Cropland productivity, carbon sequestration, and commodity prices.

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Introduction

There is widespread research showing that forestry can be a cost effective method to reduce global carbon emissions (Sohngen & Mendelsohn, 2007; Kindermann et al, 2008; Madeira, 2008). As a result there are efforts to implement policies that would slow deforestation in particular countries (e.g., Brazil), through large-scale programs (e.g., the World Bank's Prototype Forest Carbon Fund), or with specific mechanisms implemented by countries or states (e.g., California). However, many of these studies are predicated on historical assumptions about falling crop prices. As growth in crop productivity has slowed in recent decades, as income growth has increased demand for meat, and as crop production has been diverted to energy use, the costs of using land for forests rather than agriculture have risen. Efforts to slow deforestation and sequester carbon in forests could turn out to be fairly expensive and not lucrative as a policy option if food production is compromised. Furthermore, carbon sequestration policies could greatly increase global commodity prices by allocating land away from food production.

This paper 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. We also examine the implications of carbon sequestration policies on food commodity prices. To accomplish this, we build a new model based on an earlier global dynamic forestry model that can also model the agricultural sector (Choi et al, 2011). The forest sector optimizes the age class structure and the management intensity of managed forests. Additional land can be added to either the agricultural or the forestry sector by converting currently inaccessible forests to productive use. The agricultural sector optimizes inputs and output in six sectors, including three crop sectors (grain, rice, and other), and two livestock sectors (ruminant and non-ruminant). The model optimally shifts land among 5 uses.

The policy analysis 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, and bound growth in those sectors with estimates from the literature. 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

This study adopts the model from Choi et al (2011) extending to 3 crop sectors (rice, grain, and other) and to 2 livestock sectors (ruminant and non-ruminant). The model maximizes net present value of global market welfare in 6 sectors and the objective function is shown in equation (1). The variables and parameters are shown in Table 1.

(1)

$$Max\sum_{t}^{15}\rho^{t}\left\{\begin{array}{l}\sum^{QF*}DF\ (QF\ (H_{r,j,a};v,m_{r,j}))+\sum_{s=1}^{3}\sum^{QCi*}DC_{s}(QC_{s}(X_{Cs},K_{Cs},L_{Cs}))+\\ \sum_{k=1}^{2}\sum^{QLVk*}DLV_{k}(QLV_{k}(X_{LVk},K_{LVk},L_{LVk}))-\sum_{r=1}^{16}\sum_{j=1}^{18}CF_{r,j}-\sum_{s=1}^{3}\sum_{r=1}^{14}\sum_{j=1}^{18}CC_{s,r.j}-\sum_{k=1}^{2}\sum_{r=1}^{14}\sum_{j=1}^{18}CLV_{k,r,j}\end{array}\right\}$$

The first three terms (*DF*, *DC*, *DLV*) are global demand for forest product, crop, and livestock. Note that index *s* for crop represents 3 sectors (rice, other, and grain) and index *k* represents 2 sectors (ruminant and non-ruminant). 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 14 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). Unlike previous version of this model in Choi et al (2011) and Sohgen and Mendelsohn (2007), we simplify the forest sector to single representative specie in each AEZ.

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

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

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

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). 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).

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

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-a) $$X^F_{j,a,t} = X^F_{j,a-1,t-1} - H_{j,a-1,t-1} + G_{j,a=0,t-1}$$

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

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

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 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. 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). Following GTAP model (Hertel, 1997), the derivation of these constraints and parameters is based on the profit maximization problem.

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

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

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

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

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

$$\text{(5-f)} \quad XL_{j,t}^{Lv} = \frac{XE_j\left(\alpha_{Lv,j}^{\tau} \big/ R_{Lv,j,t}^{\tau}\right)}{\left[\alpha_{Cr,j}^{\tau} R_{Cr,j,t}^{1-\tau} + \alpha_{Lv,j}^{\tau} R_{Lv,j,t}^{1-\tau} + \sum_{k=1}^{6} \alpha_{F,j}^{\tau} R_{F,j,t}^{1-\tau}\right]^{\left(\frac{\tau}{\tau-1}\right)}}$$

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° Celsius (in comparison to a 3.05° Celsius change in the 'nocontrols' 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).

