Extending the GTAP Family of Models: A Partial Equilibrium Approach to Measuring the Costs of Carbon Sequestration and Avoided Deforestation.

*Selected Paper prepared for presentation at the GTAP 2011 Annual Meeting*
*Venice, Italy, June 16-18, 2011*

Sara Bushey Ohrel

US Environmental Protection Agency

ohrel.sara@epa.gov

Suk-Won Choi

Ohio State University

schoi@ucar.edu

Brent Sohngen

Ohio State University

sohngen.1@osu.edu

**Extending the GTAP Family of Models: A Partial Equilibrium Approach to Measuring the Costs of Carbon Sequestration and Avoided Deforestation.**

## INTRODUCTION

The current global forest endowment is estimated to be over 4 billion hectares (9.88 billion acres), 31% of world's total land area, and to hold 289 gigatonnes[1] (Gt) of carbon (1 trillion Gt of carbon dioxide) in biomass alone (UN FAO, 2010). Current estimates suggest that there are around 4.4 gigatons, 4.4 billion tons, of carbon dioxide ($CO_2$) emissions per year from deforestation (Houghton, 2008). The Intergovernmental Panel on Climate Change (IPCC) has found that deforestation accounts for over 17% global $CO_2$ emissions and suggests that land use change, particularly from deforestation, will continue to be the source of carbon emissions for the next century (Nabuurs et al., 2007). However, different modeling efforts generate emissions estimates that can vary widely. For example, the IPCC estimates for carbon emitted from land use and related change throughout this century range from 35 to 89 billion tons across different models simulating the same socio-economic scenario (Nakicenovic et al., 2000). Factors such as the demand for food, technological change, and the demand for other land based resources (e.g., carbon sequestration services or bioenergy) can play a significant role in future emissions estimates.

As the demand for agricultural products increases due to rising incomes, a growing human population, and the diversion of crops to the energy sector, the agricultural sector may continue to demand new land. Much of this land could be derived from forests, though the degree to which such land use change occurs will depend largely on technological advances

[1] 1 gigaton = 1 billion tons (1 ton = 1000 Kg)

within the agriculture sector. To date, a number of models have been developed to examine land use change (e.g. Ianchovichina et al., 2001; Rosegrant et al., 2008; Sohngen & Mendelsohn, 2007), but these models have not addressed forest dynamics or the impacts of an expanding agricultural margin on forest carbon emission levels. Other studies focus solely on the United States (Murray et al., 2005; Lubowski et al., 2006). The study by Sohngen and Mendelsohn (2007) does look globally, but that model considers forestry only and assumes that the agricultural sector is exogenous.

This analysis will add to the literature by utilizing a detailed dynamic optimization model of global forests and agricultural land use to account for dynamics of forest management as well as the economic conditions at the margin between crop, livestock and forest uses to properly account for the tradeoffs between land uses. Through employing the GTAP database, this paper will explore: 1) the role of technology in future land use change and carbon emissions by comparing the effects of different technological change assumptions on carbon sequestered in forests, and 2) the effect of technological change assumptions on the cost and quantity of carbon sequestered.

Specifically, this analysis builds off of a previous study from Choi et al. (2010) that analyzed the sensitivity of global forest carbon emissions to projected changes in total factor productivity (TFP) for crops and livestock production in 16 regions globally with 18 agro-ecological zones (AEZ)(Hertel et al., 2009a). The unique attributes of this modeling approach allow for analysis of dynamic adjustments in forest harvests, investments, and the extent of managed and unmanaged forests, and the related response in sequestered forest carbon as productivity changes in agriculture. Previously, Choi et al. (2010) considered changes in total factor productivity. In this analysis, we consider partial factor productivity (PFP) adjustments, and specifically, we consider the effects of technological change that enhances the productivity of land vis-à-vis other inputs. We also recalibrate the model to 18 regions in this study rather than 16.

For policy analysis, the paper examines the effects of two different land productivity assumptions on land uses. These two scenarios are two separate baselines that embody two alternative assumptions about future growth in crop yields. With these separate baselines, we examine how much carbon can be sequestered in each of these scenarios using a set of exogenous carbon prices. A rising carbon price path was developed from an analysis linking a global forestry analysis of carbon sequestration (Sohngen, 2010) with an integrated assessment model, the DICE model (Nordhaus, 2009). This price path assumes that the marginal damages and marginal costs of abating climate change are equated, where the marginal costs include energy options and forest carbon sequestration costs. It is important to note that including forest carbon sequestration as an opportunity has only a minimal impact on the price of carbon determined by the model. Thus, under scenarios where the marginal damages and marginal costs are equated, carbon prices are exogenous for new opportunities for carbon abatement, such as forestry-based activities. Lastly, we examine the carbon sequestration effects of various constant carbon price paths in comparison with the results of the DICE rising price path.

## MODEL OVERVIEW

In the model, crop and livestock sector data are derived from GTAP version 6 (Dimaranan, 2006). Global land cover and agricultural land-use data defined by regions and AEZs are also obtained from the GTAP data base (Monfreda et al., 2009; Lee et al., 2009). Global forest inventories by region, AEZ, timber types, timber ages and economic parameters in forest sector are obtained from earlier version of the global forestry model (Sohngen et al., 2009).

The model maximizes net present value of global welfare in the forestry, crop, and livestock sectors by choosing outputs, land areas and inputs.[2] The objective function is shown in equation (1) (See Table 1 for variables and parameters):

$$(1)\quad Max\sum^{\infty}\rho^{t}\left\{\begin{array}{l}\int^{QF^*} D_F(Q_F(H_{r,j,k,a};v,m_{r,j,k}))dQ_F(t)+\int^{QCr^*} D_{Cr}(Q_{Cr}(X_{Cr},K_{Cr},L_{Cr}))dQ_{Cr}(t)+\\ \int^{QLv^*} D_{Lv}(Q_{Lv}(X_{Lv},K_{Lv},L_{Lv}))dQ_{Lv}(t)-\sum_{r=1}^{18}\sum_{j=1}^{18}\sum_{k=1}^{6}C_F-\sum_{r=1}^{18}\sum_{j=1}^{18}C_{Cr}-\sum_{r=1}^{18}\sum_{j=1}^{18}C_{Lv}\end{array}\right\}$$

We assume that for each of the three markets – forest, crop, and livestock products – there is a global demand function, represented by the first three terms ($D_F$, $D_{Cr}$, $D_{Lv}$). Such a simple aggregation of global quantities into a single demand function disregards many regional differences in products, trade relations, and transportation costs. However, this assumption significantly simplifies the demand side which allows for more focus on the supply side, including the intertemporal optimization of timber supply. Thus simplified, total global consumption for each product is the sum of regional production, which implies that outputs are perfectly substitutable across regions, and that there is a single global price trend. Estimates of income elasticity used to drive future shifts in the demand function are derived from the AIDADS (An Implicitly Additive Demand System) developed by Rimmer and Powell (1996) and estimated by Yu et al. (2002).[3]

---

[2] The dynamic optimization model is solved by decade for 100 years time period and results are presented only for the first 60 years. The annual discount rate used is 5%, and is held constant over the period. The model is solved using GAMS (General Algebraic Modeling System) program with CONOPT solver algorithm.

