The Effect of Carbon Payments on Deforestation Rates and Carbon Sequestration: Estimates from a Global Forestry and Agricultural Model.

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Introduction

Deforestation is one of the largest sources of greenhouse gas (GHG) emissions globally. Current estimates suggest that there are around 4.4 billion ton CO2 (1 ton = 1 Mg = 1000 Kg) emission per year from deforestation (Houghton 2008), and the Intergovernmental Panel on Climate Change (IPCC) suggests that land use change, particularly from deforestation, will continue to be the source of carbon emission for the next century (Nabuurs et al. 2007). Estimates of future emission from land use change vary widely, for example, from 129 to 327 billion ton CO2 emission across economic models for just one socio-economic scenario according (Nakicenovic et al. 2000). While many approaches are under consideration to curb the concentration of GHGs in the atmosphere, reducing emissions from land use change and increasing carbon through forest management and afforestation could provide carbon mitigation relatively soon.

Of course, reducing emissions from deforestation, planting new forests on old agricultural land (afforestation), and conducting forest management to increase carbon all will have costs. Models account not only for the economic conditions at the margin between crop, livestock and forest uses, but they must also model the dynamics of forest management in order to properly account for the tradeoffs. To date, numerous excellent land use models have so far been developed (e.g. Ianchovichina et al, 2001; Rosegrant et al, 2008; Sohngen & Mendelsohn, 2007), but for the most part, these models have not addressed forest dynamics or the implications of an expanding agricultural margin for forest carbon emissions.

This study improves upon the existing literature in several ways. First, the widely cited works of Murray et al. (2005) and Lubowski et al. (2006) focus only on the United States. Since most forests are located in other regions of the world, and since current United States legislation is carefully considering importing carbon emissions reductions from outside the US, it is useful to look globally. Second, the work of Sohngen and Mendelsohn (2007) does look globally, but their model only considers forestry. They assume that the agricultural sector is not responsive changes in the land base. This model will improve the US only studies by developing a dynamic global forestry and agricultural model.

The objective of this study is to analyze the impact of carbon payments on land use competition between forest, agriculture, and livestock, and associated carbon sequestration. A recent partial equilibrium model of the forestry, livestock and crop sectors, has been developed to model forest dynamics and competitions between uses of land globally (Choi et al 2010). This study will adopt this model in order to assess how carbon payments may alter the amount of deforestation in important tropical countries.

Model

The model maximizes net present value of global market welfare in forestry, crop, and livestock sector. The objective function is shown in equation (1) (See table 1 for variables and parameters).

$$(1)\quad Max\sum^{\infty}\rho^{t}\left\{\begin{array}{l}\int^{QF*}D_{F}(Q_{F}(H_{r,j,k,a};v,m_{r,j,k}))dQ_{F}(t)+\int^{QCr*}D_{Cr}(Q_{Cr}(X_{Cr},K_{Cr},L_{Cr}))dQ_{Cr}(t)+\\ \int^{QLv*}D_{Lv}(Q_{Lv}(X_{Lv},K_{Lv},L_{Lv}))dQ_{Lv}(t)-\sum_{r=1}^{16}\sum_{j=1}^{18}\sum_{k=1}^{6}C_{F}-\sum_{r=1}^{16}\sum_{j=1}^{18}C_{Cr}-\sum_{r=1}^{16}\sum_{j=1}^{18}C_{Lv}\end{array}\right\}$$

The first three terms ($D_{F,}$ $D_{Cr,,}D_{Lv}$) are global demand for forest product, crop, and livestock. A simple aggregation of global quantities into a single demand function is a strong assumption that ignores many regional differences in products, trade relations among countries, and transportation costs associated with moving goods from region to region. However, a single global consumer for each of the commodities greatly simplifies the demand side of the problem and allows us to focus on the supply side, and in particular the intertemporal optimization of timber supply. Total global consumption for each product is thus 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 demand system (An Implicitly Additive Demand System) developed by Reimer and Powell (1996) and estimated by Yu et al (2002).

The last three terms in equation (1) are the sum of all costs for each sector. Forestry costs include the costs of harvesting and regenerating forests, as well as the costs of renting land. Crop and livestock costs include the costs of purchasing labor and capital inputs and land. For the purpose of our numerical simulation analysis, we divide the globe into 16 regions (index r). Within each of those regions, there are up to 18 Agro-Ecological Zones (AEZ: index j) that account for crop, livestock, and forestry productivity differences (see Hertel et al., 2009). In addition, to account for productivity and carbon differences across timber types, we allow up to six different timber types (index k) in each of the AEZs (see Sohngen et al., 2009).

Production in the forest sector is developed based on the global timber model described originally in Sedjo and Lyon (1990) and updated in Sohngen et al (1999), Sohngen and Mendelsohn (2003; 2007). The global quantity of forest product is the sum of regional timber harvest (H) multiplied by yield of trees (*V*). Timber yield is function of timber age (*a*), management input of timber (*m*), so that the total timber harvested each period is:

(2) $$Q_F = \sum_{r=1}^{16}\sum_{j=1}^{18}\sum_{k=1}^{6}\sum_{a}^{a*}\left(H_{r,j,k,a}\right)V_{r,j,k,a}(m_{r,j,k})$$

A separate timber yield function is defined for each region and timber type. Management intensity influences the yield of timber. The cost in the forest sector is 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.

Production for crop and livestock outputs is adopted from the GTAP model (Hertel, 1997). We utilize a nested constant elasticity of substitution (CES) production structure (see appendix A1). The CES functions are continuous, differentiable, monotonic and strictly quasi-concave, and they represent a constant return to scale technology. For this study, the production function of crop and livestock for each region is CES functional form with inputs such as capital, labor, and land in each sector (3). Note that the index for time t is omitted for presentation purpose.

