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The Dynamic Competitiveness of U.S. Agricultural and Forest Carbon Sequestration

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Abstract

Global society is moving towards action to reduce anthropogenic greenhouse gas emissions. This can be expensive and socially disruptive in countries like the United States where the vast majority of emissions arise from electrical energy generation and petroleum usage. Agricultural and forest carbon sequestration along with development of other greenhouse gas offsets may help hold costs and disruption down. However sequestration exhibits saturation and non permanence that may influence this role.

We examine the dynamic role that the agricultural and forest sectors can play in emissions offsets and mitigation. A 100 year modeling analysis, depicting U.S. agricultural and forest sectoral activities is applied to simulate agricultural and forestry potential mitigation response. The results reveal that agriculture and forestry can play an important role principally through cropland soil sequestration, afforestation and biofuel provision. However the importance of these strategies varies with price and time. At low carbon prices and in the near term agricultural soils are most important in the longer term and at high prices powerplant feedstock biofuels dominate. Ignoring saturation leads to an overstatement of the potential importance of sequestration strategies. Nevertheless the results show that the agricultural and forest sectors may serve as an important bridge to the future helping to hold costs down until energy emissions related technology develops.

The Dynamic Competitiveness of U.S. Agricultural and Forest Carbon Sequestration

Global warming is a societal concern. The Intergovernmental Panel on Climate Change (IPCC) summarizes evidence indicating that the Earth's temperature rose approximately 0.6 °C (1° F) during the 20th century (Houghton et al.) and projects that temperature will continue to rise, increasing by 1.4°C to 5.8°C between 1990 and 2100 (McCarthy et al.). The IPCC also asserts that anthropogenic greenhouse gas emissions (GHGE) are the dominant causal factor (Houghton et al.). In addition, their reports argue that warming effects will be time consuming to reverse, and the resultant damages are uncertain.

In the face of such events and projections, society is actively considering options to reduce GHGE. In 1992, 165 nations negotiated and signed the United Nations Framework Convention on Climate Change (UNFCCC), which sets a long-term goal "to stabilize greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous human interference with the climate". In 1997, the third session of the conference of the parties to the UNFCCC yielded the Kyoto Protocol (KP), which set emission limits on carbon dioxide and other GHGs.

Emission reductions can be expensive. The majority of U.S. emissions come from energy use with about 40% coming from each of electricity generation and petroleum usage. A large emission cut would thus require actions such as

- a large cut in energy use, which could be both costly and economically disruptive,

- development of new technologies, improving the emissions efficiency of fossil fuel usage or
- actions reducing the dependence on fossil fuel sources by switching fuels.

The costs of such actions were a prominent argument used in justification of the U.S. rejection of the terms of the Kyoto Protocol. Nevertheless as manifest in the President's climate change initiative (Bush) the U.S. and other countries have announced policies to limit GHGE.

Achievement of emission reductions through technological development or fuel switching takes time. Agriculture and forestry may be able to provide low-cost, near term GHGE reduction strategies, buying time for technological development (McCarl and Schneider, 1999). Specifically, known management manipulations may be employed to enhance sequestration by removing carbon from the atmosphere and storing it in trees or soils.

When considering agricultural and forest carbon sequestration, one needs to recognize that the capacity to sequester is limited and an ecological equilibrium will be approached effectively saturating the ecosystems ability to hold carbon. For example, West and Post in examining 67 long term tillage experiments consisting of 276 paired treatments find that "Carbon sequestration rates, with a change from [conventional tillage to no tillage]…, can be expected to peak in 5-10 yr … reaching a new equilibrium in 15-20 yrs." They also argue that under alterations in "… rotation complexity, … [soils] may reach a new equilibrium in approximately 40-60 yrs". Furthermore, while agricultural and forestry carbon sequestration activities increase ecosystem carbon storage, such activities, if discontinued, result in the return of the sequestered carbon to the atmosphere and approach to a lower carbon level equilibrium. Thus, the permanence of sequestered carbon and the need for possible maintenance of non accumulating stocks must be considered.