[3] For all three outputs demand functions, own price elasticity for forest product is -1.0, for crop -0.3, and for livestock -0.7. The income elasticity for forestry products is 0.88, for crop 0.17, and for livestock 0.62. We assume it rises to 0.92 for forest, falls to 0.08 for crop, and for livestock it rises to 0.72 over time. Income per capita is assumed to rise at 2.7% per year.

The last three terms in equation (1) are the sum of all costs for each sector (crop and livestock costs include labor and capital inputs and land, and forestry costs include harvesting and regenerating forests and renting land). The world is divided into 18 regions (index r), whereas Choi et al. (2010) used 16 regions. There are up to 18 AEZs (index j) in each region to account for crop and livestock productivity differences (Hertel et al., 2009), and up to six different timber types in each AEZ (index k) to account for productivity and carbon differences across timber types (Sohngen et al., 2009).

Production in the forest sector is based on the dynamic optimization approach in Sedjo and Lyon (1990), Sohngen et al. (1999), and Sohngen and Mendelsohn (2003; 2007). A separate timber yield function is defined for each region and timber type. Management intensity influences the yield of timber. Forest sector costs are the sum of harvest costs, management costs in regeneration for each timber types, and rental costs on the area of land in each timber type. The global quantity of forestry outputs are calculated as the sum of regional timber harvest (H) multiplied by yield of trees (*V*), timber yield being a function of timber age (*a*), management input of timber (*m*). The model therefore optimizes the age of timber harvested, and the inputs used to manage timber over the production cycle (10 to ≥110 year timber rotations). Equation (2) shows the total timber harvested each period:

(2) $$Q_F = \sum_{r=1}^{18}\sum_{j=1}^{18}\sum_{k=1}^{6}\sum_{a}^{a^*}\left(H_{r,j,k,a}\right)V_{r,j,k,a}(m_{r,j,k})$$

Production functions for crop and livestock sectors are adapted from the GTAP model (Hertel, 1997), with modified production structures that include explicit heterogeneous land endowments (Hertel et al., 2009). Production in the crop and livestock sectors is modeled with nested Constant Elasticity of Substitution (CES) production functions that aggregate the 18 AEZ-specific inputs. The nest structure includes production inputs such as capital, labor, and aggregated land inputs.[4] For the livestock sector, one additional nest is included whereby land is modeled as an input combined by feed and land CES function. The feed and land input is then used in the upper level nest where the final ruminant livestock output is calculated (equation 3):

(3) $$Q^S = \sum_{r=1}^{18} A_r^S \left( \sum_{i=K,L,Land} \delta_{S,i,r}^{\frac{1}{\sigma}} X_{S,i,r}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}$$ S= index for crop or livestock sector

The parameter $\delta_i$ is share for each input (capital, labor, and land) in each region. The input shares $\delta_i$s sum to 1 in each region. The term σ is the elasticity of substitution parameter for the inputs into the production function (see Table 1 for elasticity values).

For the initial base case (referred to in the paper as "Base"), we assume a set of technical parameters (parameter A in equation 3) that lead to yield growth of 1.5% per year over 50 years for crops. In the alternative case (referred to in the paper as "Case 2"), the land input in the crop sector is augmented, i.e. increased, such that the resulting yield growth is 2.1% per year for 50 years. This second scenario assumes a larger improvement in crop output per hectare over the next 50 years than obtained by Ludena et al. (2007) over the past 40 years. The cost of crop and livestock sector is the sum of input costs for capital, labor, and land rents. Capital and labor are region specific inputs. We hold the prices of these inputs constant across the scenario. Land rent is determined regionally at the level of the AEZs. It is endogenously determined in the model based on the equilibrium between the derived demand for land and the supply of land in each AEZ.

The supply of land is modeled with a Constant Elasticity of Transformation (CET) function to constrain the movement of land across uses within AEZs. The CET structure allows for derivation of land supply functions for each potential land use (one livestock, one crop, and

[4] To simplify production modeling across AEZs and thus derived demand for land, this approach assumes that outputs produced in each AEZ are homogeneous and that nonland input-output intensities and factor prices are the same across AEZs (see Golub et al., 2009 for more discussion on this approach).

up to six forest types), a function of own rent, other rents, and a land endowment. In each AEZ, land endowment is given expressed as composite of all land uses in each AEZ by CET function, as discussed extensively in Choi et al. (2010) including constraints and equations, the end result of which is shown here (equation 4):

$$(4) \qquad XL_{j,t}^{Lv} = \frac{XE_j \left( \alpha_{Lv,j}^{\tau} \middle/ R_{Lv,j,t}^{\tau} \right)}{\left[ \alpha_{Cr,j}^{\tau} R_{Cr,j,t}^{1-\tau} + \alpha_{Lv,j}^{\tau} R_{Lv,j,t}^{1-\tau} + \sum_{k=1}^{6} \alpha_{F,j,k}^{\tau} R_{F,j,k,t}^{1-\tau} \right]^{\left(\frac{\tau}{\tau-1}\right)}}$$

The parameter $\alpha_{Cr}$ , $\alpha_{Lv}$, and $\alpha_F$ is AEZ specific land shares for supply in crop, livestock, and forestry, sums to 1 in each AEZ. The variables $R_{Cr}$, $R_{Lv}$, and $R_F$ represent land rental for crop, livestock, and forestry. The expansion of land endowment comes from deforestation of unmanaged inaccessible forest area and it affects the land supply decision. One of important feature of this study is linked to land endowment in equation (4-c). Land endowment, represented in equation (4) as $XE_j$, is expressed as the composite of all land uses in each AEZ by the CET function (See Choi et. al, 2010). For this study the land endowment for the Boreal and Temperate regions are fixed but is allowed to expand in Tropical regions (Brazil, Central America, Rest of South America, Sub Saharan Africa, Southeast Asia, and African Middle East). This land endowment expansion typically occurs due to deforestation of unmanaged inaccessible forest area and related effects on land supply decisions.