Results

The baseline results for the global land use and regional forestland use are presented in Table 2. For all three land productivity assumptions, pasture area for ruminant livestock production increases ranging from 52 million hectares (Low) to 260 million hectares (High) due to the high future demand on meat products. These increases in pasture are mostly from Other crop sector decreasing 369 million hectares in High land productivity assumption and 279 million hectares in Low land productivity assumption. Interestingly, Grain sector increases 239 million hectares with Low land productivity assumption. This is because feed input demand is still high for the high demand in livestock output and Grain output is heavily used in feed use. Forest area increases about 60 million hectares under High land productivity, decreases about 42 million hectares under Low land productivity while it stays about the same level under Neutral land productivity assumption. However, while global forest area does not change much under Neutral assumption, regional forestland use results show different patterns depending on regions. For the Neutral case, deforestation occurs in Tropics about 59 million hectares, followed by Russia and China about 50 million hectares and 16 million hectares respectively. There is increasing forestland in the US about 80 million hectares and 46 million hectares in the ROW.

The results of global outputs and prices of each product are listed in Table 3. As expected, the crop output levels are the highest under High land productivity assumption and the lowest under Low land productivity assumption. For the High assumption, the biggest production change occurs in Grain sector among crops, rising from 74% under Neutral to 119% production increase by 2075. However, livestock production level is consistently high across land productivity assumptions, around 187% to 190%. This is because the future meat demand is high regardless of productivity differences in crop production. The price level of livestock increases about 77% to 79%. The price level of forest output rises the most, 129% to 136%. In contrast, the prices of crop decrease ranging from 59% to73% since the future demand on crop products decreases.

The impact of carbon policy on land use is shown in Table 4, indicating the difference between carbon policy results and baseline results. By the carbon policy, forestland increases about 183 million hectares under Low land productivity assumption, 289 million hectares under Neutral land productivity assumption, and 297 million hectares under High land productivity assumption. The increasing forestland is mostly shifting land away from Grain land use, 268 million hectares under High, 229 million hectares under Neutral, and 415 million hectares under Low land productivity assumption. Surprisingly, pastureland under Low assumption increases 251 million hectares. Compared to the baseline results in Table 2A, carbon policy turns the livestock sector more land use intensive since the output from crops in turn feed inputs are limited from the low productivity. The most forestland gain occurs in Tropics region (see Table 4B), accounts 233 million hectares under High assumption and 209 million hectares in Neutral assumption. There is the least gain under Low assumption about 96 million hectares and this is because the increase in livestock sector.

Carbon policy has important implications for crop output production and commodity prices (Table 5). The biggest impact occurs in Grain market that output decreases about 12% to 18% across different land productivity assumption and it has impacts on 12% to 20% price increases. Other sector is affected by carbon policy about 3% to 6% output reduction and similar increases in the price. Rice sector has the least effect by carbon policy that affects output increase about 1% under High assumptions and 2% decrease under Neutral and Low assumption. Livestock price does not change substantially across productivity assumptions.

In figure2, regional proportions of Grain productions for the baseline and carbon policy are presented. While Grain sector has the biggest impact of carbon policy among crops, carbon policy affects regional production too. In the baseline, the major Grain production is from ROW region that accounts about 51% of total production, followed by Tropical region that is about 41% of total production. Carbon policy shifts Grain production towards more to ROW region, about 65% of total production.

The carbon gain by the carbon policy is shown in Figure 1. There is about 85 billion tons of CO2 by 2075 under High land productivity assumption, 79 billion tons of CO2 under Neutral, and 68 billion tons of CO2 under Low productivity assumption. Most of carbon gains are from Tropics region accounting about 52 billion tons of CO2 under High productivity assumption, 47 billion tons of CO2 under Neutral assumption, and 31 billion tons of CO2 under Low productivity assumption.

Conclusion

This study extends previously developed dynamic optimization land use model (Choi et al, 2011) to incorporate more detailed sectors in crops (rice, grain, and other) and livestock (ruminant and non-ruminant). Using 14 regions and 6 sectors, it develops 3 different alternatives on crop yield associated with land productivity. The baseline results show that there is about 52 million hectares increase in pastureland under Low land productivity assumption and 260 million hectares of increase under High land productivity assumption. This increase is mostly from Other crop sector. Forestland use increases about 60 million hectares under High land productivity assumption, while 42 million hectares under Low land productivity assumption. Although Neutral assumption doesn't affect the global total forestland use, regional trend shows different paths. Deforestation occurs in Tropics about 59 million hectares, followed by Russia and China about 50 million hectares and 16 million hectares respectively. There is increasing forestland in the US about 80 million hectares and 46 million hectares in the ROW.

Carbon policy results suggest that there will be increasing forestland use about 183 million hectares under Low land productivity assumption and 297 million hectares under High land productivity assumption. The increasing forestland is mostly shifting land away from Grain land use, 268 million hectares under High, 229 million hectares under Neutral, and 415 million hectares under Low land productivity assumption.