The saturating behavior suggest that effectiveness, efficiency, and significance of agricultural and forestry carbon sequestration as a total society GHGE mitigation option is likely to vary dynamically. Previous studies examining carbon sequestration mitigation strategies in the agricultural and forest sectors have generally ignored the saturation and volatility characteristics embodied in ecosystem carbon pools or limited in analytical analysis (McCarl and Schneider 2000, 2001; McCarl, Murray, and Schneider; Antle et al.; Noble and Scholes; and Schuman et al.). Consequently, previous analyses may overestimate the long run mitigation potential of agricultural and forestry sequestration programs. This study will examine the dynamic role of agricultural and forestry carbon sequestration activities in the portfolio of agricultural and forestry responses to GHG emission reduction efforts when considering saturation and permanence issues.

METHODOLOGY

To examine the dynamic role of agriculture and forest carbon sequestration we need an analytical framework that can depict the time path of offsets from carbon sequestration vis a vis other agricultural and forestry possibilities as they vary over time. To do this we will use a GHG version of the Forest and Agricultural Sector Optimization

Model (FASOM - Adams et al) as developed in Lee and hereafter called FASOMGHG. This model has the forest carbon accounting of the original FASOM model unified with a detailed representation of the possible mitigation strategies in the agricultural sector adapted from Schneider and McCarl and Schneider (2001).

FASOMGHG, as developed in Lee, is an intertemporal, price-endogenous, spatial equilibrium model depicting land transfers between the agricultural and forest sectors in the United States. The model solution portrays a multi-period equilibrium that arises from a modeling structure that maximizes the present value of aggregated producers' and consumers' surpluses across both sectors. The results from FASOMGHG yield a simulation of prices, production, management, and consumption within these two sectors under the scenario depicted in the model data. A mathematical presentation of the meeting appears in the Appendix.

In terms of GHG mitigation FASOMGHG depicts the GHG mitigation alternatives summarized in Table 1. Namely, the model considers the level and potential alteration of nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2) emissions from agricultural crop and livestock plus forest management and forest establishment activities. In addition, the possibility of enhancing carbon sequestration through tillage change, and avoided deforestation is also depicted. Likewise, additional costs associated with mitigation activities are included. Furthermore, since FASOMGHG is built in a dynamic framework, saturation conditions for agricultural terrestrial pools are incorporated as explained below.

Incorporating Agricultural Soil Sequestration Saturation

Terrestrial carbon sinks are capable of accumulating carbon, but are limited by ecosystem capability in interaction with the management system. In particular carbon only accumulates until a new equilibrium is reached under the management system. Moreover, the carbon accumulated in soils or trees exists in a potentially volatile form where increased soil or vegetation disturbance can release it. Thus, current GHG emission reductions by sinks can result in potential future GHG emission increases. FASOMGHG assumes when cropland tillage practice or land use (to pasture or grasslands) is altered, the carbon gain/loss stops after the first 30 years based on the previous tillage studies (West and Post) and opinions of soil scientists (Parton). The gains in carbon vary according to the previously used and newly adopted tillage practice. Carbon gains or losses in FASOMGHG are assumed linear over 30 years. Furthermore, the sequestering tillage practice may have to remain in use even after the soil carbon content reaches equilibrium, otherwise if tillage is intensified the carbon will be released.

FASOMGHG also depicts sequestration gains from land use change namely conversion of croplands to grasslands or forests and conversion of grasslands to forests. As cropland converts to grasslands the carbon content is assumed to change over a 30 year period.

Incorporating Forest Sequestration Saturation

FASOMGHG as explained in Adams et al (1996, 1999) and Alig et al is a 100 year forest and agricultural simulator. Forest carbon accounting is based on the procedures in the FORCARB model as developed by Birdsey and associates and the HARVCARB model of Rowe. Forest carbon is accounted in four basic pools, soil, ecosystem, standing trees and products after harvest. Under afforestation actions soil carbon initially rises rapidly, but later levels off particularly after the first rotation. The ecosystem component (carbon in small vegetation, dropped leaves, woody dentritus, etc) follows a similar pattern. The standing tree parts is based in forest growth and yield tables from the Forest Service ATLAS model (Haynes, Alig, and Moore) coupled with FORCARB which exhibit rapid initial growth and then approach a near steady state forest as the stand matures. The product accounting uses the results of Rowe where products decay overtime due to characteristics or use discontinuation. Thus in all of these cases saturation occurs as stands age.