The land supply function is based on CET function, and thus does not calculate physical hectares directly beyond the first year. For this analysis, to account for physical hectares, we assume that a 10% change in cropland in the CET function requires a 15% change in physical hectares. This is based on the assumption that additional land for crop has lower productivity than currently used land in crop production and is applied all the regions and AEZs (equation 5):

(5) $$d \ln H_{Crop}^{Physical} = (1/0.66) d \ln H_{Crop}^{CET}$$

For this analysis, we do not compute the full model as described above, but we instead compute the model in two stages. First, we solve the agricultural components of the model holding the forestry rents fixed at their baseline level. Thus, in equation (1) we solve just the crop and livestock components of the model. This provides a projection of rents for crop and livestock land given the underlying technology coefficients for the two sectors. Rents will rise or fall depending on demand for the sector's products, and technology change. Second, we solve the dynamic forestry model using these inputs from the crop and livestock sectors. The crop and livestock sector rents will change over time depending on the results of the initial scenario, but they are not endogenous in this dynamic forestry model. We then conduct the carbon sequestration analysis will these results, holding crop and livestock rents fixed at this initial level.

For the carbon analysis, we utilize the carbon price path determined to represent the "optimal" carbon abatement policy, defined in Nordhaus (2009), that would yield a global temperature change of about 2.3º Celsius (in comparison to a 3.05º Celsius change in the 'no controls' scenario used in Sohngen 2010). This optimal scenario was then adapted in Sohngen (2010) through linking a global forestry analysis of carbon sequestration with the DICE model (Nordhaus, 2009). The original optimal policy scenario from Nordhaus (2009) was adjusted to account for land-based sequestration and as such sequestration magnitudes are rather large, the models iterated until the prices and quantities of sequestration in the two models matched (for methods used, see Sohngen and Mendelsohn, 2003).

The carbon sequestration price path from the combined forestry and DICE model for the optimal scenario forestry would start in 2010 at $7.23, resulting in 5,727 tons $CO_2$ sequestered a year (t $CO_2$/year) increasing to a price of $25 in 2060 and 4,679 t $CO_2$/year, reaching almost $50 in 2100 with resulting sequestration of approximately 5, 078 t $CO_2$/year (Sohngen 2010 price path, corresponding temperatures and sequestration rates can be found in Table 3). That study concluded that forest could efficiently accomplish 30% of the total abatement needed over the century (e.g., from 2010 to 2110) to realize a 2.3º Celsius change in global temperatures. In order to account for carbon in the model, the objective function in (1) above is modified to include rental on carbon stocks in forests, and payments for carbon storage in harvested wood products. Carbon rents are calculated from the carbon price path described above.

**RESULTS**

For the results, we first present the base scenarios for the crop and livestock sectors. We then present the implications of these results for the forestry sector, and finally show how these alternative baselines influence carbon sequestration. In the Base case, average crop yields rise by 1.5% per year between 2010 and 2060. As a result, the model projects that both crop and livestock prices fall over time, with the most significant decrease occurring in crop prices (Figure 1). Global output for crops and livestock products increase, but most substantially in the livestock sector. The large increase in output in the livestock sector results from our assumed high income elasticity for livestock goods, and consistent improvements in agricultural productivity, which lowers the average cost of production. Although not shown graphically, the largest increases in output occur in China, followed by the tropics, especially Central and South America. The highest growth in crop output occurs in the ROW[5] countries followed by Brazil and the EU.

[5] ROW includes EU Annex 1, EU non-Annex 1, South Asia, Oceania, Japan, East Asia, India

Under the Base case technology assumptions, there is significant land use change by 2060 (Figure 2). The increase in crop yields globally allows less land to be used for crops, and total global land devoted to crops falls by 13% by 2060, while land dedicated to livestock production increases by 20%. It is perhaps surprising to see the area of land in livestock expand so dramatically, but this results from the strong increases in demand for livestock products and continued downward trend in land rents due to rising productivity. The largest cropland losses are in the temperate zone, with significant decreases in Asia and South America (excluding Brazil). Cropland area, however, increases in some regions where deforestation can occur to increase overall land in production, such as Brazil and other areas of ROW. Pasture land increases in most regions, except some ROW countries (Japan, India and EU/non-EU Europe) and Sub-Saharan Africa. It declines in Sub-Saharan Africa because we assume that technology for livestock falls initially in that region. In the Base case, forest area decreases over time, with a loss of approximately 450 million hectares of forestland by 2060 (Table 4). These losses occur both in the temperate regions as well as the tropics.

In the alternative baseline scenario with higher crop yields, Case 2, global average crop yields increase 2.1% per year. As a result of the increased crop yields, prices fall relative to the original Base case (Figure 1), and output in the crop and livestock sectors increases. In Case 2, 15% more land is devoted to livestock by 2060, and crop land decreases by around 40%, as less land is needed to produce more output (Figure 2). Given the large losses in cropland, approximately 50 million additional hectares are devoted to forestry by 2060. Some of this additional land results from reductions in deforestation in tropical regions, but about 20% of it occurs in the temperate zone (Table 4).

In the forestry sector, prices rise 0.7% per year over the period 2010-2060 in the Base case. As expected, with higher crop yields (Case 2), more land is devoted to forestry, forestry outputs increase, and forest prices fall (by about 3% in 2060). In the Base case, total forest area declines 438 million hectares by 2060, with around 266 million hectares of this loss occurring in the tropics (Table 4). For Case 2, total forest area falls by 400 million hectares by 2060, with a loss of about 250 million in the tropics. For both of these scenarios, the forestland losses result in an additional carbon emission, amounting to 80 billion t $CO_2$ by 2060 for the Base case, and 47 billion tons $CO_2$ for Case 2.

From 2010-2060, the amount of tropical forested land that was once inaccessible but is accessed and used for crops, livestock or forest management increases by 191 million hectares. In the tropical region, total forest carbon stocks decline from about 393 billion ton $CO_2$ in 2010 to 345 billion ton $CO_2$ in 2060. Brazil loses about 14% of its forested land in the base case, releasing 11.4 billion tons of $CO_2$ by 2060. Central America loses 29% its forested land and releasing 6.2 billion tons $CO_2$. However, it is important to note the relative differences: Brazil only loses 7% of its aboveground carbon whereas Central America loses 56%. Case 2 with higher crop yields results in a smaller loss of forestland over the next century, and a smaller carbon emission (Tables 4 and 5).

The DICE carbon prices described above are applied to these two baseline scenarios, the initial Base case and Case 2. Carbon prices increase total cumulative forest area by 806 million hectares by 2060 in the Base case, essentially stopping net deforestation in the tropics (Table 4). Carbon prices increase total forest area 715 million hectares by 2060 in Case 2 (Table 4). With higher crop yields, carbon prices have a smaller total effect on forest area. The difference is concentrated in the tropics, where under the Base case there are 584 million additional hectares in forests and in Case 2 there are 517 million additional hectares.

