The Impact of Cropland Productivity on Crop Prices, Deforestation, and Carbon Sequestration Costs

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INTRODUCTION

It is widely suggested that forest sector activities could offer cost effective and interim approaches to curb global greenhouse gas emissions (Sohngen & Mendelsohn, 2007; Kindermann et al, 2008; Madeira, 2008). Current estimates suggest that there are around 4.4 billion ton CO_2 (1 ton = 1 Mg = 1000 Kg) emission per year from deforestation (Houghton, 2008): however, future land use projections are highly uncertain. One element of this uncertainty is the degree to which future productivity and technology progress in the agricultural and forestry sectors could alter the demand for land. Many studies have recently suggested, for example, that crop prices will rise due to a slowing of technological change in the agricultural sector, coupled with continued increases in global population and income, which in turn will increase demand for agricultural land. These factors – potential changes in productivity, commodity prices, agricultural land rents and related demand, and global socio-economics – could substantially increase the costs of carbon sequestration in forests.

This study examines whether earlier estimates of the costs of carbon sequestration in forests were too low, in particular because they were too optimistic about future crop productivity growth or future demand growth. It also examines the implications of carbon sequestration policies on food commodity prices. To accomplish this, we built a new dynamic global forest and agriculture model. The forest sector optimizes the age class structure and the management intensity of managed forests, and is based on the earlier work of Sohngen et al. (1999) and Sohngen and Mendelsohn (2007). The agricultural sector optimizes inputs and output in five subsectors, including three crop sectors (grain, rice, and other crops), and two livestock sectors (ruminant and non-ruminant). It is based on Global Trade and Agriculture Project (GTAP) data, including Agro-Ecological Zone-specific land use and land price data. The model optimally shifts land between the two sectors. One novel feature of our approach is that new land can be added to either the agricultural or the forestry sectors over time by converting currently inaccessible forests to productive use.

The policy analysis conducted in this study considers alternative projections of crop productivity related to land and carbon sequestration policy. We begin with the recent estimates of potential future crop yields by Tweeten and Thompson (2008), and use their methods to make future projections of crop yields by region. We then incorporate those projected crop yields into our model. We conduct sensitivity analysis for our modeling results using 90% confidence intervals for their projections. Similarly, we project future income and population growth, bounding growth for both using estimates from Yu et al. (2002). For the carbon sequestration analysis, this paper will apply the carbon price path utilized in Sohngen (2010). This carbon price path was developed from an analysis linking a global forestry analysis of carbon sequestration 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.

MODEL

The model maximizes the sum of net present value of global welfare in the forestry sector, 3 crop subsectors (grain, rice, other crops), and 2 livestock subsectors (ruminant and non-ruminant) by optimally choosing inputs and outputs. Equation (1) depicts the objective function of the model (see table 1 for detailed description of variables).

$$(1)\; Max \sum_{t}^{T-1} \rho^{t} \left\{ \begin{array}{l} \sum^{QF^*} DF\;(QF\;(H_{r,j,a}; v, m_{r,j})) + \sum_{s=1}^{3} \sum^{QCs^*} DC_s (QC_s (X_{Cs}, K_{Cs}, L_{Cs})) + \\ \sum_{k=1}^{2} \sum^{QLVk^*} DLV_k (QLV_k (X_{rum}, K_{LVk}, L_{LVk})) - \sum_{j=1}^{18} CF_j \; - \sum_{s=1}^{3} CC_s - \sum_{k=1}^{2} CLV_k \end{array} \right\} + \rho^T S^T$$

The first 3 terms in the bracket denote the global demand in forestry (*DF*), crops (*DC*), and livestock (*DLV*) and the last 3 terms in the bracket are associated total costs for each sector. We assume that there is a global demand function for each of the three markets in the model. This 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 model and allows us to focus on the intertemporal optimization in the forestry sector. Global consumption for each product is the sum of regional production, and there is a single global price trend for each commodity. For all three output demand functions, the price elasticity for forest products is -1.0 (Simangunsong and Buongiorno, 2001), for crops -0.3, and for livestock -0.7 (Choi, 2004). The income elasticity for forestry products is 0.88, for crops 0.17, and for livestock 0.62 (Yu et al., 2002). We assume it rises to 0.92 for forest products, falls to 0.08 for crops, and for livestock it rises to 0.72 over time (Yu et al., 2002). Income per capita is assumed to rise at 2.7% per year. 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. The last term in the benefit function (*S*) is the terminal value. For the purpose of our numerical simulation analysis, we divide the globe into 14 regions (for presentation purposes, regional index is omitted in the above equation). 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).

