inputs and the costs for domestic and international transportation, respectively.

Appendix 2 Agricultural management alternatives in ASMGHG

Decision parameter	Available options in ASMGHG
Crop choice (index c)	Cotton, Corn, Soybeans, Winter wheat, Durum wheat, Hard red winter wheat, Hard red and other spring wheat, Sorghum, Rice, Barley, Oats, Silage, Hay, Sugar Cane, Sugar Beets, Potatoes, Tomatoes, Oranges, Grapefruit Switchgrass, Willow, Hybrid poplar
Irrigation alternatives[10]	No irrigation Full irrigation
Tillage system alternatives**Error! Bookmark not defined.**	Conventional tillage (<15% plant cover) Reduced tillage (15-30% plant cover) Zero tillage (>30% plant cover)
Fertilization alternatives**Error! Bookmark not defined.**	Observed nitrogen fertilizer rates Nitrogen fertilizer reduction corresponding to 15% stress Nitrogen fertilizer reduction corresponding to 30% stress
Animal production choice	Dairy, cow-calf, feedlot beef cattle, heifer calves, steer calves, heifer yearlings, steer yearlings, feeder pigs, pig finishing, hog farrowing, sheep, turkeys, broilers, egg layers, and horses
Feed mixing choice	1158 specific processes based on 329 general processes differentiated by 10 US regions
Livestock production alternatives	Four different intensities (feedlot beef), two different intensities (hog operations), liquid manure treatment option (dairy and hog operations), BST treatment option (dairy)

---

[10] Irrigation, tillage, and fertilization alternatives are contained in index j

Appendix 3 Spatial Scope of ASMGHG

Region class	Class Elements	Associated ASMGHG Features
Non-US world regions[11]	Canada, East Mexico, West Mexico, Caribbean, Argentina, Brazil, Eastern South America, Western South America, Scandinavia, European Islands, Northern Central Europe, Southwest Europe, France, East Mediterranean, Eastern Europe, Adriatic, former Soviet Union, Red Sea, Persian Gulf, North Africa, West Africa, South Africa, East Africa, Sudan, West Asia, China, Pakistan, India, Bangladesh, Myanmar, Korea, South East Asia, South Korea, Japan, Taiwan, Thailand, Vietnam, Philippines, Indonesia, Australia	Excess demand and supply function parameter for 8 major crop commodities; transportation cost data; Computation of trade equilibrium
US	US	Demand function parameters for crop, livestock, and processed commodities
US macro regions (10)	Northeast, Lake States, Corn belt, Northern Plains, Appalachia, Southeast, Delta States, Southern Plains, Mountain States, Pacific States	Feed mixing and other process data; labor endowment data;
US minor regions (63)	Alabama, Arizona, Arkansas, N-California, S-California, Colorado, Connecticut, Delaware, Florida, Georgia, Idaho, N-Illinois, S-Illinois, N-Indiana, S-Indiana, W-Iowa, Central Iowa, NE-Iowa, S-Iowa, Kansas, Kentucky, Louisiana, Maine, Maryland, Massachusetts, Michigan, Minnesota, Mississippi, Missouri, Montana, Nebraska, Nevada, New Hampshire, New Jersey, New Mexico, New York, North Carolina, North Dakota, NW-Ohio, S-Ohio, NE-Ohio, Oklahoma, Oregon, Pennsylvania, Rhode island, South Carolina, South Dakota, Tennessee, TX-High Plains, TX-Rolling Plains, TX-Central Blackland, TX-East, TX-Edwards Plateau, TX-Coastal Belt, TX-South, TX Transpecos, Utah, Vermont, Virginia, Washington, West Virginia, Wisconsin, Wyoming	Crop and livestock production data and activities, land type and water resource data
Land types (6)	Agricultural Land: Land with wetness limitation, Low erodible land (Erodibility Index (EI) < 8), Medium erodible land (8 < EI < 20), Highly erodible land (EI < 20); Pasture; Forest	Land endowments; Cost, yield, and emission data adjustment

---

[11] The international regional resolution differs across the 8 traded crops. For livestock and processed crop commodities one rest of the world region is used.