(3) $$Q^S = \sum_{r=1}^{16} A_r^S \Big(\sum_{i=K,L,Land} \delta_{S,i,r}^{\frac{1}{\sigma}} X_{S,i,r}^{\frac{\sigma-1}{\sigma}} \Big)^{\frac{\sigma}{\sigma-1}}$$ S= index for crop or livestock sector

The parameter δ_i is share for each input (capital, labor, and land) in each region. The input shares δ_is 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).

We assume a single sectoral production function in each of the 16 regions. The land in the individual AEZ's within each region is aggregated via a nested CES function. With this specification, products in each AEZ are assumed to be relatively homogeneous, and the rents in each of the AEZs will move together over time. While this entails a potentially strong assumption, it is consistent with our highly aggregated demand structure. See Golub et al (2009) for an additional application and discussion using this approach.

With the demand for livestock products likely growing more rapidly in the low income countries, productivity growth in this sector will be a critical determinant of the price of these products, and hence land rents in those regions where livestock production is significant. This, in turn, will affect the degree of competition with forestry for scarce land. We assume different total factor productivity (TFP) growth in each region for both the crop and livestock sectors (captured by the parameter A). These parameters are drawn from Ludena et al. (2007).

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 AEZ's. 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 side is discussed below.

There are several constraints in the model. The constraints for the forest sector are shown in equations (4-a) to (4-c). The index *k*, *j*, *a*, and *t* denotes timber types, AEZ, timber age, and time period in each region. Note that the subscript for region (r) is omitted.

$$\text{(4-a)} \qquad X^F_{k,j,a,t} = X^F_{k,j,a-1,t-1} - H_{k,j,a-1,t-1} + G_{k,j,a=0,t-1}$$

$$\text{(4-b)} \qquad H^F_{k,j,a,t} \le X^F_{k,j,a,t}$$

$$\text{(4-c)} \qquad X^F_{k,j,a,t} = \frac{XE_j\left(\alpha^{\tau}_{F,a} \big/ R^{\tau}_{F,k,j,a,,t}\right)}{\left[\alpha^{\tau}_{Cr,j} R^{1-\tau}_{Cr,j,t} + \alpha^{\tau}_{Lv,j} R^{1-\tau}_{Lv,j,t} + \sum_{k=1}^{6} \alpha^{\tau}_{F,j,k} R^{1-\tau}_{F,j,k,t}\right]^{\left(\frac{\tau}{\tau-1}\right)}}$$

Equation (4-a) indicates the forestry equation of motion that maintains the total acres of forestland at time t. It is straightforward that forestry area at time t depends on harvest (*H*) and timber regeneration (*G*) at time t-1. Total harvest at time t should not be greater than the available forestland (4-b). Forestland is also constrained by land supply in equation (4-c). With equation (4-a), it indicates that the supply of forestland equals the total forestland maintained for forest outputs demand. The derivation of equation (4-c) is shown in Appendix 2. The land supply constraint is derived from Constant Elasticity of Transformation (CET) function used to constrain the movement of land across uses within AEZs. The parameter α_{Cr}, α_{Lv}, and α_F is AEZ specific land shares for supply in crop, livestock, and forestry, sums to 1 in each AEZ. The variable R_{Cr}, R_{Lv}, and R_F is land rental for crop, livestock, and forestry. One of important feature of this study is linked to land endowment (XE_j) in equation (4-c). In each AEZ, land endowment is given expressed as composite of all land uses in each AEZ by CET function (See Appendix A2). While land endowment is fixed for Boreal and Temperate regions, the model in this study allows expansion of land endowment in Tropical regions such as Brazil, Central America, Rest of South America, Sub Saharan Africa, Southeast Asia, and African Middle East. The expansion of land endowment comes from deforestation of unmanaged inaccessible forest area and it affects the land supply decision (equation 4-c).

The constraints for livestock sector are shown in equation (5-a) to (5-f)[1]. Following GTAP model (Hertel, 1997), the derivation of these constraints and parameters is based on the profit maximization problem, shown in Appendix (See Appendix1 for 5-a to 5-e and see Appendix 2 for 5-f).

$$\text{(5-a)} \quad XUL_t = (\sum_{j=1}^{18} \gamma_j \left(XL_{j,t}^{Lv}\right)^{(\beta-1)/\beta})^{\beta/(\beta-1)}$$

$$\text{(5-b)} \quad X_t^{Lv} = (\phi XUL_t^{\frac{(\omega-1)}{\omega}} + (1-\phi) F_t^{\frac{(\omega-1)}{\omega}})^{\frac{\omega}{(\omega-1)}}$$

$$\text{(5-c)} \quad X_t^{Lv} = \frac{\delta_{i=land}}{p_{land\&F,t}^{\sigma}} \frac{Q_t^{Lv}}{A_t^{Lv}} (\sum_{i=L,K,Land} \delta_i p_i^{1-\sigma})^{-\frac{\sigma}{\sigma-1}}$$

$$\text{(5-d)} \quad XUL_t = X_t^{Lv} \left(\frac{\phi p_{land\&F,t}}{P_{XUL,t}} \right)^{\omega}$$

$$\text{(5-e)} \quad XL_{j,t}^{Lv} = XUL_t \left(\frac{\gamma_j p_{XUL,t}}{R_{Lv,j,t}} \right)^{\beta}$$

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[1] For the presentation purpose, we omit constraints for crop sector which has the exact same sets of constraints except equation (5-b) and (5-e). This is because livestock sector has additional nest between land and feed. See Appendix 1.

$$\text{(5-f)} \quad XL^{Lv}_{j,t} = \frac{XE_j \left(\alpha^{\tau}_{Lv,j} \Big/ R^{\tau}_{Lv,j,t} \right)}{\left[\alpha^{\tau}_{Cr,j} R^{1-\tau}_{Cr,j,t} + \alpha^{\tau}_{Lv,j} R^{1-\tau}_{Lv,j,t} + \sum_{k=1}^{6} \alpha^{\tau}_{F,j,k} R^{1-\tau}_{F,j,k,t} \right]^{\left(\frac{\tau}{\tau-1}\right)}}$$

Equation (5-a) is a CES function for land composite input into the value added nest CES production function in each region (i.e. equation 3 above). The land composite input for production, X^{Lv}, is a function of primary factor, i.e. actual hectares (XL_j^{Lv}) in each AEZ, with a share parameter (γ) and a parameter for elasticity of substitution (β) (See derivation of these parameters in Appendix A1).