RESULTS AND IMPLICATIONS

The basic exercise in this paper is to examine the dynamic portfolio of GHG offsets that arise from agriculture and forestry under different carbon equivalent (CE) prices. The CE price is applied to CO2, CH_4, and N_2O emissions/offsets time their Global Warming Potential (GWP), and the conversion of CO_2 to C. FASOMGHG will be used to simulate the strategies chosen CE price incentives ranging from \$0 to \$100 per ton of carbon equivalent (TCE) in \$5 increments, which are constant over time.

Offset estimates are computed on a total U.S. basis relative to responses under a business as usual -zero carbon price scenario and are thus only those additionally stimulated by carbon prices plus account for all domestic leakage..

Dynamic GHG Emission Changes in Different TCE Price Scenarios

Figures 1 to 3 present the accumulated GHG mitigation credits from forest sequestration, agricultural soil sequestration, powerplant feedstock biofuel offsets, and non-CO_2 strategies.

At low prices (below $25 with $10 portrayed in Figure 1) and in the near term, the carbon stock on agricultural soil grows rapidly initially and is the dominant strategy. However the offset quantity later diminishes and becomes stable with saturation setting in after 30 years. Carbon stocks in the forest grow over time at low prices and non-CO_2 strategies continually grow throughout the whole time period. Biofuel is not a factor as it is too expensive to be part of a low carbon price mitigation plan.

When the prices are higher ($50 to $100 per tonne), the forest carbon stock increases first then diminishes and becomes stable; the agricultural soil carbon stock is much less important in the big picture especially in the later decades; non-CO_2 mitigation credit grows over time but is not a very large player. Powerplant feedstock biofuel potential grows dramatically (ethanol is not used) over time and becomes the dominant strategy in the later decades.

Across these and other runs several patterns emerge.

- Carbon sequestration, including agricultural soil and forest carbon sequestration, and powerplant feedstock biofuel offsets are the high quantity mitigation strategies in the agricultural and forest sectors. The importance of these three strategies varies by price and time.
- At low prices and in early periods agricultural soil carbon is the dominant strategy. When prices get higher this is replaced by afforestation and powerplant feedstock biofuels as they have higher per acre carbon production rates.
- The sequestration activities tend to rise then stabilize largely due to saturation phenomena. Soils saturate faster than trees.
- The higher the price the more carbon stored in the forests in the early decades, but the intensified forest sequestration comes with a price in that CO_2 emissions from forests increase later. When the forest carbon sequestration program starts, reforestation or afforestation is encouraged and the harvest of existing timber is slowed down. However, the future harvest increases because of the increased mature forests by the increasing inventory of reforestation, afforestation, and previous postponed harvests. By 2050, the forest sector annually emits 29 MMT of carbon compared to the BAU scenario when the price is $50, and this goes up to 46 MMT when the price is $100. Although the mitigation potential is smaller in the early decades when the price is low, e.g. $10,

the carbon capacity of forest is not saturated until 2070, and thus extends the time to sequester additional carbon.

- In the early stage of the mitigation program, the higher the price, the more forest sequestration is desired Agricultural soil carbon sequestration annually mitigates 54 MMT of carbon at a $10 price and its mitigation potential peaks at a price of $35 with 66 MMT of carbon mitigation potential in the first decade.
- Biofuels do not enter the mitigation portfolio until the price reaches $35 in the first decade. The higher the price, the more power plant feedstock biofuel production is encouraged. The potential of annual biofuel offsets is 26 MMT of CE at $35, increases up to 118 MMT at $50, and reaches 191 MMT of CE at $100 in the first decade.
- After the agricultural sequestration program has lasted for 30 years, the agricultural carbon pool begins to contribute to CO_2 emissions, although higher prices slow down such a process. About 30 MMT are added to the air annually in the fourth decade when the price is $10. When the price is $50, the annual carbon increment is 10 MMT in the fourth decade and when the price goes up to $100, releases do not occur until 70 years after the program begins.

Sensitivity Test on Soil Saturation

This study incorporates the saturation and volatility characteristics of agricultural soil carbon sequestration. In a joint mitigation implementation program, FASOMGHG results generally show that after 30 years of sequestration programs, the net emissions increase from cropland compared with the BAU scenario. If we overlook the saturation characteristic in agricultural soil carbon sequestration, and assume that cropland can sustainably absorb or emit CO_2 once it is in some specific tillage management. FASOMGHG is modified to simulate such change by using a 30-year average carbon intake or discharge of different tillage management for all future decades.