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. 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*), and 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:

(2a) $$QF = \sum_{r=1}^{14}\sum_{j=1}^{18}\sum_{a}^{a*}\left(H_{r,j,a}\right)V_{r,j,a}(m_{r,j}),$$

(2b) $V = \exp(\alpha - \beta / a)$ a is timber age, α and β is parameter

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. 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 (Equation 3). Note that the index for time (*t*) and sector (*s*) is omitted for presentation purposes.

$$(3) \quad Q = \sum_{r=1}^{14} \Big(\sum_{i=K,L,Land} (\delta_{i,r}^{\frac{1}{\sigma}} (A_{i,r} XL_{i,r})^{\frac{\sigma-1}{\sigma}} \Big)^{\frac{\sigma}{\sigma-1}}$$

The parameter δ_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). Unlike the model in Choi et al. (2011), we apply factor specific technology assumption *A* for each input, land, labor, and capital from Ludena et al. (2007).

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

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

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

(4-c) $$X^{F}_{j,a,t} = \frac{XE_j\left(\alpha^{\tau}_{F,a} \big/ R^{\tau}_{F,j,a,,t}\right)}{\left[\sum_{s=1}^{3}\alpha^{\tau}_{s,j}R^{1-\tau}_{s,j,t} + \alpha^{\tau}_{k,j}R^{1-\tau}_{k,j,t} + \alpha^{\tau}_{F,j}R^{1-\tau}_{F,j,t}\right]^{\left(\frac{\tau}{\tau-1}\right)}}$$ for all *s* (crops) & *k*=1 (ruminant)

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 timber harvest area (*H*) and timber regeneration area (*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 output demand. 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 parameters α_{Cr}, α_{Lv}, and α_F are AEZ-specific land shares for supply in crops, livestock, and forestry, and sum to 1 in each AEZ. The variables R_{Cr}, R_{Lv}, and R_F represent land rental for crops, 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 expressed as composite of all land uses in each AEZ by CET function. 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 following constraints are land demand and supply for all crops and livestock sectors (see Appendix for derivations).

(5-a) $$XL_t^{s\&k} = (\sum_{j=1}^{18} \gamma_j \left(X_{j,t}^{s\&k}\right)^{(\beta-1)/\beta})^{\beta/(\beta-1)}$$ for all *s* (crops) & *k*=1(ruminant)

(5-b) $$XL_t^{s\&k} = \frac{\delta_{i=land}}{p_{i=Land,t}^{\sigma}} \frac{Q_t^{s\&k}}{A_t^{s\&k}} (\sum_{i=L,K,Land} \delta_i p_i^{1-\sigma})^{-\frac{\sigma}{\sigma-1}}$$ for all *s* (crops) & *k*=1(ruminant)

(5-c) $$X_{j,t}^{s\&k} = XL_t^{s\&k} \left(\frac{\gamma_j p_{Land,t}^{s\&k}}{R_{s\&k,j,t}} \right)^{\beta}$$ for all *s* (crops) & *k*=1 (ruminant)

(5-d) $$P_{Land,t}^{s\&k} = (\sum_{j=1}^{18} \gamma_j R_{s\&k,j,t}^{(1-\tau)})^{1/(1-\tau)}$$ for all *s* (crops) & *k*=1 (ruminant)

(5-e) $$XF_t^{k} = (\phi XL_t^{\frac{(\omega-1)}{\omega}} + (1-\phi) F_t^{\frac{(\omega-1)}{\omega}})^{\frac{\omega}{(\omega-1)}}$$ for ruminant livestock only

(5-f) $$X_{j,t}^{`s\&k} = \frac{XE_j \left(\alpha_{s\&k,j}^{\tau} \big/ R_{s\&k,j,t}^{\tau} \right)}{\left[\sum_{s=1}^{3} \alpha_{s,j}^{\tau} R_{s,j,t}^{1-\tau} + \alpha_{k,j}^{\tau} R_{k,j,t}^{1-\tau} + \alpha_{F,j}^{\tau} R_{F,j,t}^{1-\tau} \right]^{\left(\frac{\tau}{\tau-1}\right)}}$$ for all *s* (crops) & *k*=1(ruminant)