Appendix 4 Environmental Accounts in ASMGHG

Account type	Account elements
Greenhouse gas emission accounts affected by energy tax policy (index g)	Carbon emissions from on-farm fossil fuel use for agricultural machinery (fuelc), carbon emissions from irrigation (irrgc), carbon emissions from grain drying (drygc), carbon emissions from fertilizer manufacture (fertc), carbon emissions from pesticide manufacture (pestc), greenhouse gas emission offsets from bioenergy
Greenhouse gas emission accounts not affected by energy tax policy	Soil carbon changes, carbon sequestration from afforestation, methane emission from rice cultivation, nitrous oxide emissions from nitrogen applications, methane emissions from ruminant animals, methane emissions from livestock manure, nitrous oxide emissions from livestock manure, methane emission savings from livestock manure digestion
Other environmental accounts not affected by energy tax policy	Soil erosion through wind and water, nitrogen and phosphorous losses from surface runoff, subsurface flow, percolation, immobilization, and other processes

Research Unit Sustainability and Global Change, Hamburg University and Centre for Marine and Atmospheric Science

Working Papers

Schneider, U.A. and Bruce A. McCarl, (2005), *Appraising Agricultural Greenhouse Gas Mitigation Potentials: Effects of Alternative Assumptions*, **FNU-81**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Zandersen, M., M. Termansen, and F.S. Jensen, (2005), *Valuing new forest sites over time: the case of afforestation and recreation in Denmark,* **FNU-80**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Guillerminet, M.-L. and R.S.J. Tol (2005), *Decision making under catastrophic risk and learning: the case of the possible collapse of the West Antarctic Ice Sheet*, **FNU-79,** Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Nicholls, R.J., R.S.J. Tol and A.T. Vafeidis (2005), *Global estimates of the impact of a collapse of the West Antarctic Ice Sheet: An application of FUND,* **FNU-78,** Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Lonsdale, K., T.E. Downing, R.J. Nicholls, D. Parker, A.T. Vafeidis, R. Dawson and J.W. Hall (2005), *Plausible responses to the threat of rapid sea-level rise for the Thames Estuary,* **FNU-77,** Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Poumadère, M., C. Mays, G. Pfeifle with A.T. Vafeidis (2005), *Worst Case Scenario and Stakeholder Group Decision: A 5-6 Meter Sea Level Rise in the Rhone Delta, France,* **FNU-76,** Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Olsthoorn, A.A., P.E. van der Werff, L.M. Bouwer and D. Huitema (2005), *Neo-Atlantis: Dutch Responses to Five Meter Sea Level Rise,* **FNU-75,** Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Toth, F.L. and E. Hizsnyik (2005), *Managing the inconceivable: Participatory assessments of impacts and responses to extreme climate change*, **FNU-74,** Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Kasperson, R.E. M.T. Bohn and R. Goble (2005), *Assessing the risks of a future rapid large sea level rise: A review,* **FNU-73,** Hamburg University and Centre for Marine and Atmospheric Science, Hamburg.