Modified FASOMGHG results show the agricultural soil is a sink during the total modeling period (Table 1). In addition, the agricultural soil carbon sequestration potential in the first decade is higher than a "with saturation" case. However, this strategy becomes less important in the later decades because other strategies such as biofuels can more efficiently offset GHG emissions. In general, biofuels are less important in a "without saturation" assumption than in a "with saturation" one. Neglecting sequestration limits overestimates the cropland sequestration potential and the aggregate mitigation potentials of the total agricultural and forest sectors.

CONCLUSIONS

This study analyzes the optimal dynamic portfolio of GHG mitigation strategies in the agricultural and forest sectors. Focus is placed on the role of agricultural and forest carbon sequestration activities in a dynamic portfolio of agricultural and forestry responses to GHG emission reduction efforts with consideration of ecosystem and management system related saturation.

Our results show that the agricultural and forest sectors offer substantial potential to mitigate GHG emissions, offsetting 3.5 to 39 percent of U.S. projected GHG emissions by 2010 for a CE price ranging from $10 to $100. The optimal mitigation portfolio to achieve such offsets changes dynamically depending on price and time. Carbon sequestration is the primary mitigation strategy implemented in the early decades and at low prices (below $25 per ton) but then saturate and even turn into sources after 20 to 40 years. Agricultural soil carbon sequestration is the most efficient approach at low carbon prices ($10 and below) and forest carbon sequestration is more desirable at prices in the $25 range. On the other hand, power plant feedstock biofuel activites become more important in the longer run or at higher prices

This study also examines the importance of saturation consideration in regard to agricultural soil. If we ignore saturation, then the importance of agricultural soil as a carbon sink is overstated as is the potential of the entire agricultural and forestry sectors.

The findings of this study support the argument that agricultural and forest carbon sequestration provides more time to find long-run solutions such as new technologies to halt the increasing ambient greenhouse gas concentration as discussed in Marland et al. It also shows that power plant feedstock biofuels is likely to be an important long run strategy.

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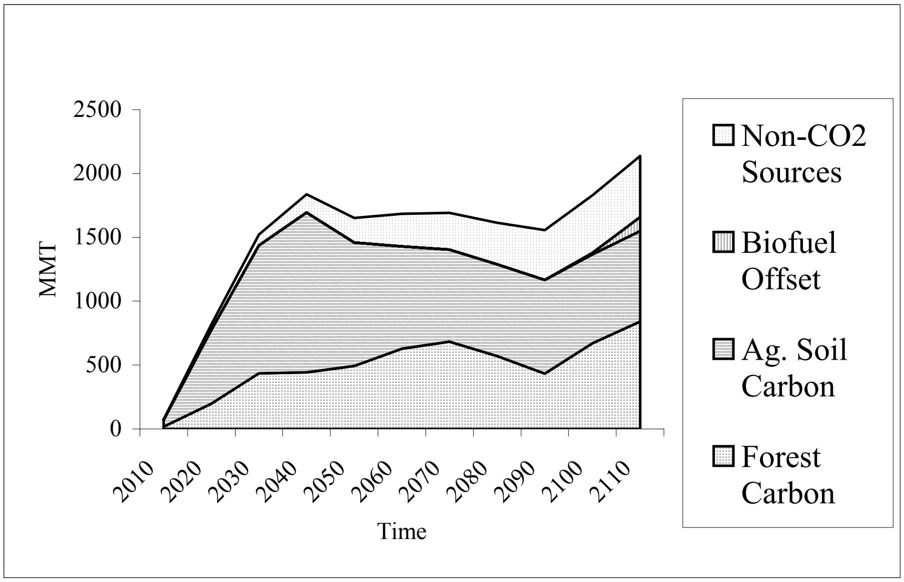

Figure 1. Cumulative mitigation contributions from major strategies at a $10 carbon equivalent price