As a result of these changes, less carbon is sequestered with carbon prices in Case 2 than the Base case (Figure 3). Most of this reduction in sequestered carbon occurs in the tropics (Table 5), and in particular in Central and South America and Tropical Asia. The baseline scenario with higher crop yields (Case 2) but no carbon prices leads to less land in crops, and more land in livestock and forests. These higher crop yields, however, by reducing the amount of deforestation that would occur in tropical regions in the baseline, increase the costs of carbon sequestration (Table 5). This result varies across regions. In the temperate zone, increased crop yields lower the costs of carbon sequestration (i.e., the total carbon sequestered for any given price is greater), while in the tropics, higher crop yields tend to raise carbon sequestration costs. While higher crop yields free up land for forestry, they also reduce the amount of deforestation that occurs in the baseline. Avoided deforestation is generally considered a relatively low cost option for sequestering carbon, but when higher agricultural technology yields added to the scenario, options to reduce deforestation in the tropics are scarcer, even with carbon payment incentives.

To illustrate the differences between the results for avoided deforestation in the tropics versus other regions, we present marginal cost curves based on a series of constant carbon price scenarios. Rather than using the carbon prices from the DICE model as noted above, we assume that carbon prices are constant and we consider the amount of carbon sequestered over a series of constant carbon prices (from \$13.62 per t $CO_2$ to 218 per t $CO_2$). Marginal cost functions for avoided deforestation in the tropics and for temperate regions are shown in Figure 4. Here we see that marginal costs of carbon sequestration are lower in the Base case for both regions, but they are substantially lower in the Base case for the tropics.

## CONCLUSION

This paper presents the results of an analysis that examines the role of technological change in the agricultural sector on the costs of carbon sequestration. There is quite a bit of debate globally about future trends in the productivity of the world's crops. We use a new global model of forests and agricultural land to assess how different assumptions about crop yield growth will affect the costs of carbon sequestration. Our model utilizes a dynamic optimization approach for the forestry sector and thus models the dynamic decision to sequester carbon in forests. For this analysis, we model different rents for crop and livestock sectors depending on assumptions about crop yields, but then we assume that the resulting crop and livestock land rents are fixed vis-à-vis the forest sector. We present two different baseline cases representing alternative assumptions about future growth in crop yields. We then introduce carbon sequestration prices on these two baseline cases and compare them.

As expected technology change in the crop sector has important implications for land use. Higher crop yields reduce the demand for cropland in the future, but increase the amount of land devoted to livestock and forests. Crop and livestock prices both decline with higher crop yields, as do forest prices. We calculate that under our base assumption about technology change, around 438 million hectares would be lost cumulatively from forests by 2060, with about 60% of this loss in tropical regions. Losses are smaller, around 400 million hectares, in our Case 2, which assumes higher yield growth for crops. As a result of these losses in forestland, nearly 80 billion tons $CO_2$ are emitted to the atmosphere by 2060 in our Base Case. The emission falls to 47 billion tons $CO_2$ by 2060 in Case 2 when crop yields are greater.

Overall, higher crop yields increase the costs of carbon sequestration globally. This increase results mainly from higher costs of avoiding deforestation in the tropics. In the temperate zone, the costs of carbon sequestration are fairly close in both the Base case and Case 2. Improved technology change has important implications for the baseline, namely higher technology change reduces the need to deforest land in the tropics so it leaves more land untouched in that region in the base case. This reduces the opportunity for low cost carbon abatement through avoiding deforestation and hence raises global costs of carbon sequestration. Globally, however, increasing technology change in the model has a relatively small impact on the costs of carbon sequestration.

As expected, technology change has potentially important implications both for estimates of the baseline quantity of carbon emissions from deforestation, and for estimates of the costs of costs of carbon sequestration. The largest differences in carbon sequestration costs occur in the tropics, where technology change in the crop sector is expected to alter the amount of land that would be deforested for crop production. Improved crop productivity reduces deforestation by reducing the need for new land in crop production, and it reduce carbon emissions from deforestation but it also eliminates these low cost option for carbon mitigation. Thus, improved technology shifts the marginal cost function upwards.

There are several limitations in this study that are important to recognize. First, we have not made the agricultural and forestry sectors fully endogenous. We are using projections of crop and livestock rents from an agricultural model as exogenous inputs into our dynamic forestry model. Future efforts will make these fully endogenous. Second, we have included a feed component in the livestock sector, such that crop outputs are an input into livestock production, but given the large increases in land in livestock production we observe, it is possible that we have under-estimated the substitutability between feed and land. We will address this in the future by disaggregating the livestock sector into ruminants and non-ruminants, and then assess the implications of the feed and land substitution parameter on the ruminant sector. Third, we have not accounted for the effects of carbon pricing in the crop and livestock sectors. Given that these sectors account for a reasonably large proportion of total global carbon emissions, it will be important to include the effects of the carbon policy in those sectors endogenously.

**Table 1. Variables and Parameters for the Global Land Use Model**

| Notation | Definition |
|---|---|
| $D_{F}, D_{Cr,}, D_{Lv}$ | Demand function for forestry, crop, and livestock sector |
| $Q_{F}, Q_{Cr,}, Q_{Lv}$ | Production function for forestry, crop, and livestock products |
| $X_{Cr,}, X_{Lv}$ | Composite land inputs for crop and livestock |
| $X^{F}, XL_{Cr,}, XL_{Lv}$ | Total land area in forestry, crop, and livestock sector (million ha) |
| $C_{F}, C_{Cr,}, C_{Lv}$ | Cost function for crop and livestock |
| $K_{Cr}, K_{Lv}$ | Capital inputs for crop and livestock |
| $L_{Cr}, L_{Lv}$ | Labor inputs for crop and livestock |
| $r,j,k$ | Index for region (r=1-16), AEZ (j=1-18), and timber type (k=1-6) |
| $i$ | Index for inputs capital, labor, and land |
| $I(t)$ | Global income (GDP) |
| $N(t)$ | Global population |
| $\mu$ (t) | Global income elasticity |
| $\eta$ | Global price elasticity |
| $V$ | Timber yield function |
| $m$ | Timber management intensity input |
| $H$ | Timber harvest area |
| $G$ | Timber replant area |
| $A^{Cr}, A^{Lv}$ | Total production technology factor for crop and livestock |
| $\delta_{i=land,capital,labor}$ | Shares of land, capital, and labor for production function |
| $\sigma$ | Elasticity of production function (0.2391) |
| $\alpha_{F}, \alpha_{Cr}, \alpha_{Lv}$ | Shares of land for timber types, cropland, and livestock |
| $P_{i=K,L,Land}$ | Input price for capital, labor, and land composite in crop and livestock |
| $R_{F}, R_{Cr}, R_{Lv}$ | Land rentals for forestry, crop, and livestock in each AEZ |
| $\gamma$ | Land shares for crop and livestock land composite in each AEZ |
| XE | Land endowment as composite of all land uses by CET function |
| $\tau$ | Elasticity in CET function for land supply (-0.9) |
| $\beta$ | Elasticity in CET function for composite land inputs to production (20) |
| XUL | Composite livestock land |
| F | Feed amount from crop to livestock |
| $\phi$ | Share for the crop into composite with feed into livestock |
| $\omega$ | CET parameter for livestock land and feed (0.5) |
| $\rho$ | Discount rate (0.05) |
| RC | Carbon rental payment |
| CB | Carbon stock |