Although it is not expressed in equations above, we apply additional constraints to land equations (equation 4-a, 4-b, 4-c, and 5-f). Since the land supply function is based on CET function, it does not provide physical hectares but it represents as effective hectares. For the carbon scenario analysis, however, it is important to keep track physical hectares. To account physical hectares, we assume following relation.

$$\text{(6)} \quad d\ln H^{Physical}_{Crop} = (1/0.66)\,d\ln H^{CET}_{Crop}$$

Equation (6) indicates that 10% change in cropland by CET function requires 15% change in physical hectares. It is based on the assumption that additional land for crop has lower productivity than currently used land in crop production. It applies all the regions and AEZs. With equation (6) and constraint for fixing total land sum same as the initial condition, we keep all the land in physical terms in each time t.

For the carbon analysis, we hypothesize a series of carbon payment scenarios, ranges from \$5 per ton C to \$400 per ton C, and introduce a carbon valuation function into the model. Specifically, we rent the stock of carbon gains in forests (above ground carbon only in this study) relative to the baseline, and we pay for storage in wood products. We assume that the carbon price is constant over time. Assuming interest rate at 5%, carbon renting amount for each scenario is simply multiplying 0.05 to each carbon price per ton. The objective function for carbon payment scenario is shown as follows:

$$Max\sum^{\infty}\rho^{t}\left\{\begin{array}{l}\int^{QF*}D_{F}(Q_{F}(H_{r,j,k,a};v,m_{r,j,k}))dQ_{F}(t)+\int^{QCr*}D_{Cr}(Q_{Cr}(X_{Cr},K_{Cr},L_{Cr}))dQ_{Cr}(t)+\\ \int^{QLv*}D_{Lv}(Q_{Lv}(X_{Lv},K_{Lv},L_{Lv}))dQ_{Lv}(t)-\sum_{r=1}^{16}\sum_{j=1}^{18}\sum_{k=1}^{6}C_{F}-\sum_{r=1}^{16}\sum_{j=1}^{18}C_{Cr}-\sum_{r=1}^{16}\sum_{j=1}^{18}C_{Lv}+\\ RC*CB(X_{r,j,k.a}^{F},v,m_{r,j,k})\\ \end{array}\right\}$$

The last term in the function shows the payment on carbon stock, RC indicates the carbon rental value (a constant \$/t C in this case) and CB indicates carbon stock.

The dynamic optimization model is solved by decade for 100 years time period and results are considered for the initial 60 years to eliminate any possible effects from terminal period. The annual discount rate is used at 5% over the period. The model is solved using GAMS (General Algebraic Modeling System) program with CONOPT solver algorithm.

Results

The baseline suggests that there around 874 million hectares will be deforested globally over the next 60 years, or around 14 million hectares per year (Figure 1A). Most of this deforestation, about 61%, occurs in tropical regions. This is greater deforestation than some historical estimates, such as Houghton (2008), but results from the relatively larger increases in demand for crop and livestock outputs in our model. Carbon payments reduce the amount of deforestation and increase the amount of afforestation, so that total forest area increases. With these estimates, a $5 per ton C carbon payments reduces 37 million hectares of deforestation, with 11 million hectares gained in and 13 million in Sub-Saharan Africa region (13 mill ha) (Table 1). Deforestation is basically eliminated when carbon prices reach $400/t C.

While carbon payments reduce deforestation, it affects differently on crop and livestock sector (see table 2). Under Baseline scenario, total cropland usage reduces by 11% while livestock area increases up 32% for 60 years. The production of output in crop sector increases about 94% and the output in livestock sector grows up to 517%. The growth of livestock sector is intense and this is because of the assumption that there will be strong demand increase on livestock products, based on income growth world wide.

The impact of carbon payment on forest affects more on cropland usage than livestock land use. As carbon price increases, cropland area reduces 12% at $5 pet ton C and it reduces further about 33% at $400 per ton C. However, livestock land use is not affected much up to $40 per ton C and increasing rate is down to 25% at $400 per ton C. Given the increasing land use change in livestock and decreasing land use in crop under Baseline scenario, carbon payment reduces deforestation based on less conversion to cropland than livestock land use. However, there is still overall livestock land increase over time, 25% with $400 per ton C. Under high carbon price scenarios, for example at $400 per ton C, livestock land expansion comes mostly from cropland rather than deforestation.

It is expected that less land use input would result in reduced output production. While Baseline scenario suggests that crop sector output production increases up about 94% and livestock output increases up 517% for 60 years, carbon renting scenario with $20 per ton C suggests there will be 89% total crop output change and 506% of livestock output change. It reduces down to 75% and 279% respectively under $400 per ton C scenario. The rate of production reduction in livestock sector is much greater than crop production compared to the rate of reduction in land use change. This is because of the livestock production has fewer available feed input from crop production. Although it is not presented in this paper, it indicates that crop sector uses more inputs of labor and capital to meet not only food demand but also to supply feed inputs in livestock production.