Schleupner, C. (2005), *Evaluation of coastal squeeze and beach reduction and its consequences for the Caribbean island Martinique,* **FNU-72**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Schleupner, C. (2005), *Spatial Analysis As Tool for Sensitivity Assessment of Sea Level Rise Impacts on Martinique,* **FNU-71**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Sesabo, J.K. and R.S.J. Tol (2005), *Factor affecting Income Strategies among households in Tanzanian Coastal Villages: Implication for Development-Conservation Initiatives,* **FNU-70**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Fisher, B.S., G. Jakeman, H.M. Pant, M. Schwoon. and R.S.J. Tol (2005), *CHIMP: A Simple Population Model for Use in Integrated Assessment of Global Environmental Change*, **FNU-69,** Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Rehdanz, K. and R.S.J. Tol (2005), *A No Cap But Trade Proposal for Greenhouse Gas Emission Reduction Targets for Brazil, China and India*, **FNU-68,** Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Zhou, Y. and R.S.J. Tol (2005), *Water Use in China's Domestic, Industrial and Agricultural Sectors: An Empirical Analysis*, **FNU-67**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Rehdanz, K. (2005), *Determinants of residential space heating demand in Germany*, **FNU-66**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Ronneberger, K., R.S.J. Tol and U.A. Schneider (2005), *KLUM: A simple model of global agricultural land use as a coupling tool of economy and vegetation,* **FNU-65**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Tol, R.S.J. (2005), *The Benefits of Greenhouse Gas Emission Reduction: An Application of* FUND, **FNU-64**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Röckmann, C., M.A. St.John, F.W. Köster, F.W. and R.S.J. Tol (2005), *Testing the implications of a marine reserve on the population dynamics of Eastern Baltic cod under varying environmental conditions,* **FNU-63**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Letsoalo, A., J. Blignaut, T. de Wet, M. de Wit, S. Hess, R.S.J. Tol and J. van Heerden (2005), *Triple Dividends of Water Consumption Charges in South Africa*, **FNU-62**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Zandersen, M., Termansen, M., Jensen, F.S. (2005), *Benefit Transfer over Time of Ecosystem Values: the Case of Forest Recreation,* **FNU-61**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Rehdanz, K., Tol, R.S.J. and Wetzel, P. (2005), *Ocean Carbon Sinks and International Climate Policy*, **FNU-60,** Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Schwoon, M. (2005), *Simulating The Adoption of Fuel Cell Vehicles*, **FNU-59,** Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Bigano, A., J.M. Hamilton and R.S.J. Tol (2005), *The Impact of Climate Change on Domestic and International Tourism: A Simulation Study*, **FNU-58**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Bosello, F., R. Roson and R.S.J. Tol (2004), *Economy-wide estimates of the implications of climate change: Human health*, **FNU-57,** Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Hamilton, J.M. and M.A. Lau (2004), *The role of climate information in tourist destination choice decision-making*, **FNU-56,** Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Bigano, A., J.M. Hamilton and R.S.J. Tol (2004), *The impact of climate on holiday destination choice*, **FNU-55**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Bigano, A., J.M. Hamilton, M. Lau, R.S.J. Tol and Y. Zhou (2004), *A global database of domestic and international tourist numbers at national and subnational level*, **FNU-54**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Susandi, A. and R.S.J. Tol(2004), *Impact of international emission reduction on energy and forestry sector of Indonesia*, **FNU-53**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Hamilton, J.M. and R.S.J. Tol (2004), *The Impact of Climate Change on Tourism and Recreation*, **FNU-52,** Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Schneider, U.A. (2004), *Land Use Decision Modelling with Soil Status Dependent Emission Rates*, **FNU-51,** Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Link, P.M., U.A. Schneider and Tol, R.S.J. (2004), *Economic impacts of changes in fish population dynamics: the role of the fishermen's harvesting strategies*, **FNU-50**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Berritella, M., A. Bigano, R. Roson and R.S.J. Tol (2004), *A General Equilibrium Analysis of Climate Change Impacts on Tourism*, **FNU-49**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Tol, R.S.J. (2004), *The Double Trade-Off between Adaptation and Mitigation for Sea Level Rise: An Application of* FUND, **FNU-48**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Erdil, Erkan and Yetkiner, I. Hakan (2004), *A Panel Data Approach for Income-Health Causality,***FNU-47**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Tol, R.S.J. (2004), *Multi-Gas Emission Reduction for Climate Change Policy: An Application of* FUND, **FNU-46**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Tol, R.S.J. (2004), *Exchange Rates and Climate Change: An Application of* FUND, **FNU-45**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. *download*

Gaitan, B., Tol, R.S.J, and Yetkiner, I. Hakan (2004), *The Hotelling's Rule Revisited in a Dynamic General Equilibrium Model*, **FNU-44**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Rehdanz, K. and Tol, R.S.J (2004), *On Multi-Period Allocation of Tradable Emission Permits*, **FNU-43**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Link, P.M. and Tol, R.S.J. (2004), *Possible Economic Impacts of a Shutdown of the Thermohaline Circulation: An Application of* FUND, **FNU-42**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Zhou, Y. and Tol, R.S.J. (2004), *Evaluating the costs of desalination and water transport*, **FNU-41**, revised, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Lau, M. (2004), *Küstenzonenmanagement in der Volksrepublik China und Anpassungsstrategien an den Meeresspiegelanstieg*, **FNU-40**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Rehdanz, K. and Maddison, D. (2004), *The Amenity Value of Climate to German Households*, **FNU-39 revised**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Bosello, F., Lazzarin, M., Roson, R. and Tol, R.S.J. (2004), *Economy-wide Estimates of the Implications of Climate Change: Sea Level Rise*, **FNU-38**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Schwoon, M. and Tol, R.S.J. (2004), *Optimal* CO_2*-abatement with socio-economic inertia and induced technological change*, **FNU-37**,Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Hamilton, J.M., Maddison, D.J. and Tol, R.S.J. (2004), The Effects of Climate Change on International Tourism, **FNU-36**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Hansen, O. and R.S.J. Tol (2003), *A Refined Inglehart Index of Materialism and Postmaterialism*, **FNU-35**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Heinzow, T. and Tol, R.S.J. (2003), *Prediction of Crop Yields across four Climate Zones in Germany: An Artificial Neural Network Approach,* **FNU-34,** Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Tol, R.S.J. (2003), *Adaptation and Mitigation: Trade-offs in Substance and Methods,* **FNU-33,** Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Tol, R.S.J. (2003), *The Marginal Costs of Carbon Dioxide Emissions*, Department of the Environment, Food and Rural Affairs, London. *download*