**Table 2. Annual Total Factor Productivity (TFP) Growth Values**

| Region | Crop | Livestock |
|---|---|---|
| US | 1.14 | 0.41 |
| CHINA | 1.45 | 3.10 |
| BRAZIL | 0.62 | 2.60 |
| CANADA | 1.14 | 0.41 |
| RUSSIA | 1.39 | 1.16 |
| EU ANNEX I | 1.14 | 0.41 |
| EU NON ANNEX I | 1.39 | 1.16 |
| SOUTH ASIA | 0.96 | 2.10 |
| CENTRAL AMERICA | 0.62 | 2.60 |
| REST OF SOUTH AMERICA | 0.62 | 2.60 |
| SUB SAHARAN AFRICA | 0.91 | 0.35 |
| SOUTH EAST ASIA | -0.66 | 2.70 |
| OCEANIA | 1.14 | 0.41 |
| JAPAN | 1.14 | 0.41 |
| AFRICA MIDDLE EAST | 0.45 | -0.30 |
| EAST ASIA | -0.66 | 2.70 |

Source: Ludena et al., 2007

**Table 3. Carbon sequestration pathways for combined forestry and DICE model for the optimal scenario and a maximum 2ºC temperature change.**

| | Optimal Scenario | | |
|---|---|---|---|
| | Sequestration t $CO_2$/yr | \$/t $CO_2$ | Δ°C |
| 2010 | 5,727 | $7.23 | 0.83 |
| 2020 | 5,552 | $11.07 | 1.02 |
| 2030 | 6,076 | $14.09 | 1.21 |
| 2040 | 5,998 | $17.54 | 1.39 |
| 2050 | 6,114 | $21.45 | 1.56 |
| 2060 | 4,679 | $25.87 | 1.74 |
| 2070 | 3,951 | $30.85 | 1.91 |
| 2080 | 3,658 | $36.43 | 2.08 |
| 2090 | 4,762 | $42.69 | 2.24 |
| 2100 | 5,078 | $49.68 | 2.39 |

**Table 4: Change in forest area between 2010 and 2060.**

| | Base Case (1.5% crop yield increase) | | | Case 2 (2.1% crop yield increase) | | |
|---|---|---|---|---|---|---|
| | Base | DICE Carbon Price | Gain | Base | DICE Carbon Price | Gain |
| Temperate | | | million ha | | | |
| North America | 0.0 | 64.9 | 64.9 | 10.0 | 64.9 | 55.0 |
| Europe | -71.7 | 62.3 | 134.0 | -73.0 | 43.1 | 116.0 |
| Temperate Asia | -100.7 | -77.3 | 23.4 | -87.2 | -60.3 | 26.9 |
| **Temperate Total** | -172.3 | 49.9 | 222.3 | -150.3 | 47.7 | 198.0 |
| Tropical | | | | | | |
| Central&South America | -161.7 | -42.4 | 119.4 | -146.5 | -37.7 | 108.8 |
| Africa | -32.8 | 81.9 | 114.6 | -13.2 | 78.1 | 91.3 |
| India | -30.8 | 215.3 | 246.1 | -42.6 | 190.8 | 233.4 |
| Tropical Asia | -40.4 | 63.6 | 104.0 | -47.0 | 36.3 | 83.4 |
| **Tropical Total** | -265.7 | 318.4 | 584.2 | -249.3 | 267.5 | 516.8 |
| **TOTAL** | -438.0 | 368.4 | 806.4 | -399.5 | 315.2 | 714.7 |

**Table 5: Change in forest carbon between 2010 and 2060.**

| | Base Case (1.5% crop yield increase) | | | Case 2 (2.1% crop yield increase) | | |
|---|---|---|---|---|---|---|
| | Base | DICE Carbon Price | Gain | Base | DICE Carbon Price | Gain |
| Temperate | Billion tons CO2 | | | | | |
| North America | 4.5 | 17.3 | 12.8 | 6.3 | 19.4 | 13.1 |
| Europe | 15.5 | 31.6 | 16.1 | 18.4 | 35.9 | 17.5 |
| Temperate Asia | -7.1 | -0.2 | 6.8 | -4.0 | 3.5 | 7.5 |
| **Temperate Total** | 13.0 | 48.7 | 35.7 | 20.7 | 58.8 | 38.1 |
| Tropical | | | | | | |
| Central&South America | -70.9 | -45.1 | 25.8 | -60.0 | -42.2 | 17.8 |
| Africa | -10.3 | 7.4 | 17.8 | 5.9 | 23.9 | 18.0 |
| India | -1.1 | 40.0 | 41.0 | -5.3 | 36.7 | 42.0 |
| Tropical Asia | -10.1 | 4.0 | 14.1 | -8.0 | -0.6 | 7.4 |
| **Tropical Total** | -92.5 | 6.3 | 98.7 | -67.4 | 17.8 | 85.1 |
| **TOTAL** | -79.5 | 55.0 | 134.5 | -46.7 | 76.6 | 123.3 |