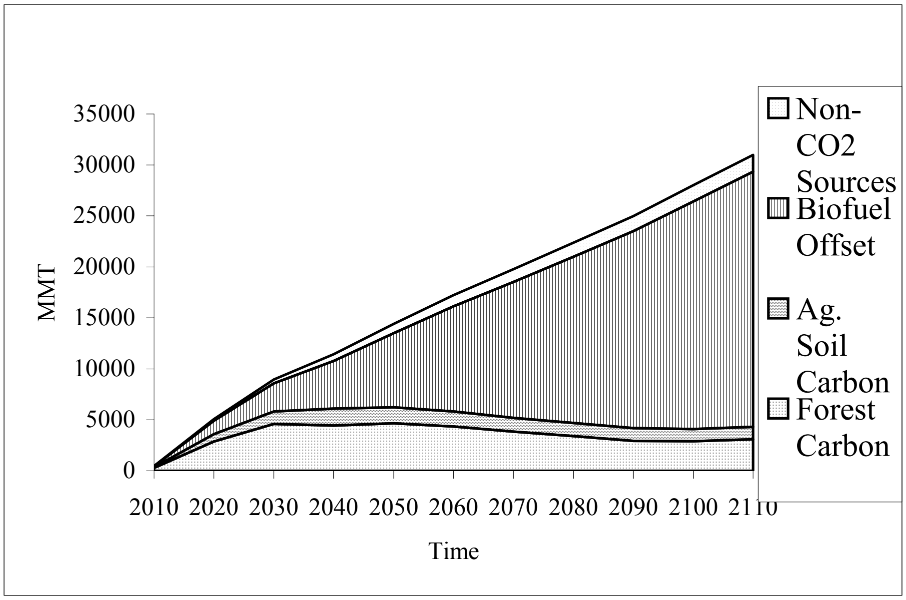

Figure 2. Cumulative mitigation contributions from major strategies at a $50 carbon equivalent price

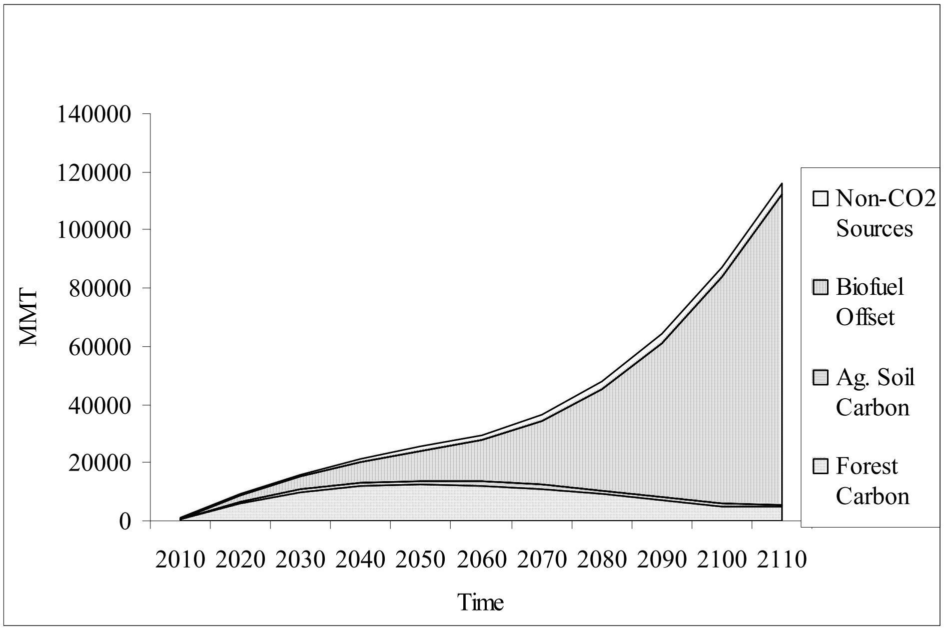

Figure 3. Cumulative mitigation contributions from major strategies at a $100 carbon equivalent price

Table1. Mitigation in Million Metric Tons of Carbon Equivalent per year relative to the Business as Usual Scenario with and without Cropland Saturation for Selected Carbon Equivalent Prices