The land composite input for production, *XL*, is a function of primary factor, i.e. actual hectares (X_j) in each AEZ, with a share parameter γ and a parameter for elasticity of substitution β (Equation 5-a). Land input demand for production is in equation (5-b). The relation between AEZ-specific actual hectares (X_j) and composite land input (*XL*) can be defined by equation (5-c) and (5-d). All above constraints should be satisfied for all crops and livestock except (5-e) which applies to ruminant livestock only. It is a composite between land (*XL*) and feed input so that it allows substitution between land and feed input for ruminant livestock production. Land market equilibrium requires land demand equates land supply (5-f) for all crops and livestock.

We apply three different assumptions on the factor specific technology changes. For the "Neutral" land productivity assumption, we use the same A_i (Equation 3) parameter for all three inputs (land, labor, and capital) so that the total productivity is consistent to the estimates by Ludena et al (2007). For the "High" land productivity assumption, we alter the $A_{i=land}$ parameter for land input to set a higher level of productivity while labor and capital remain the same level as Neutral assumption. Similarly, for the "Low" productivity assumption, we apply $A_{i=land}$ parameter for land input to set a lower level of productivity while labor and capital remain the same level as the Neutral assumption. The total output level for the High assumption is about 50% higher than Neutral and the Low assumption produces about 50% lower than the Neutral assumption.

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 2.3^{o} Celsius (in comparison to a 3.05^{o} 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 2.3° 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.

$$Max\sum_{t}^{T-1}\rho^{t}\left\{\begin{array}{l}\sum^{QF*}DF\ (QF\ (H_{r,j,a};v,m_{r,j}))+\sum_{s=1}^{3}\sum^{QCs*}DC_{s}(QC_{s}(X_{Cs},K_{Cs},L_{Cs}))+\\ \sum_{k=1}^{2}\sum^{QLVk*}DLV_{k}(QLV_{k}(X_{rum},K_{LVk},L_{LVk}))-\sum_{j=1}^{18}CF_{j}-\sum_{s=1}^{3}CC_{s}-\sum_{k=1}^{2}CLV_{k}+\\ RC*CB(X_{r,j,k.a}^{F},v,m_{r,j,k})\end{array}\right\}+\rho^{T}S^{T}$$

The model optimizes production and land use for 150 years with 10-year time steps beginning in [Year X], and results are considered for the first 70 years to minimize terminal period effects. The annual discount rate is 5%. The model is solved using a General Algebraic Modeling System (GAMS) program with the CONOPT solver.

RESULTS

The base case productivity assumption results suggest that there will be increasing pasture land use for all three scenarios (Neutral, High, and Low), ranging 292 million new hectares of pasture in 2070 under the High productivity assumption to 192 million hectares in

2070 under Low productivity assumption (Table 2a). High income elasticity on meat products combined with robust increases in global income drive the increase in pastureland. This model allocates more land to pasture than many other models because pasture land is relatively cheap. Other models tend to increase the production of new crops to feed ruminants and non-ruminants, however our model expands low cost land at the margin. For example, most of the new land devoted to ruminant livestock production in our model result mostly from conversions of forestland. These conversions from forestland range from between 259 million hectares in 2070 under the High land productivity assumption and 355 million hectares under the Low productivity scenario. The grain sector allocates more land over time, increasing by 25 million hectares in 2070 in the High land productivity scenario to 162 million hectares in the Low land productivity scenario. This is because grain product is an important component for animal feed.

For all three productivity assumptions, deforestation in the tropics is substantial, ranging 100 million hectares of forests converted to agriculture over the next 60 years, to 150 million hectares in 2070. In addition, perhaps not surprisingly, the tropics are the most sensitive to the productivity assumptions. Following the global trend, there is decreasing forestland in the US, about 11 million hectares to 25 million hectares in 2070 depending on productivity assumptions.