**Figure 1: Baseline crop and livestock prices indices, indexed to 2010 = 100.**

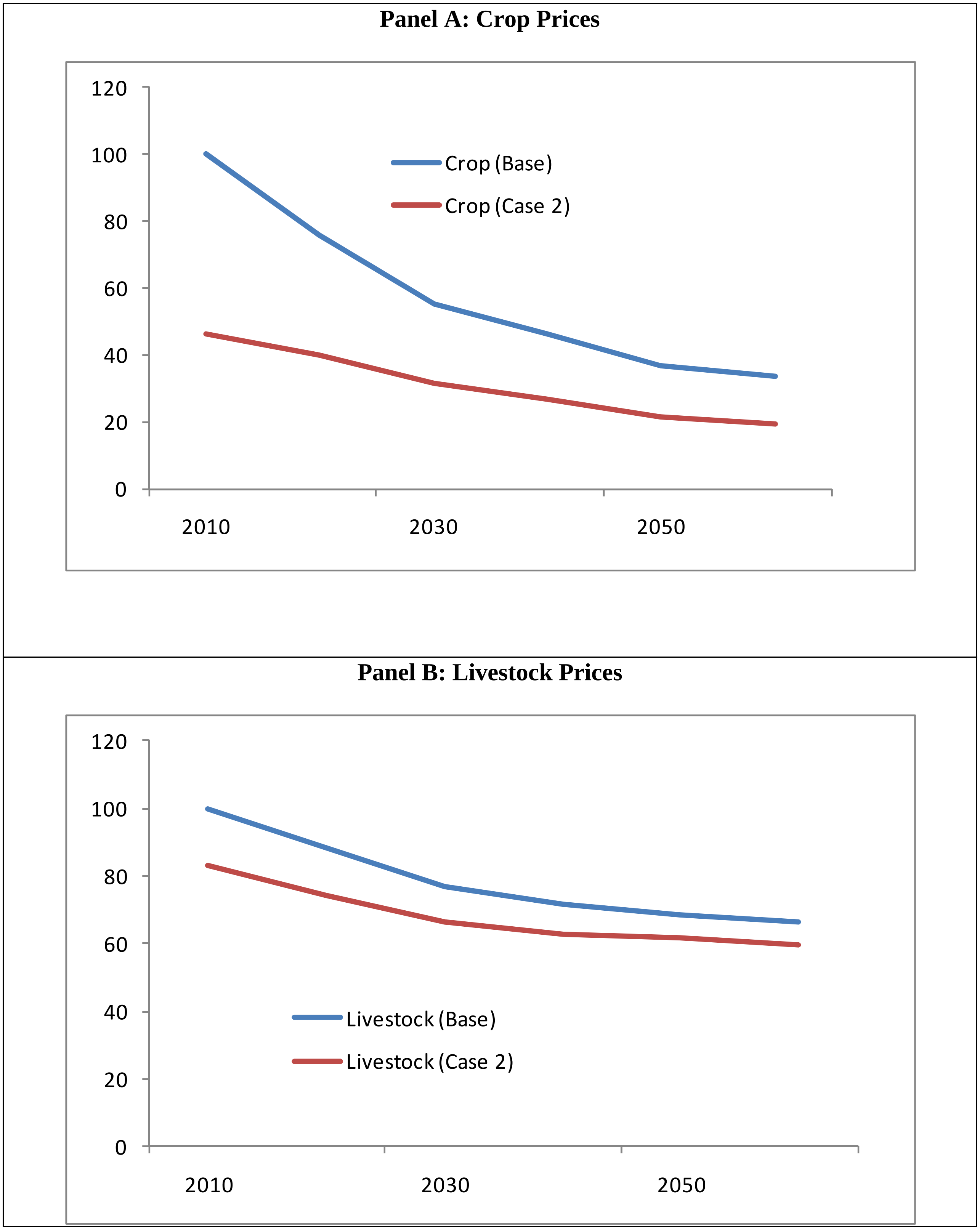


**Figure 2: Historical crop and pastureland areas and projected areas under alternative crop yield change assumptions. Historical data based on UN FAO estimates.**

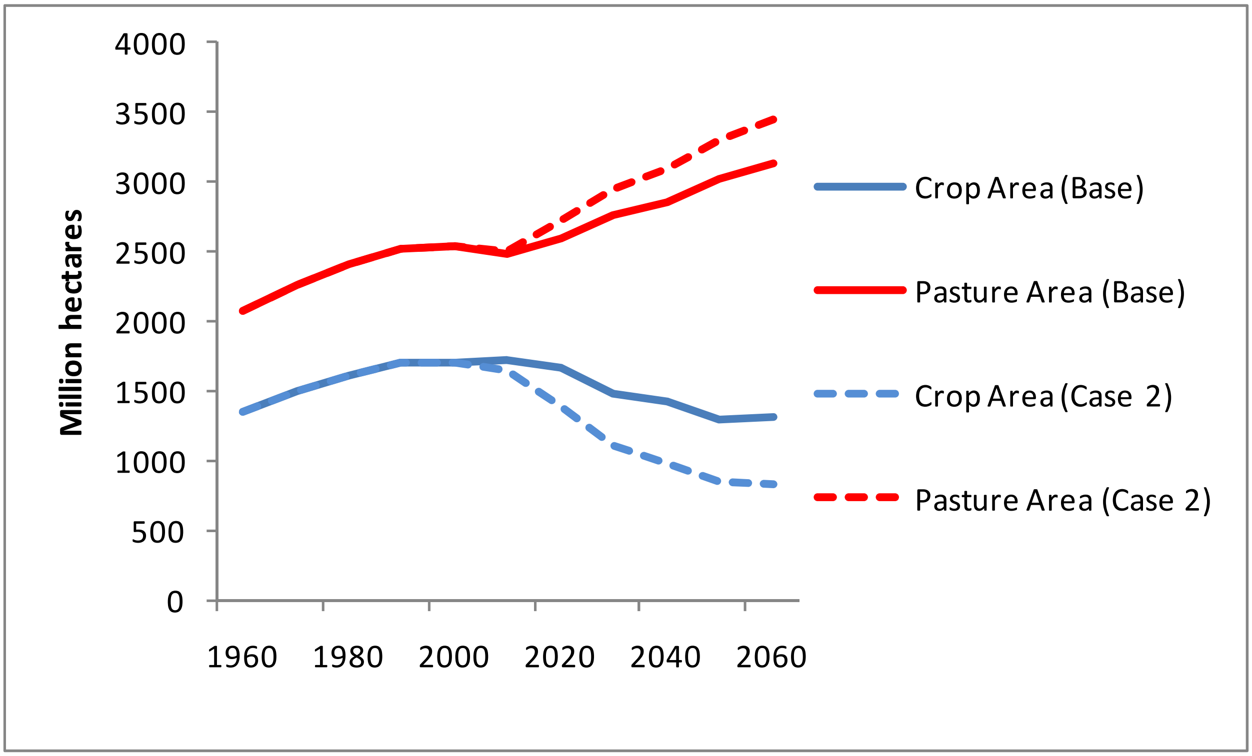


**Figure 3: Cumulative change in carbon sequestered in forests between carbon price scenario (using DICE prices) and each respective baseline scenario.**