The present value and annual equivalent amount of carbon gain associated with avoided deforestation across the carbon prices are listed in table 3. The present values are calculated as the present value of the annual carbon gain for the scenario relative to the baseline, discounted at a 5% rate of interest. The carbon calculations include all above ground carbon, below ground carbon, and carbon contents in forest products at market. Global carbon gain lies between 32 million to 630 million ton C per year depending on carbon price. Under $5 per ton C scenario, carbon gain comes mostly from Sub Saharan region about 10 million ton C per year followed by Brazil at 6.92 million ton C per year and Rest South America region at 6.78 million ton C per year. Under $40 per ton C scenario, there will be carbon gain about 91 million ton C per year from Brazil while there is gain about 82 million ton C per year in Sub Saharan Africa. In general, carbon gains are consistent with the avoided deforestation area in the region (table 1). The annual equivalent carbon gain is plotted for each region in figure 2. The global total marginal cost curve is the sum of all regional cost curves. As can be seen, Brazil has the largest potential carbon gains followed by Rest South America region.

This study employs direct land use competition among forestry, crop, and livestock via CET land supply function and it is useful to compare the carbon sequestration results with other models, for example the Global Timber Model (Sohngen & Mendelsohn, 2007). In figure 3, global marginal cost curve of carbon sequestration for each model is presented. It shows that this study has higher marginal cost curve particularly at high carbon price assumption. With carbon price at $5 per ton C, GTM suggests about 49 million ton C per year while this study estimates about 32 million ton C per year. As carbon price rises, the difference of carbon gains is significantly bigger. The carbon gain under $20 per ton C scenario is about 154 million ton per year by GTM while 112 million ton per year from this study. With carbon price at $100 per ton C assumption, GTM estimates about 598 million ton C per year and this study suggest about 474 million ton C per year. One major explanation for this is because of the difference in model approach particularly land competition. GTM has more detailed specification on timber types while land use transition across other sectors is out of the system using exogenous assumption. Whereas, the model in this study uses endogenous land use competition and that constrains land use transfer compared to the exogenous manner.

Conclusion

This study examines the impact of carbon payment scenarios on deforestation trend and carbon sequestration cost. We develop Global Forest Agriculture Model, extended from Global

Timber Model to deal with land use competition with crop and livestock sector by applying these sectors adopted from GTAP model. Baseline model results suggest that there will be about 822 million hectares of deforestation globally and Tropical region accounts for 499 million hectares of deforestation. We apply carbon rental payment scenarios through different carbon prices ($5 pet ton C to $400 per ton C). Carbon payment policy suggests that, with $5 per ton C, there will be about 51 million hectares of avoided deforestation globally and 37 million hectares from Tropical region. The avoided deforestation goes further up to 268 million hectares globally and 54 million hectares in Tropics as carbon price is at $100 per ton C. Carbon payment affects differently on crop and livestock sector. The impact of carbon payment on forest affects more on cropland than livestock land use. As carbon price increases, cropland area proportional change reduces to 12% at $5 pet ton C and it reduces further down to 33% at $400 per ton C. However, livestock land use is not affected up to $40 per ton C and it reduces down to 25% at $400 per ton C. The impact of carbon payment affects differently on crop and livestock. Livestock output reduction is greater than crop output due to the carbon renting because of livestock has fewer inputs for feed from reduced crop production. Carbon gains from avoided deforestation ranges from 32 million ton C per year ($5 per ton C) to 630 million ton C per year ($400 per ton C). Large gain is obtained from Tropical region, particularly from Brazil (between 6.92 to 179 million ton C per year) and Rest South America (between 6 to 115 million ton C per year). However this estimate is smaller than other study such as GTM suggesting between 49 million ton C per year and 1487 million ton C per year ($500 per ton C).

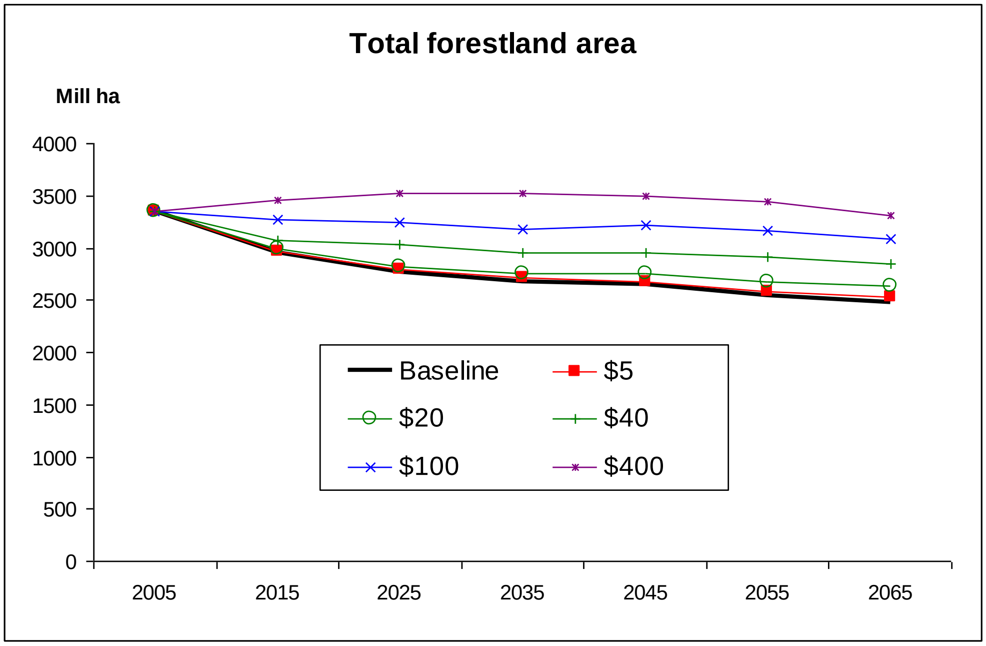
There could be several areas to make this study for further development. We use several useful estimates and assumptions from literature but it would be more helpful to test different way, for example assumptions on global demand, income, and elasticities for production and land supply. Technology change assumption could be important factor related to future land use change and carbon sequestration (see Choi et al 2010 for sensitivity results related to total factor productivity). We currently adopt total factor productivity changes but factor specific technology change could be additional topic that deserves examination. In addition, our current assumption on new cropland productivity for physical hectare calculation is same across regions and this could attract further development attention.