Although output in the crop sector rises in most scenarios (Table 3), it uses different land use mixes over time depending on the crop. (Table 2A). Interestingly, grain land use under Low productivity scenario is the greatest while production level is the lowest. In general, output increases the most under the High productivity assumptions and the least under the Low productivity assumptions. (Table 3). The largest increases in output occur in the livestock sector, ranging 402% to 486% by 2070. These are driven by the high income elasticity on livestock demand and the large increases in income assumed over the time period. In addition, productivity change allows greater feed production, so not only is more land used to produce livestock outputs (as shown earlier) but more feed is used as well. Livestock output is sensitive to productivity change assumptions. In particular, the Low productivity change assumption leads to higher feed input uses and less land used in the livestock sector. The Low technology change assumption also leads to significantly less land devoted to livestock production through pastures (Table 2a). Under the Low productivity assumption, there is more land devoted to grain production, more deforestation, less feed, and higher livestock prices. For the crops, the alternative land productivity assumptions show expected outcomes, the crop and livestock output levels are the highest under High land productivity assumption and the lowest under Low land productivity assumption. Compared to crops and meat products, cropland productivity assumptions have relatively small impacts on timber outputs (Table 3).

The price level of crop products decreases significantly for all productivity assumptions because future demand on crops is assumed to fall. It ranges from 52% to 78% across crop types and productivity assumptions. For the livestock output price, the result of High productivity assumption suggests that there will be 6% price decreases even with increasing demand assumption because of cheaper and more available feed combined with increasing land input. However, under the Low productivity assumption, output price rises about 8%. Timber price generally rises about 33% to 41%.

The impact of carbon policy on land use change is shown in Table 4, and the data in the table and the related discussion focus on the difference between carbon policy results and base case results of the different productivity cases in 2070. As expected, the carbon policy case suggests that there will be increasing forestland use ranging 526 million hectares under the High productivity assumption and 655 million hectares under Low productivity assumption by 2070 compared to the no carbon policy case (as in Table 2A). The largest increase in forestland occurs under the Low cropland productivity assumption for several reasons. First, the deforestation rate under Low productivity assumption is the largest so there is more land to maintain in forests, and second, land rents are lowest when productivity change is low. Under the Low technology change scenario, significantly more land is converted from rainforest to agriculture in tropical regions, increasing the supply of land and lower its value. Under the High land productivity assumption, almost half of the forestland expansion is from pasture, 205 million hectares, followed by 127 million hectares from land used to cultivate other crops and 121 million hectares from the grain sector. It shows the same land shifting pattern for the Neutral and Low land productivity cases, in that the major land use shifts to forestland are from the livestock sector, accounting for 274 million hectares (45% of total shift) to 316 million hectares (48% of total shift) respectively. Shifts of land from the grain sector range between 121 million hectares (High) and 342 million hectares (Low). The most forestland gain occurs in the tropics region ranging from 243 million hectares under High land productivity to 266 million hectares under Low productivity, more than 46% and 40% of total gain.

The carbon policy case has important implications for crop output production and commodity prices (Table 5). Grain markets experience the largest price impacts among all the crops, with an 11% to 22% increase by 2070 relative from the different productivity assumption cases to our dynamically optimal carbon price scenario. The other crops sector (crops other than grains and rice) is also affected by the carbon policy case, resulting in about 5% to 15% output reduction and similar increases in the price. The rice sector has carbon policy impacts by decreasing output about 6% under Neutral productivity assumptions and decreasing output 11%

under the High and Low productivity assumption cases. Overall livestock output decreases 7% to 16%. The forest sector increases timber production between 18% and 36%.

The total carbon gains under alternative cropland assumptions are presented in Figure 1. It shows that there will be up to 200 billion tons of CO_2 by 2070 under Low cropland productivity assumption. It is surprising that the carbon gain is the largest under Low cropland productivity and it is because forestland shift is the greatest under Low while total forestland is similar across productivity assumptions when carbon price is attached.

CONCLUSION

This study develops a dynamic optimization model of global land use in forest, 3 sectors of crops (grain, rice, and other crops), and 2 sectors of livestock (ruminant and non-ruminant). Using 14 regions and 6 sectors, this study develops 3 different alternatives on crop yield associated with land productivity. The productivity cases results show that there will be increasing land use in pasture for livestock production ranging 192 million hectares and up to 292 million hectares. Deforestation occurs ranging from 259 million hectares and up to 355 million hectares depending on the cropland productivity assumptions. The most deforestation occurs in Tropics that accounts up to 39% to 50% of global deforestation.