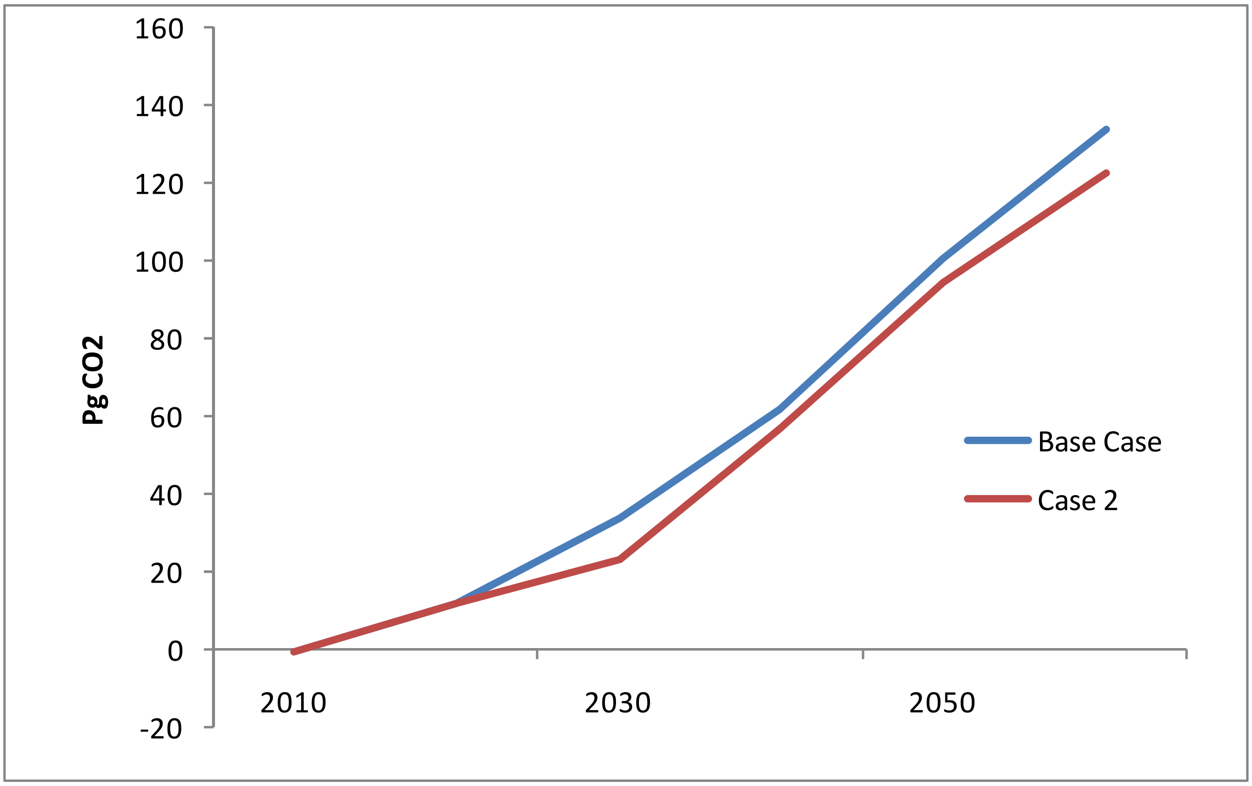
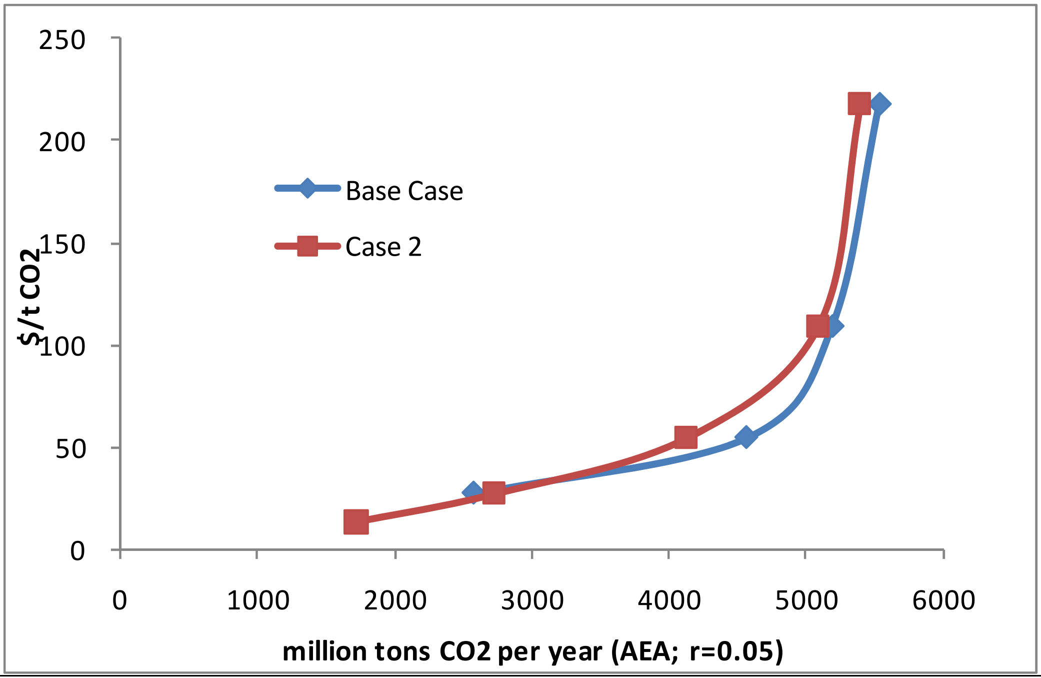
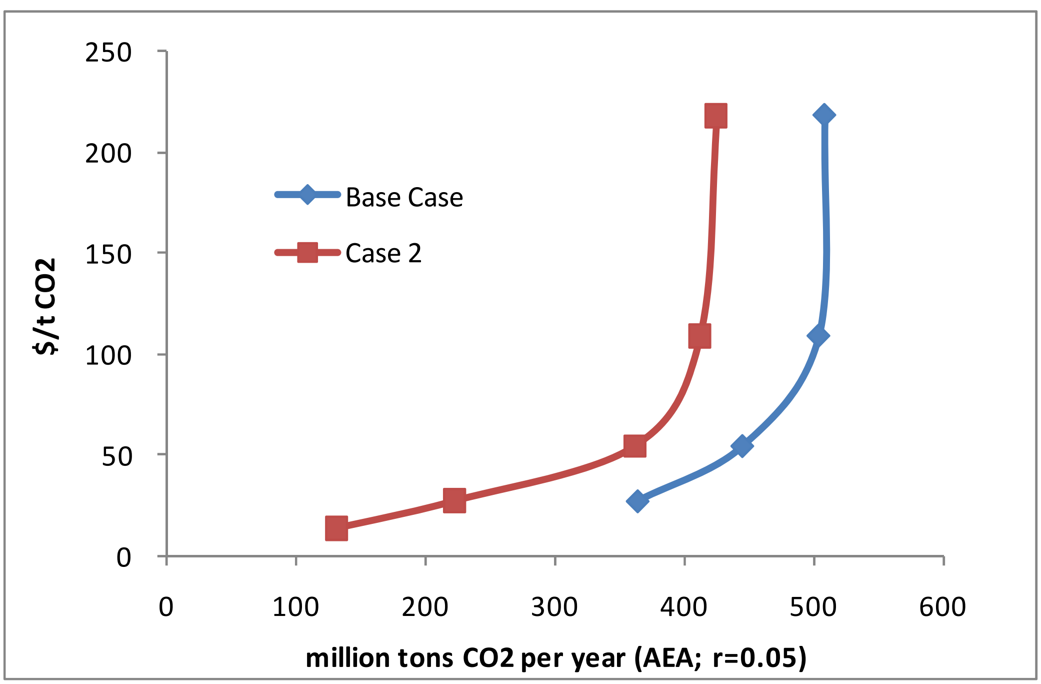