Time	Price	Saturation Assumption	Aggregate	Forest	Ag. Sequestration	Biofuel
2010	$10	No	94.62	17.34	69.35	
		Yes	76.51	17.00	53.52	
	$25	No	206.91	105.60	86.44	
		Yes	179.82	103.23	63.78	
	$50	No	462.30	247.44	84.57	108.22
		Yes	476.19	269.82	63.15	118.41
	$100	No	877.04	592.75	67.06	179.93
		Yes	852.87	570.92	52.08	192.02
2020	$10	No	79.64	26.99	45.23	
		Yes	74.86	26.52	43.18	
	$25	No	161.61	83.77	47.99	11.80
		Yes	151.31	81.97	51.88	5.58
	$50	No	406.01	199.69	52.82	117.49
		Yes	414.75	192.38	52.84	138.92
	$100	No	709.48	414.18	29.34	204.11
		Yes	703.49	401.95	43.22	200.48
2030	$10	No	33.42	-1.68	28.39	
		Yes	38.75	0.60	30.96	
	$25	No	74.04	22.86	38.43	
		Yes	69.28	17.48	39.15	
	$50	No	248.28	0.86	40.59	170.67
		Yes	248.53	-20.67	47.31	185.28
	$100	No	571.09	191.63	28.74	280.68
		Yes	598.05	214.29	38.64	277.27
2040	$10	No	30.87	4.31	19.45	
		Yes	-19.87	3.70	-30.18	
	$25	No	52.28	3.94	35.75	
		Yes	-13.00	6.89	-30.28	
	$50	No	352.63	22.00	40.82	253.06
		Yes	306.31	28.56	-11.67	257.20
	$100	No	431.55	27.79	41.81	300.27
		Yes	408.85	46.65	4.73	300.27

Table 1. Continued

Time	Price	Saturation Assumption	Aggregate	Forest	Ag. Sequestration	Biofuel
2050	$10	No	34.31	13.53	14.09	
		Yes	4.28	14.16	-18.12	
	$25	No	24.28	-13.14	27.00	
		Yes	-18.64	-10.86	-18.72	
	$50	No	329.97	-35.19	35.94	300.27
		Yes	296.22	-29.26	-6.39	300.27
	$100	No	392.27	-53.02	43.05	352.60
		Yes	408.21	-38.85	16.77	376.46
2060	$10	No	26.53	7.18	15.22	
		Yes	1.41	7.54	-10.27	
	$25	No	27.23	-4.39	24.30	
		Yes	-11.10	-3.54	-13.15	
	$50	No	310.42	-48.82	36.10	300.27
		Yes	261.53	-51.32	-12.21	300.27
	$100	No	547.47	-90.93	44.07	549.12
		Yes	645.54	-87.94	6.44	675.58
2070	$10	No	6.78	-10.25	12.00	
		Yes	-3.68	-10.76	1.45	
	$25	No	22.63	-3.10	17.40	
		Yes	2.30	-3.64	-4.16	
	$50	No	309.01	-42.46	28.38	300.27
		Yes	273.77	-42.15	-7.32	300.27
	$100	No	1140.70	-159.41	24.43	1227.24
		Yes	1129.88	-171.04	-21.03	1264.55

Appendix

Table A1. Mitigation Strategies in FASOMGHG

Mitigation Strategy	Data Source/Reference	Greenhouse Gas Emission Effect		
		CO_2	CH_4	N_2O
Existing Forest Stand	FASOM	-[a]		
Reforestation	FASOM	-		
Deforestation	FASOM	+		
Afforestation/timberland	FASOM	-		
Biofuel production	POLYSIS analysis, GREET model, EPIC model	-	-	+
Crop mix alteration	EPIC model	+/-		+/-
Rice acreage reduction	EPA		-	
Crop fertilizer rate reduction	EPIC model, IMPLAN software	+/-		-
Other crop input alteration	USDA data	+/-		
Crop tillage alteration	EPIC model	+/-		+/-
Grassland conversion	EPIC model	-		
Irrigated/dry land conversion	Ag-Census	+/-		+/-
Livestock management	EPA data, IPCC		+/-	
Livestock herd size alteration	EPA data, IPCC		+/-	+/-
Livestock production system substitution	EPA data, IPCC		+/-	+/-
Liquid manure management	EPA data, IPCC		-	

[a] A negative sign refers to a GHG emission offset and a positive sign refers to a GHG emission increase.
Source: Adams et al. (1996) and McCarl and Schneider (2001).