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
μ (t)	Global income elasticity
η	Global price elasticity
V	Timber yield function
m	Timber management intensity input
H	Timber harvest area
G	Timber replant area
$\mathrm{A}^{\mathrm{Cr}},\mathrm{A}^{\mathrm{Lv}}$	Total production technology factor for crop and livestock
$\delta_{i=land,capital,labor}$	Shares of land, capital, and labor for production function
σ	Elasticity of production function (0.2391)
$\alpha_F, \alpha_{Cr}, \alpha_{Lv}$	Shares of land for timber types, cropland, and livestock
$\mathrm{P}_{\mathrm{i=K,L,Land}}$	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
γ	Land shares for crop and livestock land composite in each AEZ
XE	Land endowment as composite of all land uses by CET function
τ	Elasticity in CET function for land supply (-0.9)
β	Elasticity in CET function for composite land inputs to production (20)
XUL	Composite livestock land
F	Feed amount from crop to livestock
ϕ	Share for the crop into composite with feed into livestock
ω	CET parameter for livestock land and feed (0.5)
ρ	Discount rate (0.05)
RC	Carbon rental payment
CB	Carbon stock

Figure 1 Total forestland area and deforestation in Tropic region

A. Total forestland under carbon payment



B. Total deforestation area under carbon payment in Tropical region

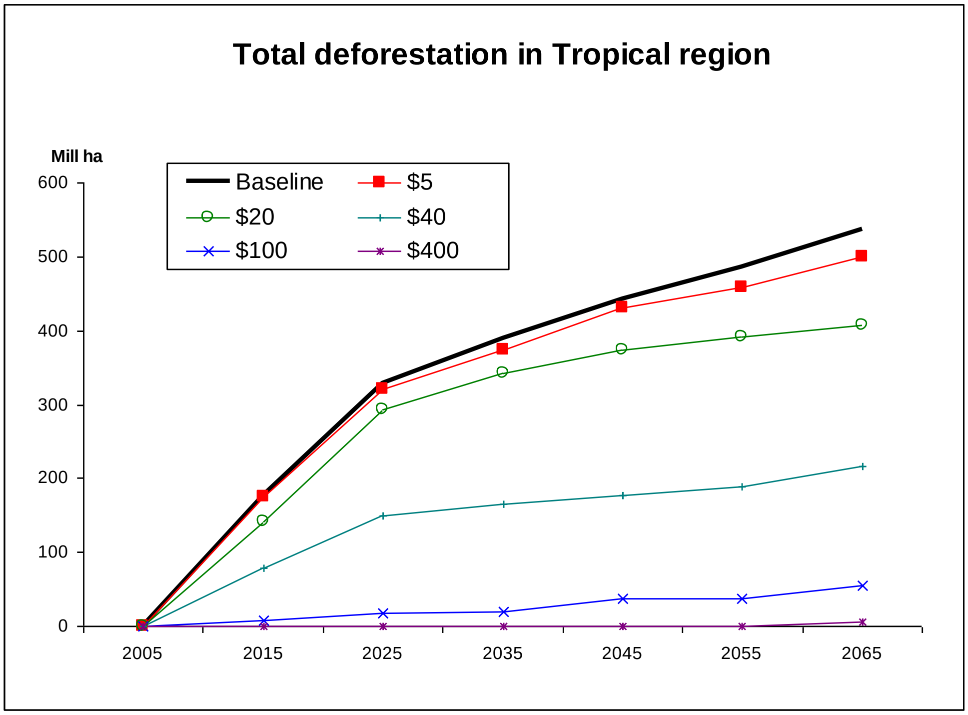


Table 1 Avoided deforestation in Tropical region for 60 years (Million ha)

	$5	$10	$20	$40	$100	$400
Brazil	11.73	18.6	44.37	125.39	184.09	199.63
Central America	0.87	1.05	1.36	6.03	20.45	26.63
Rest South America	5.14	9.73	16.92	40.63	118.14	118.7
Sub Saharan Africa	12.99	15.6	33.44	93.71	104.12	130.13
Southeast Asia	7.13	23.8	33.92	56.23	56.23	56.23
Tropical Total	37.86	68.78	130.01	321.99	483.03	531.32

Table 2 Impact of carbon payment on crop and livestock sector (Proportional change compared to initial value by 2065)

	Baseline	$5	$10	$20	$40	$100	$400
Crop Area	-11%	-12%	-12%	-14%	-20%	-23%	-33%
Livestock Area	32%	32%	31%	32%	31%	26%	25%
Crop Output	94%	92%	91%	89%	93%	91%	75%
Livestock Output	517%	514%	511%	506%	507%	448%	279%

Table 3 Carbon gain from avoided deforestation in Tropical region for 60 years (million ton C)

A. Present value of carbon gain for 60 years (r=0.05)

Carbon Price	US	China	Brazil	Central America	Rest South America	Sub Saharan Africa	Southeast Asia	Rest of World	Total
$5	24.71	17.27	133.42	15.17	130.72	202.51	72.51	30.13	626.44
$10	46.17	30.82	205.87	18.05	246.68	332.56	291.52	75.75	1247.43
$20	69.61	78.31	440.50	24.29	450.04	559.75	393.99	145.91	2162.41
$40	217.35	126.45	1765.11	106.79	928.46	1583.75	702.90	288.15	5718.96
$100	323.89	352.68	3070.09	382.95	2108.65	1707.52	702.91	509.82	9158.51
$400	814.78	1148.00	3470.08	508.27	2224.24	2192.63	711.85	1100.46	12170.31