**Figure 4: Marginal cost of carbon sequestration across a series of constant carbon prices. Results are shown for the annual equivalent amount of carbon sequestered at each price for the period 2010-2060, discounted at 5%.**

**Panel A: Temperate regions**




**Panel B: Avoided deforestation in Tropics**



## REFERENCES


Choi, S., Sohngen, B., Rose, S., Hertel, T., and A. Golub. 2010 “Total Factor Productivity Change in Agriculture and Emissions from Deforestation” Paper presented at ASSA meeting at Atlanta, GA.

Dimaranan, Betina V., Editor (2006). *Global Trade, Assistance, and Production: The GTAP 6 Data Base*, Center for Global Trade Analysis, Purdue University.

Food and Agriculture Organization of the United Nations. 2010. Global Forests Resource Assessment 2010. Rome, Italy.

Golub, A., T. Hertel, H-L. Lee, S. Rose, and B. Sohngen, 2009. “The Opportunity Cost of Land Use and the Global Potential for Greenhouse Gas Mitigation in Agriculture and Forestry,” Resource and Energy Economics, in press, available online.

Hertel, T.W. (Ed.) 1997. *Global Trade Analysis Modeling and Applications*. Cambridge University Press, Cambridge.

Hertel, TW, S. Rose, R. Tol. 2009. Economic Analysis of Land Use in Global Climate Change Policy. New York: Routledge.

Houghton, R. 2008. Carbon Flux to the Atmosphere from Land-Use Changes: 1850-2005. In TRENDS: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A

Ianchovichina, E., Darwin, R., and Shoemaker, R. 2001. “Resource Use and Technological Progress in Agriculture: A Dynamic General Equilibrium Analysis” Ecological Economics, v38, 275-291.

Lee, H-L, T. Hertel, S. Rose, M. Avetisyan, 2009. “An Integrated Global Land Use Data Base for CGE Analysis of Climate Policy Options” in Thomas W. Hertel, Steven Rose, Richard Tol (eds.), *Economic Analysis of Land Use in Global Climate Change Policy*, Routledge Publishing.

Lubowski, R., A. Plantinga, R. Stavins. 2006. “Land-use change and carbon sinks:Econometric estimation of the carbon sequestration supply function.” Journal of Environmental Economics and Management. 51: 135-152.

Ludena, C., T. Hertel, P. Preckel, K. Foster and A. Nin. 2007. “Productivity Growth and Convergence in Crop, Ruminant and Non-Ruminant Production: Measurement and Forecasts” Agricultural Economics 37:1-17.

Monfreda, C., N. Ramankutty, T. W. Hertel, 2009. “Global Agricultural Land Use Data for Climate Change Analysis” in Thomas W. Hertel, Steven Rose, Richard Tol (eds.), Economic Analysis of Land Use in Global Climate Change Policy, Routledge Publishing.

Murray, B.C., W.N. Thurman, and A. Keeler. 2005. “Tax Interaction Effects, Environmental Regulation, and ‘Rule of Thumb’ Adjustments to Social Cost.” *Environmental and Resource Economics* 30(1):73-92.

Nabuurs, G.J., O. Masera, K. Andrasko, P. Benitez-Ponce, R. Boer, M. Dutschke, E. Elsiddig, J. Ford-Robertson, P. Frumhoff, T. Karjalainen, O. Krankina, W.A. Kurz, M. Matsumoto, W. Oyhantcabal, N.H. Ravindranath, M.J. Sanz Sanchez, X. Zhang. 2007. “Forestry” In *Climate Change 2007: Mitigation.* Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. ed., B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Nakicenovic, N., J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Grübler, T.Y. Jung, T. Kram, E.L. La Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K. Riahi, A. Roehrl, H-H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. van Rooijen, N. Victor, Z. Dadi. 2000. *Special Report on Emissions Scenarios*. Special report to the Intergovernmental Panel on Climate Change. ed., Nakicenovic, N. and R. Swart, Cambridge University Press, Cambridge, United Kingdom.

Nordhaus, W. 2009. *A Question of Balance.* New Haven: Yale University Press. 234 p.

Rimmer, M. and A. Powell,1996 "An implicitly additive demand system" *Applied Economics*, 28, 1613–1622.

Rosegrant, M. W., S. Msangi, C. Ringler, T. B. Sulser, T. Zhu, and S. A. Cline. 2008. *International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model description.* Washington, D.C.: International Food Policy Research Institute.

Sedjo, R.A. and K.S. Lyon. 1990. The Long-Term Adequacy of World Timber Supply. Resources for the Future, Washington, DC.

Sohngen, B. and R. Mendelsohn. 2003. "An Optimal Control Model of Forest Carbon Sequestration" *American Journal of Agricultural Economics.* 85(2): 448-457.

Sohngen, B. and R. Mendelsohn. 2007. "A Sensitivity Analysis of Carbon Sequestration" in Human-Induced Climate Change: An Interdisciplinary Assessment. Edited by M. Schlesinger, H.S. Kheshgi, J. Smith, F.C. de la Chesnaye, J.M. Reilly, T. Wilson, and C. Kolstad. Cambridge: Cambridge University Press.

Sohngen, B., C. Tennity, M. Hnytka, K. Meeusen. 2009. "Global forestry data for the economic modeling of land use." Chapter 3 in Hertel et al., Economic Analysis of Land Use in Global Climate Change Policy, New York: Routledge.

Sohngen, B. 2010. An Analysis of Forestry Carbon Sequestration as a Response to Climate Change. Copenhagen Consensus on Climate Change. Copenhagen Consensus Center.

Yu, W., Hertel, T. W., Preckel, P. V., and J. S. Eales, 2002. “Projecting World Food Demand using Alternative Demand Systems” *Economic Modeling*, 21: 99-129.