Carbon policy has important implications for crop production and prices. The biggest impact occurs in Grain market that output decreases about 12% to 18% across different land productivity assumption and it has impacts on 12% to 20% price increases. Other sector is affected by carbon policy about 3% to 6% output reduction and similar increases in the price. Rice sector has the least effect by carbon policy that affects output increase about 1% under High assumptions and 2% decrease under Neutral and Low assumption. Livestock price does not change substantially across productivity assumptions.

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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
CF, CC, CLV	Cost function for crop and livestock
s	Index for crop sectors (rice, grain, and other)
k	Index for livestock sectors (ruminant and non-ruminant)
X_C, X_{Lv}	Composite land inputs for crop and livestock
X^F, XL_C, XL_{Lv}	Total land area in forestry, crop, and livestock sector (million ha)
K_{Cr}, K_{Lv}	Capital inputs for crop and livestock
L_{Cr}, L_{Lv}	Labor inputs for crop and livestock
r, j	Index for region (r=1-14) and AEZ (j=1-18)
i	Index for inputs capital, labor, and land
$I(t)$	Global income (GDP)
$N(t)$	Global population
$\mu(t)$	Global income elasticity
η	Global price elasticity
V	Timber yield function
m	Timber management intensity input
H	Timber harvest area
G	Timber replant area
$A_{i,r}$	Factor specific production technology for input land, labor, and capital
$\delta_{i=land,capital,labor}$	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)
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

Table 2

A) Global Land use changes by 2075 (Baseline)

(Mill. ha)	High	Neutral	Low
Forest	60	2	-42
Grain	3	26	239
Other	-369	-339	-279
Rice	46	38	31
Pasture	260	273	52

B) Regional Forestland changes by 2075 (Baseline)

(Mill. Ha)	High	Neutral	Low
US	85	80	78
CHINA	-8	-16	-20
RUSSIA	-48	-50	-60
Tropics	-24	-59	-82
ROW	54	46	42

Table 3 Global output and price changes by 2075

	Output			Price		
	High	Neutral	Low	High	Neutral	Low
Forest	5%	4%	1%	129%	130%	136%
Grain	119%	74%	45%	-73%	-67%	-61%
Other	61%	42%	24%	-68%	-64%	-59%
Rice	94%	64%	38%	-71%	-66%	-60%
Livestock	190%	189%	187%	77%	78%	79%

Table 4 A) Carbon policy impacts on global Land use by 2075

(Mill. ha)	High	Neutral	Low
Forest	297	289	183
Grain	-268	-229	-415
Other	4	-16	3
Rice	-21	-21	-21
Pasture	-12	-23	251

B) Total forest area changes by carbon policy

(Mill. ha)	High	Neutral	Low
US	10	15	20
CHINA	17	17	18
RUSSIA	25	37	37
Tropics	233	209	96
ROW	11	11	11

Table 5 Carbon policy impacts on global outputs and prices in 2075

	Output			Price		
	High	Neutral	Low	High	Neutral	Low
Forest	23%	23%	24%	-17%	-17%	-18%
Grain	-18%	-19%	-12%	20%	21%	12%
Other	-3%	-6%	-5%	3%	6%	5%
Rice	1%	-2%	-2%	-1.0%	2.1%	2%
Livestock	-0.2%	-0.3%	-0.2%	0.2%	0.3%	0.2%