Tol, R.S.J. and T. Heinzow (2003), *Estimates of the External and Sustainability Costs of Climate Change*, **FNU-32,** Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Hamilton, J.M., Maddison, D.J. and Tol, R.S.J. (2003), Climate change and international tourism: a simulation study, **FNU-31**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Link, P.M. and R.S.J. Tol (2003), *Economic impacts of changes in population dynamics of fish on the fisheries in the Barents Sea*, Research Unit Sustainability and Global Change **FNU-30**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Tol, R.S.J., T.E. Downing, O.J. Kuik and J.B. Smith (2003), *Distributional Aspects of Climate Change Impacts*, OECD Working Paper ENV/EPOC/GSP(2003)14/FINAL, Organisation for Economic Cooperation and Development, Paris. *download*

Link, P.M. (2003), *Auswirkungen populationsdynamischer Veränderungen in Fischbeständen auf die Fischereiwirtschaft in der Barentssee*, Research Unit Sustainability and Global Change **FNU-29**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Lau, M. (2003), *Integrated Coastal Zone Management in the People's Republic of China – An Assessment of Structural Impacts on Decision-making Processes*, Research Unit Sustainability and Global Change **FNU-28 (revised)**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Lau, M. (2003), *Coastal Zone Management in the People's Republic of China – A Unique Approach?*, Research Unit Sustainability and Global Change **FNU-27**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *China Environment Series,* Issue 6, pp. 120-124; *download*

Roson, R. and R.S.J. Tol (2003), **An Integrated Assessment Model of Economy-Energy-Climate – The Model Wiagem: A Comment*****, Research Unit Sustainability and Global Change*** *FNU-26****, Centre for Marine and Climate Research, Hamburg University, Hamburg.*** **download**

Yetkiner, I.H. (2003), *Is There An Indispensable Role For Government During Recovery From An Earthquake? A Theoretical Elaboration*, Research Unit Sustainability and Global Change **FNU-25**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Yetkiner, I.H. (2003), *A Short Note On The Solution Procedure of Barro And Sala-i-Martin for Restoring Constancy Conditions*, Research Unit Sustainability and Global Change **FNU-24**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Schneider, U.A. and B.A. McCarl (2003), *Measuring Abatement Potentials When Multiple Change is Present: The Case of Greenhouse Gas Mitigation in U.S. Agriculture and Forestry*, Research Unit Sustainability and Global Change **FNU-23**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Zhou, Y. and R.S.J. Tol (2003), *The Implications of Desalination for Water Resources in China: An Economic Perspective,* Research Unit Sustainability and Global Change **FNU-22**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Yetkiner, I.H., de Vaal, A., and van Zon, A. (2003), *The Cyclical Advancement of Drastic Technologies*, Research Unit Sustainability and Global Change **FNU-21**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Rehdanz, K. and Maddison, D. (2003), *Climate and Happiness*, Research Unit Sustainability and Global Change **FNU-20**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Tol, R.S.J., (2003), *The Marginal Costs of Carbon Dioxide Emissions: An Assessment of the Uncertainties*, Research Unit Sustainability and Global Change **FNU-19**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Lee, H.C., B.A. McCarl, U.A. Schneider, and C.C. Chen (2003), *Leakage and Comparative Advantage Implications of Agricultural Participation in Greenhouse Gas Emission Mitigation*, Research Unit Sustainability and Global Change **FNU-18**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Schneider, U.A. and B.A. McCarl (2003), *Implications of a Carbon Based Energy Tax for U.S. Agriculture*, Research Unit Sustainability and Global Change **FNU-17**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Tol, R.S.J. (2002), *Climate, Development and Malaria: An Application of* FUND*,* Research Unit Sustainability and Global Change **FNU-16**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Susandi, A. and R.S.J. Tol (2002), *The Impact of International Climate Policy on Indonesia*', Report No **341**, *Max Planck Institute of Meteorology*, Hamburg.