Simplified Mathematical Presentation of FASOMGHG

(1) Objective Function of FASOMGHG

$$
\begin{aligned}
Max\ W = \sum_t (1+d)^{-t} \{ [& \sum_i \int F\varphi_i (FQ_{i,t})\, dFQ_{i,t} + \sum_{i,r} FE\varphi_{i,r}(FEX_{i,r,t}) dFEX_{i,r,t} \\
& - \sum_{i,r} FI\varphi_{i,r}(FIM_{i,r,t}) dFIM_{i,r,t} \\
& + FT \sum_r (FS_{r,t} - FS_{r,t-1})] \\
& + N[\sum_i \int A\varphi_i (AQ_{i,t})\, dAQ_{i,t} - \sum_r \sum_j AC_{r,j,t} AX_{r,j,t} \\
& + \sum_{i,c} E\varphi_{i,c} (\sum_{c'} AEX_{i,c,c',t}) d(\sum_{c'} AEX_{i,c,c',t}) \\
& - \sum_{i,c} I\varphi_{i,c} (\sum_{c'} AIM_{i,c,c',t}) d(\sum_{c'} AIM_{i,c,c',t}) \\
& - \sum_{r,n} M_{r,n,t} \times MC_n + \sum_{s,g} T_g \times (TS_{s,g,t} - TE_{s,g,t})] \} \\
+ (1+d)^{-T} \frac{TI}{(1+d)^{10} - 1} &
\end{aligned}
$$

(2) Existing Forest Inventory

$$
\sum_{ot} EX_{ot,a,r,c,m} \le IEX_{a,r,c,m} \qquad \forall \text{ a, r, c, m}
$$

(3) Forest Land Balance

$$
\begin{aligned}
& -\sum_{a,m} EX_{t,a,c,r,m} + \sum_{ot,w,m|(ot=t)} N_{w,ot,r,c,m,t} \\
& - \sum_{w,m,ot|(w+ot-1=t)} N_{w,ot,r,c,m,t} + \sum_l (TA_{c,l,r,t} - FA_{c,l,r,t}) = -LO_{c,r,t}
\end{aligned}
\qquad \forall \text{ t, c, r}
$$

(4) Transferable Forest Land Limitation

$$
\sum_{l,ot|(ot \le t)} (TA_{c,l,r,ot} - FA_{c,l,r,ot}) \le FL_{c,r} \qquad \forall \text{ t, c, r}
$$

(5) Forest Product Balance

$$\sum_{a,r,c,m} OY_{t,a,r,c,m,i} \times EX_{t,a,r,c,m} + \sum_{w,ot,r,c,m|(w+ot-1=t)} NY_{w,r,c,m,i} \times N_{w,ot,r,c,m,t,i} - FQ_{i,t} \le 0 \qquad \forall\ t, i$$

(6) Forest Carbon Stock Accounting

$$\sum_{ot,a,c,m} OC_{ot,a,r,c,m,t} \times EX_{ot,a,r,c,m} + \sum_{ot,w,c,m} NC_{t,ot,w,r,c,m} \times N_{w,ot,r,c,m,t} = FS_{r,t} \qquad \forall\ t, r$$

(7) Agricultural Land Balance

$$\sum_{tl} CP_{t,r,l,tl} - \sum_{c,ot|(ot\le t)} (FA_{c,l,r,ot} - TA_{c,l,r,ot}) \le LA_{r,l} \qquad \forall\ t, r, l$$

(8) Transferable Agricultural Land Limitation

$$\sum_{l,ot|(ot\le t)} (FA_{c,l,r,ot} - TA_{c,l,r,ot}) \le AL_{r,c} \qquad \forall\ t, r, c$$

(9) Agricultural Resource Constraints

$$\sum_{j} (A_{r,j,k,t} \times AX_{r,j,t}) - R_{r,k,t} \le 0 \qquad \forall\ t, r, k$$

(10) Production Balance Constraints

$$AQ_{i,t} - \sum_{r} \sum_{j} (B_{r,i,j} \times AX_{r,j,t}) + \sum_{c,r} AIM_{i,c,r,t} - \sum_{c,r} AEX_{i,c,r,t} \le 0 \qquad \forall\ t, i$$

(11) Agricultural Commodity Export Balance

$$\sum_{c'} AIM_{i,c,c',t} - S_{c,i,t} \le 0 \qquad \forall\ t, c, i$$

(12) Agricultural Commodity Import Balance

$$-\sum_{c'} AEX_{i,c',c,t} + D_{i,c,t} \le 0 \qquad \forall\ t, c, i$$

(13) Agricultural Emission Account:

$$\sum_{r,j} (E_{r,j,s,g,t} \times X_{r,j,t}) = TE_{s,g,t} \qquad \forall s, g, t$$