B. Annual equivalent of carbon gain (r=0.05)

Carbon Price	US	China	Brazil	Central America	Rest South America	Sub Saharan Africa	Southeast Asia	Rest of World	Total
$5	1.28	0.90	6.92	0.79	6.78	10.50	3.76	1.56	32.48
$10	2.39	1.60	10.67	0.94	12.79	17.24	15.11	3.93	64.67
$20	3.61	4.06	22.84	1.26	23.33	29.02	20.43	7.56	112.10
$40	11.27	6.56	91.51	5.54	48.13	82.10	36.44	14.94	296.48
$100	16.79	18.28	159.16	19.85	109.32	88.52	36.44	26.43	474.80
$400	42.24	59.51	179.90	26.35	115.31	113.67	36.90	57.05	630.94

Figure 2 Marginal cost of carbon sequestration

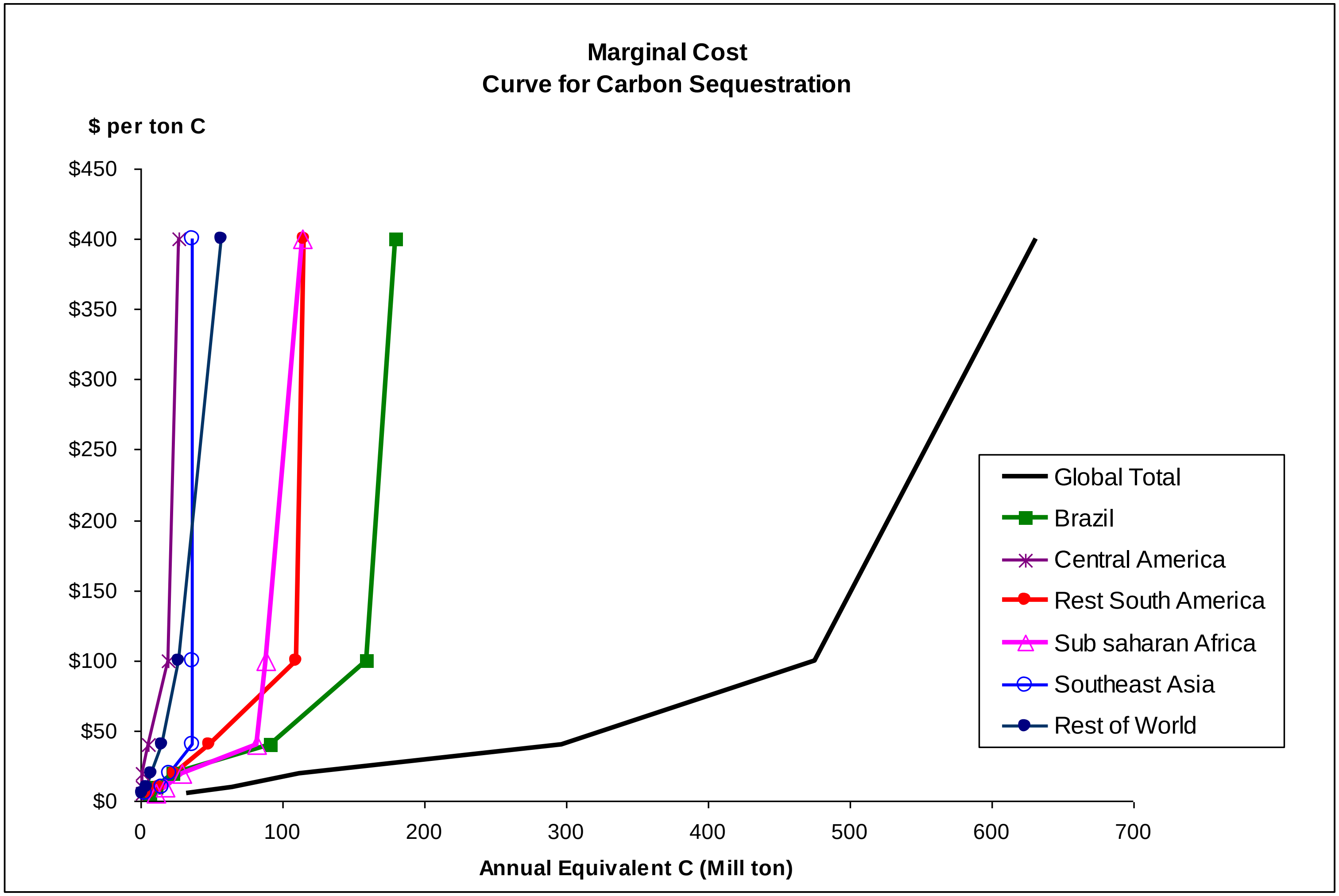
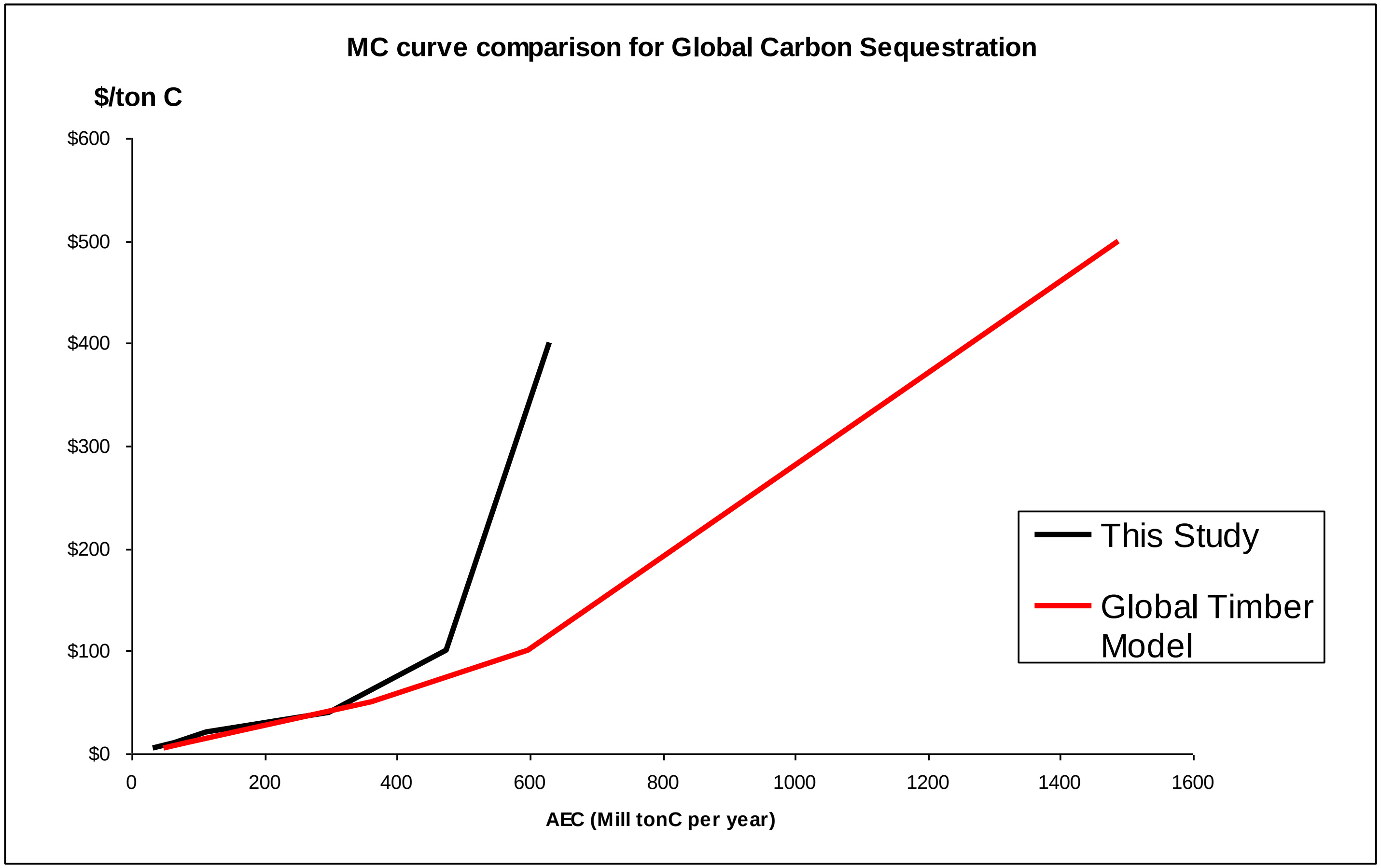