Figure 1 Proportions of regional grain productions in 2075

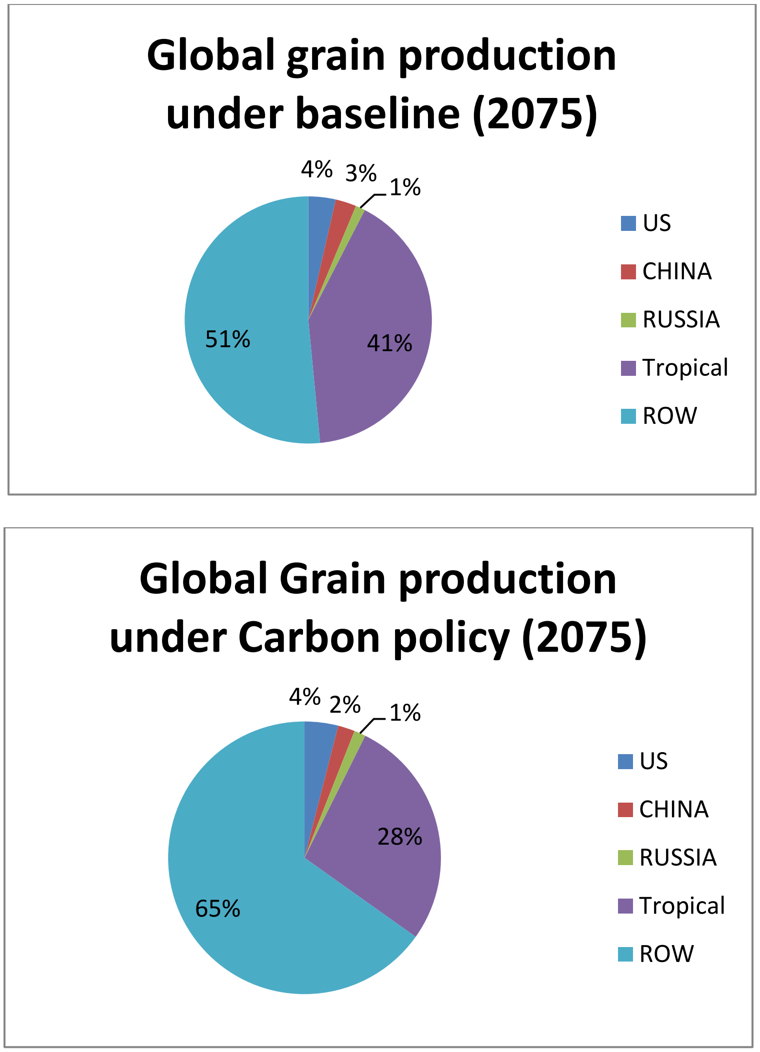
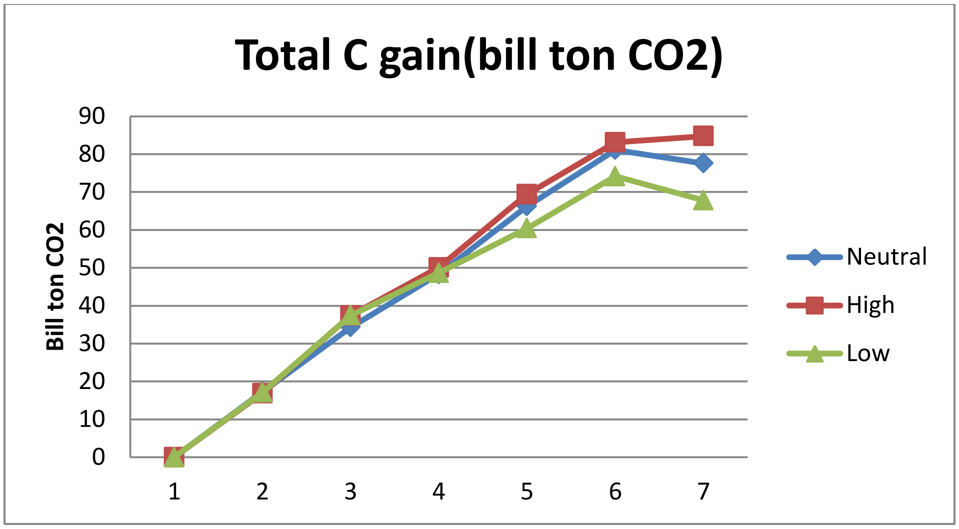
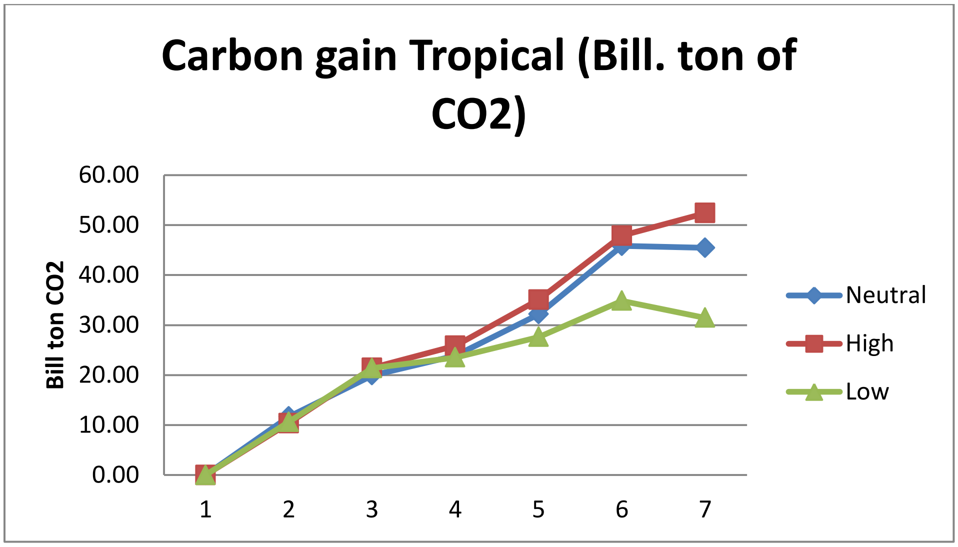


Figure 2 Global total carbon gain





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