Under the carbon policy case, there is increasing forestland ranging 526 million hectares under High productivity assumption and 655 million hectares under Low productivity assumption by 2070 compared to the Neutral case. The increasing forestland is mostly shifting land away from the livestock and grain sectors. Under the High land productivity assumption, almost half of the forestland expansion is from pasture, 205 million hectares followed by 127 million hectares from the other crop sector and 121 million hectares from grain sector. Grain markets experience the largest price impacts among all crops, with nearly a 22% increase by 2070 relative to the Neutral case. The other crops sector is affected by the carbon policy, with about a 5% to 15% output reduction and similar increases in the price. The rice sector has carbon policy impacts by decreasing output about 6% under Neutral assumptions and 11 % under High and Low assumption.

There are several elements that could be further developed in this model. Examples include a more detailed agriculture sector covering additional crop types; as well as expanding the single timber type in this model and include more timber types in order to provide more accurate carbon accounting in forest sector. In addition, this study does not consider greenhouse contents from agriculture sector such as methane and it would be more complete.

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

Notation	Definition
$DF_{,} DC_{,,} DLV$	Demand function for forestry, crop, and livestock sector
$QF_{,} QC_{,,} QLV$	Production function for forestry, crop, and livestock products
$XL_{,,} XF$	Composite land inputs for crop and livestock
$X^F{}_{,} X^s{}_{,,} X^k$	Total land area in forestry, crop, and livestock sector (million ha)
$CF_{,} CC_{,,} CLV$	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,s,k	Index for region (r=1-14), AEZ (j=1-18),crop (s=1-3), livestock (k=1-2)
i	Index for inputs capital, labor, and land
V	Timber yield function
m	Timber management intensity input
H	Timber harvest area
G	Timber replant area
A	Productivity factorfor capital, labor, and land
$\delta_{i=land,capital,labor}$	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
$P_{i=K,L,Land}$	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
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)
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 (1.2)
ρ	Discount rate (0.05)
S	Terminal value
RC	Carbon rental payment
CB	Carbon stock

Table 2 A) Productivity case results: Total land use change from 2010 to 2070 (Million hectares)

	High	Neutral	Low
Forest	-259	-274	-355
Grain	25	68	162
Other Crops	1	-35	-2
Rice	-59	-32	3
Pasture	292	273	192

B) Productivity case results: Regional Forestland changes from 2010 to 2070 (Million hectares)

	High	Neutral	Low
US	-11	-17	-25
CHINA	32	53	-41
RUSSIA	-69	-61	-42
Tropics	-100	-136	-150
ROW	-111	-113	-97
Total	-259	-274	-355

Table 3 Global output and price changes by 2070

	Output			Price		
	High	Neutral	Low	High	Neutral	Low
Forest	90%	69%	79%	33%	48%	41%
Grain	172%	110%	80%	-78%	-72%	-68%
Other Crops	213%	127%	120%	-75%	-66%	-65%
Rice	137%	67%	52%	-68%	-56%	-52%
Livestock	486%	436%	402%	-6%	1%	8%

Table 4 A) Changes in land use relative to the baseline case in 2070 under the carbon policy case and the three technology change assumptions.

(Mill. ha)	High	Neutral	Low
Forest	526	609	655
Grain	-121	-267	-342
Other Crops	-127	3	37
Rice	-72	-71	-34
Pasture	-205	-274	-316