Figure 3 Comparison of marginal cost curve between models



APPENDIX 1. Production structure and derivation of constraints

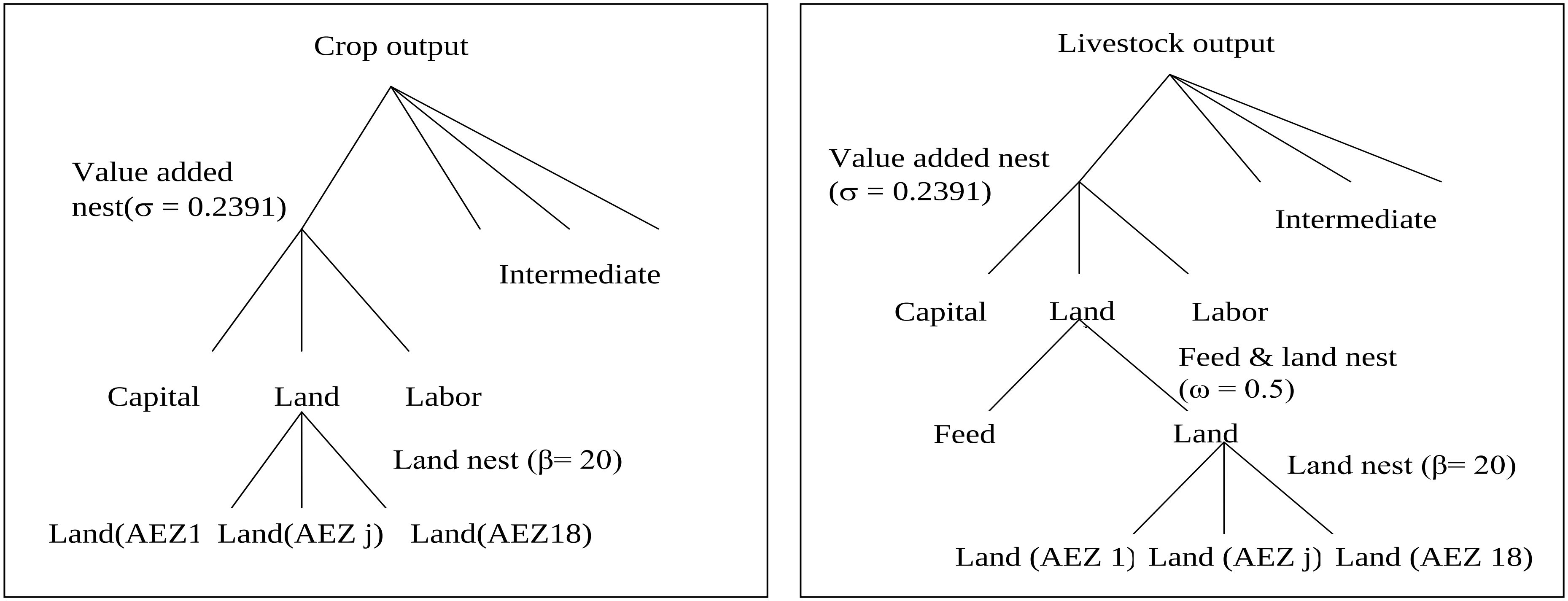


Figure A-1 Nested CES production for Crop and Livestock sector

The structure of crop output for a single region is shown in figure A-1 above. The top of the nest tree is the final output which consists of value added nest and intermediate inputs. In value added nest, it consists of inputs such as capital, labor, and land composite. In the land nest at the bottom, it consists of actual hectares of cropland for each AEZ. In each nest, constant elasticity substitution (CES) function is defined and the elasticity parameter for value added nest and land nest is σ and β respectively. The restricted profit function is equation (A-2)

$$\text{(A-1)} \quad \Pi = PQ - \sum_{i=K,L} p_i X_i - \sum_j R_j XL_j - \sum_{n=1}^{N} p_n Z_n$$

$$\text{s.t.} \quad Q = A\left(\sum_{i=K,L,Land} \delta_i^{1/\sigma} X_i^{(\sigma-1)/\sigma}\right)^{\sigma/(\sigma-1)}$$

$$X_{land} = \left(\sum_{j=1}^{18} \gamma_j XL_j^{(\beta-1)/\beta}\right)^{\beta/(\beta-1)}$$

$$Q = \alpha_n Z_n$$

The profit maximization problem for a representative industry firm in crop sector chooses inputs to maximize profit where Q is the output, X_i is capital and labor inputs and P_i is the unit input cost. R_j is unit input cost (rental) for land (XL) and Z is the intermediate inputs.

After setting up maximization problem and taking the first order conditions with respect to the capital, labor, and land composite and arranging the ratios of the first order conditions for inputs i and capital gives following condition (A-2).

$$\text{(A-2)} \quad \frac{\delta_i}{\delta_K} = \left(\frac{p_i}{p_K}\right)^{\sigma} \frac{X_i}{X_K}$$

The share parameter δs sum to 1, δs could be obtained for capital, labor and land. Rearrange equation (A-2) for other inputs and substitute into the production function gives the input demand for land.

(A-3) $$X_i = \frac{\delta_i}{p_i^{\sigma}} \frac{Q}{A} \Big(\sum_{i=L,K,Land} \delta_i p_i^{1-\sigma} \Big)^{-\frac{\sigma}{\sigma-1}}$$

The first order conditions with respect to land in each AEZ gives

(A-4) $$\frac{R_j}{R_l} = \frac{\left(\gamma_j XL_j^{-1/\beta} \right)}{\left(\gamma_l XL_l^{-1/\beta} \right)}$$

Because γ are sum to 1, γ_j could be calculated for all j. Take the ratios in (A-4) and substitute into the land composite equation constraint in (A-2) gives land demand in each AEZ.

(A-5) $$XL_j = X_{land} \left(\frac{\gamma_j p_{i=Land}}{R_j} \right)^{\beta}$$

APPENDIX 2. Land Supply

Cost minimization problem for land supply for each land use categories could be expressed as (A-6), where to choose land X_{Cr}, X_{Lv} , and X_F given rental rates for crop, livestock, and forestry repectively, R_{Cr}, R_{Lv}, and R_F.

(A-6) $$\text{Min } R_{Cr}X_{Cr} + R_{Lv}X_{Lv} + \sum_{k=1}^{6} R_{F,k} X_{F,k}$$

$$\text{s.t. } XE = (\alpha_{Cr} X_{Cr}^{\frac{(\tau-1)}{\tau}} + \alpha_{Lv} X_{Lv}^{\frac{(\tau-1)}{\tau}} + \sum_{k=1}^{6} \alpha_{F,k} X_{F,k}^{\frac{(\tau-1)}{\tau}})^{\frac{\tau}{(\tau-1)}}$$

The composite land *XE* is expressed in constant elasticity of transformation (CET) function and α is the share for each land use sum up to 1.Taking the first order conditions for each choice variable will give series of ratios as following. Note that the subscript for timber type (k) is omitted in equations (A-7).

(A-7) $$\frac{R_{Cr}}{R_F} = \frac{\alpha_{Cr}}{\alpha_F}\left(\frac{X_F}{X_{Cr}}\right)^{\frac{1}{\tau}};\ \frac{R_{Cr}}{R_{Lv}} = \frac{\alpha_{Cr}}{\alpha_{Lv}}\left(\frac{X_{Lv}}{X_{Cr}}\right)^{\frac{1}{\tau}};\ \frac{R_{Lv}}{R_F} = \frac{\alpha_{Lv}}{\alpha_F}\left(\frac{X_F}{X_{Lv}}\right)^{\frac{1}{\tau}}$$

Since the sums of α is 1 and with equations in (A-7) will give each share of α. If these first order conditions in (A-7) substitute into the constraint in (A-6), the supply function could be obtained such as in (A-8).

(A-8) $$X_k^F = \frac{XE\left(\alpha_{F,k}^{\tau} \big/ R_{F,k}^{\tau}\right)}{\left[\alpha_{Cr}^{\tau} R_{Cr}^{1-\tau} + \alpha_{Lv}^{\tau} R_{Lv}^{1-\tau} + \sum_{k=1}^{6} \alpha_{F,k}^{\tau} R_{F,k}^{1-\tau}\right]^{\left(\frac{\tau}{\tau-1}\right)}}$$

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