(14) Agricultural Emission Offset Account:

$$\sum_{r,j}(S_{r,j,s,g,t} \times X_{r,j,t}) = TS_{s,g,t} \qquad \forall s, g, t$$

Where:

W = Objective,

d = Discount rate,

$F\varphi_i(*)$ = Inverse demand function for timber product i,

$FQ_{i,t}$ = Forest product i demand at time t,

$FE\varphi_{i,r}(*)$ = Inverse forest export demand function for timber product i, in region r,

$FEX_{i,r,t}$ = Forest product i export from region r at time t,

$FI\varphi_{i,r}(*)$ = Inverse forest import supply function for timber product i, in region r,

$FIM_{i,r,t}$ = Forest product i import to region r at time t,

FT = Price of per unit forest carbon sequestration,

$FS_{r,t}$ = Forest carbon stock in region r at time t,

N = Factor to convert annual agricultural value to decadal basis,

$A\varphi_i(*)$ = Inverse demand function for agricultural product i,

$AQ_{i,t}$ = Agricultural product i produced at time t,

$AC_{r,j,t}$ = Cost of agricultural production activity j in region r and time t,

$AX_{r,j,t}$ = Agricultural production activity j in region r at time t,

$E\varphi_{i,r}(*)$ = Inverse agricultural export demand function for product i, in region r,

$AEX_{i,c,c',t}$ = Agricultural product i export from country c to country c' at time t,

$I\varphi_{i,r}(*)$ = Inverse agricultural import supply function for product i, in region r,

$AIM_{i,c,c',t}$ = Agricultural product i import from country c to c' at time t,

MC_n = Cost of manure management for animal n,

T_g = Price of per unit emission/offset for different strategy gas g,

T = Last explicit time period,

TI = Terminal value,

$EX_{ot,a,r,c,m}$ = Existing forest stand at the beginning of modeling period with cohort age a, region r, land class c , management m, and harvested at time ot,

$IEX_{a,r,c,m}$ = Initial forest inventory at the beginning of the modeling period at age a, region r, land class c, and management m,

$N_{w,ot,r,c,m,t}$ = New timber stand at time t planted in time ot, region r, land class c, management m, harvested w decades after planted,

$TA_{c,l,r,t}$ = Land convert to agricultural use in land class c, land type l, region r, and time t,

$FA_{c,l,r,t}$ = Land converted from agriculture in land class c, land type l, region r, and time t,

$LO_{c,r,t}$ = Land converted to urban in land class c, region r, and time t ,

$FL_{c,r}$ = Available land converted to agricultural use in region r and land class c,

$OY_{t,a,r,c,m,i}$ = Product i yield of existing forest stand harvested at time t in region r, land class c, management m, when cohort age a at the beginning of the modeling period,

$NY_{w,r,c,m,i}$ = Product i yield of new forest stand w decade after planted in region r, land class c, and management m,

$OC_{ot,a,r,c,m,t}$ = Carbon yield of per acre land in existing forest stand at time ot when cohort age a at the beginning of the modeling period and harvested w decades afterward, in region r, land class c, and management m,

$NC_{t,ot,w,r,c,m}$ = Carbon yield of per acre land in newly planted forest stand at time t period, when planted at time ot, harvested w decades later, in region r, land class c, and management m,

$FS_{r,t}$ = Forest carbon stock in region r and at time t,

$LA_{r,l}$ = Available agricultural land in region r, land type l,

$AL_{r,c}$ = Limit on land moved from agriculture in region r and land class c,

$A_{r,j,k,t}$ = Per acre factor k used in production activity j in region r at time t,

$R_{r,k,t}$ = Resource k available in region r at time t,

$B_{r,i,j}$ = Per acre yield of commodity i using production activity j in region r,

$S_{c,i,t}$ = Country c excess supply of commodity i at time t, and

$D_{i,c,t}$ = Country c excess demand of commodity i at time t.

$E_{r,j,s,g,t}$ = Per acre GHG g emission from source s in region r, activity j, and time t,

$X_{r,j,t}$ = Acreage in production activity j in region r and time t,

$TE_{s,g,t}$ = Total emission of GHG g from source s at time t,

$S_{r,j,s,t}$ = Per acre GHG g emission offset from source s in region r, activity j, and time t,

$TS_{s,g,t}$ = Total emission reduction of GHG g from source s at time t, and