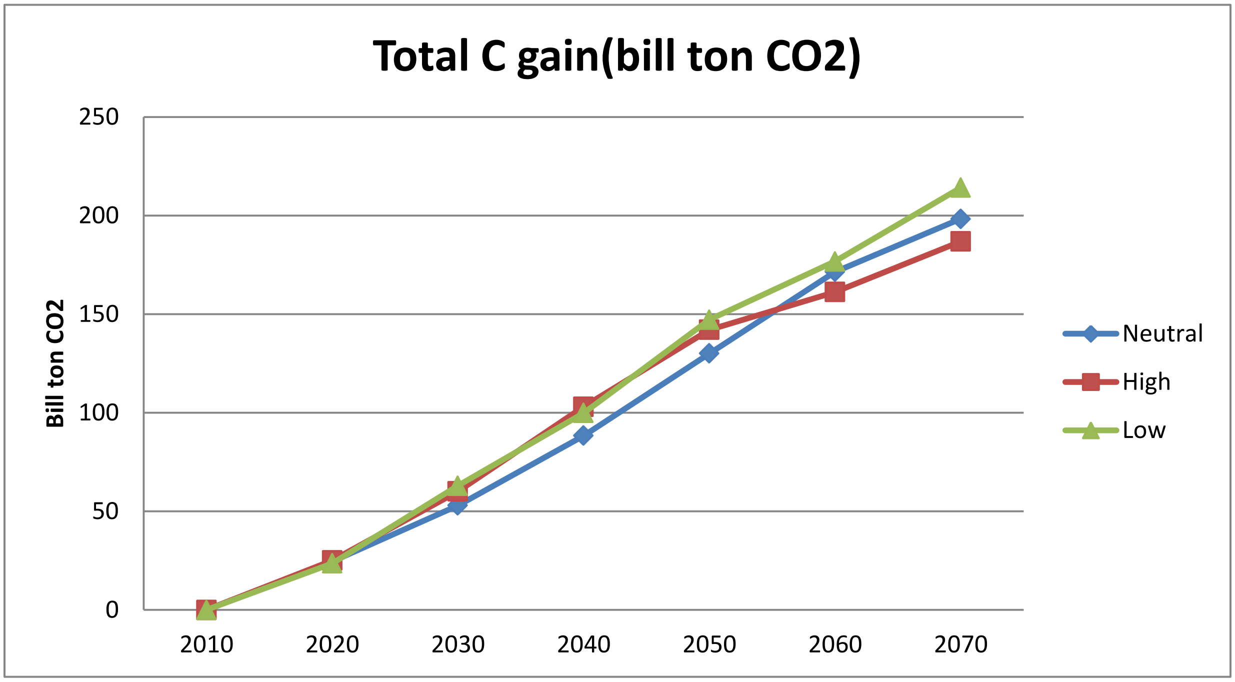
B) Changes in total forest area relative to the baseline case in 2070 under the carbon policy case and the three technology change assumptions Total forest area changes by carbon policy

(Mill. ha)	High	Neutral	Low
US	73	101	88
CHINA	50	60	136
RUSSIA	20	67	19
Tropics	243	246	266
ROW	140	135	147
Total	526	609	655

Table 5 Carbon policy impacts on global outputs and prices relative to the productivity base cases in 2070

	Output			Price		
	High	Neutral	Low	High	Neutral	Low
Forest	18%	36%	29%	-14%	-24%	-21%
Grain	-11%	-20%	-19%	11%	22%	21%
Other Crops	-8%	-5%	-15%	7%	5%	15%
Rice	-11%	-6.0%	-11%	11.6%	5.8%	11%
Livestock	-6.9%	-11.9%	-16.2%	6.7%	12.2%	17.4%