Hamilton, J.M. (2002), *Climate and the Destination Choice of German Tourists,* Research Unit Sustainability and Global Change **FNU-15 revised** (2003), Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Tol, R.S.J. (2002), *Technology Protocols for Climate Change: An Application of* FUND*,* Research Unit Sustainability and Global Change **FNU-14**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Rehdanz, K (2002), *Hedonic Pricing of Climate Change Impacts to Households in Great Britain*, Research Unit Sustainability and Global Change **FNU-13**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Tol, R.S.J. (2002), *Emission Abatement Versus Development As Strategies To Reduce Vulnerability To Climate Change: An Application Of* FUND, Research Unit Sustainability and Global Change **FNU-12** (revised), Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Rehdanz, K. and Tol, R.S.J. (2002), *On National and International Trade in Greenhouse Gas Emission Permits*, Research Unit Sustainability and Global Change **FNU-11 (revised)**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Fankhauser, S. and Tol, R.S.J. (2001), *On Climate Change and Growth*, Research Unit Sustainability and Global Change **FNU-10 (revised)**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Tol, R.S.J.and Verheyen, R. (2001), *Liability and Compensation for Climate Change Damages – A Legal and Economic Assessment*, Research Unit Sustainability and Global Change **FNU-9**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Yohe, G. and R.S.J. Tol (2001), *Indicators for Social and Economic Coping Capacity – Moving Toward a Working Definition of Adaptive Capacity*, Research Unit Sustainability and Global Change **FNU-8**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Kemfert, C., W. Lise and R.S.J. Tol (2001), *Games of Climate Change with International Trade*, Research Unit Sustainability and Global Change **FNU-7**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Tol, R.S.J., W. Lise, B. Morel and B.C.C. van der Zwaan (2001), *Technology Development and Diffusion and Incentives to Abate Greenhouse Gas Emissions*, Research Unit Sustainability and Global Change **FNU-6**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Kemfert, C. and R.S.J. Tol (2001), *Equity, International Trade and Climate Policy*, Research Unit Sustainability and Global Change **FNU-5**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Lise, W., R.S.J. Tol and B.C.C. van der Zwaan (2001), *Negotiating Climate Change as a Social Situation*, Nota di Lavoro **44.01**, Fondazione Eni Enrico Mattei, Milan. *download*

Tol, R.S.J., Downing T.E., Fankhauser S., Richels R.G. and Smith J.B. (2001), *Progress in Estimating the Marginal Costs of Greenhouse Gas Emissions*, Research Unit Sustainability and Global Change **FNU-4**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Tol, R.S.J. (2000), *How Large is the Uncertainty about Climate Change?*, Research Unit Sustainability and Global Change **FNU-3**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Tol, R.S.J., S. Fankhauser, R.G. Richels and J.B. Smith (2000), *How Much Damage Will Climate Change Do? Recent Estimates*, Research Unit Sustainability and Global Change **FNU-2**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download*

Lise, W. and R.S.J. Tol (2000), *Impact of Climate on Tourism Demand*, Research Unit Sustainability and Global Change **FNU-1**, Centre for Marine and Climate Research, Hamburg University, Hamburg. *download* Revised (2001): Nota di Lavoro **48.01**, Fondazione Eni Enrico Mattei, Milan. *download*

Kemfert, C. and R.S.J. Tol (2000), *The Liberalisation of the German Electricity Market – Modelling and Oligopolistic Structure by a Computational Game Theoretic Modelling Tool,* Oldenburg Working Paper **V-208-00**. *download*

Tol, R.S.J. and T.E. Downing (2000), *The Marginal Costs of Climate Changing Emissions*, Institute for Environmental Studies **D00/08**, Vrije Universiteit, Amsterdam. *download*

Tol, R.S.J., W. Lise and B.C.C. van der Zwaan (2000), *Technology Diffusion and the Stability of Climate Coalitions*, Nota di Lavoro **20.00**, Fondazione Eni Enrico Mattei, Milan. *download*

Tol, R.S.J. (1999), *Equitable Cost-Benefit Analysis of Climate Change*, Nota di Lavoro **41.99**, Fondazione Eni Enrico Mattei, Milan. *download*

Tol, R.S.J., N.M. van der Grijp, A.A. Olsthoorn and P.E. van der Werff (1999), *Adapting to Climate Change: A Case Study on Riverine Floods in the Netherlands*, Institute for Environmental Studies **D99/10**, Vrije Universiteit, Amsterdam. *download*

Darwin, R.F. and R.S.J. Tol (1998), *Estimates of the Economic Impacts of Sea Level Rise*, Institute for Environmental Studies **D98/11**, Vrije Universiteit, Amsterdam. *download*