Figure 1. Total carbon gain by carbon price



APPENDIX 1. Production structure and derivation of constraints

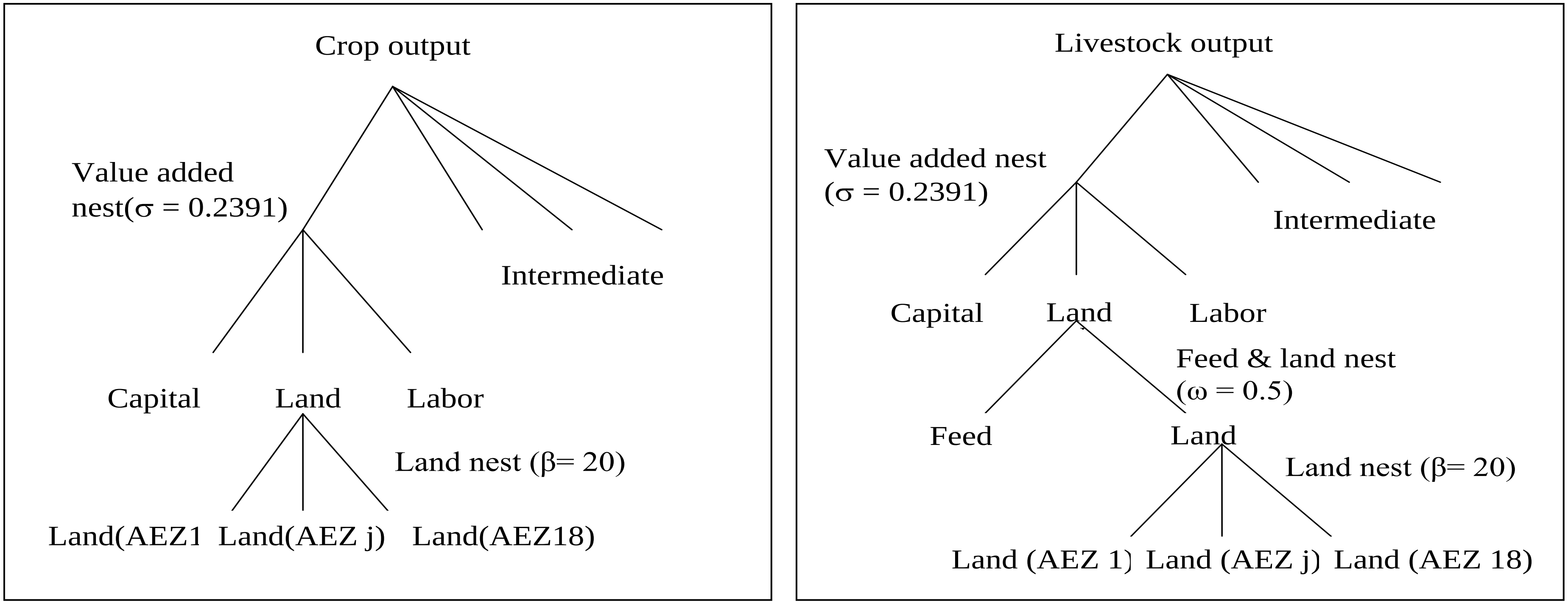


Figure A-1 Nested CES Production for Crop and Livestock Sectors

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-1)

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

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

$$XL = \left(\sum_{j=1}^{18} \gamma_j X_j^{(\beta-1)/\beta}\right)^{\beta/(\beta-1)}$$

$$Q = \alpha_n Z_n$$

The profit maximization problem for a representative industry firm in the crop sector chooses inputs to maximize profit where Q is the output, XL_i is capital and labor inputs and P_i is the unit input cost. R_j is unit input cost (rental) for land (X) 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 (K) gives following condition (A-2).

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

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) $$XL_i = \frac{\delta_i}{p_i^{\sigma}} \frac{Q}{A} \left(\sum_{i=L,K,Land} \delta_i p_i^{1-\sigma} \right)^{-\frac{\sigma}{\sigma-1}}$$

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

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

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) $$X_j = XL \left(\frac{\gamma_j p_{i=Land}}{R_j} \right)^{\beta}$$

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 respectively, R_{Cr}, R_{Lv}, and R_F.

$$\text{(A-6)} \quad \text{Min} \quad \sum_{s=1}^{3} R_s X_x + R_{LV} X_{LV} + R_F X_F$$

$$\text{s.t.} \quad XE = (\sum_{s=1}^{3} \alpha_x X_s^{\frac{(\tau-1)}{\tau}} + \alpha_{Lv} X_{Lv}^{\frac{(\tau-1)}{\tau}} + \alpha_{F,k} X_{F,k}^{\frac{(\tau-1)}{\tau}})^{\frac{\tau}{(\tau-1)}}$$

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).

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

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).

$$\text{(A-8)} \quad X_{j,a,t}^{F} = \frac{XE_j \left(\alpha_{F,a}^{\tau} \Big/ R_{F,j,a,,t}^{\tau} \right)}{\left[\sum_{s=1}^{3} \alpha_{s,j}^{\tau} R_{s,j,t}^{1-\tau} + \alpha_{k,j}^{\tau} R_{k,j,t}^{1-\tau} + \alpha_{F,j}^{\tau} R_{F,j,t}^{1-\tau} \right]^{\left(\frac{\tau}{\tau-1}\right)}}$$

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