The Optimal Choice of Residue Management, Crop Rotations, and the Cost of Soil Carbon sequestration

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Paper prepared for presentation at the American Agricultural Economics Association Annual Meeting, Montreal, Canada, July 27-30, 2003

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INTRODUCTION

The potential for carbon to be sequestered in agricultural soils has recently gained considerable attention because carbon in the soil pool could be an attractive mitigation alternative. It is estimated that the total soil carbon pool contains 3.5% of the earth's carbon stock, compared with 1.7% in the atmosphere (Lal et al, 1995). To date, several studies have examined the potential and the cost of carbon sequestration in agricultural soils in the United States (Antle et al., 2001; Pautsch et al., 2001; McCarl & Schneider, 2001). The studies to date use a wide variety of methods and many of them focus on particular regions. McCarl and Schneider (2001), for example, use a mathematical programming model for the entire U.S. agricultural sector. Antle et al (2001) integrate a bio-physical process model and econometric simulation model for the Northern Plains region. Pautsch et al (2001) estimates the probability of tillage adoption in Iowa, and links these results to a physical process model. The estimate of soil carbon sequestration cost from the studies ranges from $2 to $60 per ton of carbon.

These studies provide important insights on the cost of carbon sequestration, but to date, several important intertemporal aspects have been ignored. First, soils

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[Ψ] The funding of this study was obtained from a seed grant at the Ohio Agricultural Research and Development Center (OARDC) and from the USDA-Consortium for Agricultural Soils Mitigation of Greenhouse Gases (CASMGS). We thank Rattan Lal and Brian Slater from Department of Soil Science in School of Natural Resource at The Ohio State University for soil carbon data and greatly helpful comments and discussions.

accumulate carbon slowly, and different levels of residue management could lead to different rates of accumulation and different steady-state levels in the future (Lal et al., 2000). This could have important implications for carbon sequestration because different types of soils in different regions, and different types of farmers lead to a wide range of observed residue levels. Most studies to date have compared conventional tillage systems to no-till systems, or they have used fixed rental payments per acre to spur conversion of land to no-till, and thus have ignored the effects of the intensity of residue management on the costs of carbon sequestration. There could be efficiency gains associated with designing policies that match payments more closely to the intensity of carbon stored on a site, however. This may be particularly important because landowners are observed to choose a range of residue levels, depending on their equipment, rotations, and other factors.

Second, there is evidence that even small reductions in residue on a site could lead to instantaneous emissions of much of the stored carbon into the atmosphere by plowing the land (Reicosky, 1997; Reicosky et al., 2002; Hansmeyer et al, 1998). Data from the USDA NRI (2001) suggests that since 1982, farmers have shifted into and out of conservation tillage frequently. Further, evidence from eastern Corn Belt states, like Ohio, suggests that farmers typically use conservation tillage with soybeans but not with corn (CTIC, 2002). Thus, many typical rotations used in eastern Corn Belt states would lead to cycles of carbon accumulation followed by instantaneous emissions when the land is plowed. When designing policies for carbon sequestration, it is thus important to account for crop rotations and potential cycles in sequestered carbon that could occur. Further, given the potentially important link between carbon payments, conservation tillage, and crop rotations, payments could alter the proportion of land in different types of crops, and ultimately prices. Several existing studies ignore these price effects, potentially leading to biased estimates of the cost of carbon sequestration.

The objective of this study is to develop a dynamic optimization model that explores the costs of carbon sequestration in row crop agriculture production activities. First, we estimate empirical model that explores how residue management affects crop yield. While residue management reduces yields for some crops, like corn, and potentially raises yields for others, like soybeans, it reduces costs for both. The empirical model explores how residue management affects yields for different types of crops, and how these impacts vary across land of different quality, as suggested by Porter et al. (1997). It is entirely possible that the marginal changes in profits could differ dramatically across different types of land, and consequently affect optimal strategies for sequestering carbon.

Second, this paper examines the optimal choice of crop rotation and residue management when crop price is treated as exogenous. Although a more thorough analysis of a larger region with prices exogenous will be conducted in the future, the dynamic model for this analysis is applied to one county in Ohio, Henry County, under the assumption that crop prices are exogenous. Baseline results of crop rotation between corn and soybean, production, and tillage intensity choice are first estimated. Carbon sequestration policy is implemented by renting carbon in agricultural soils. For this analysis, carbon prices are assumed to be constant, using estimates from Nordhaus and Boyer (2000) to develop a range of potential prices that could occur over the next 20 – 30 years. A sensitivity analysis explores differences in the results under alternative assumptions about relative corn and soybean prices. As mentioned, future analysis will expand these results to include additional regions with endogenous prices.

DATA AND PARAMETERS

This study employs a dynamic optimization model of crop choice in Ohio. To parameterize the profit functions in the model, various sources of data are used to estimate empirical parameters. The dynamic optimization model for this study focuses on corn and soybean alone because they are the major land use in our Eastern Corn Belt study region in general, and in Ohio. In 1997, the proportion of total corn and soybean harvested land among total harvested land in Ohio is 76% according to the Census of Agriculture (USDA, 1999). In addition to the various studies from agronomy, crop science, and soil science that are used to estimate initial carbon levels, carbon dynamics, and "steady state" of carbon, we develop empirical estimates of the effects of residue management and soil quality on corn and soybean yields.

The effects of residue management on crop yields have been investigated by numerous studies (for examples, Uri, 2000; Dick et al., 1997; Stecker et al, 1995; Dick & Van Doren, Jr., 1985; Bone et al, 1977). These authors suggest a wide range of impacts of residue management on crop yields, depending on crop, location, soil type, and experimental design. Although these findings provide useful information, they usually do not capture the relation between yield and actual land owners' behaviors, and they are not statistically representative (Antle et al, 2001; Segerson & Dixon, 1999).

Following Segerson and Dixon (1999), yield impacts of residue management for corn and soybean are estimated using annual county level data for Ohio from 1988 to 1998. Using OLS estimation, residue management effects on corn and soybean yield are investigated. Corn and soybean yield (bushel per acre) are separately regressed on the dependent variables such as precipitation, soil physical characteristics, and tillage adoption rates (See table 1 for variables). CLAG and SLAG variables are lagged dependent variables for corn and soybean yields respectively to capture possible autocorrelation. Yield data for each crop were obtained from USDA NASS data base for each year (USDA, 2002).

Total precipitation for January, April, July, and October in each year are used to capture climatic impacts on yield. Climatic data is obtained from 10 different climatic divisions in Ohio and it is estimated for each county (MRCC, 2002). The K-factor measures how erodible the soil is. The higher the number for the k-factor, the less productive the land. For the analysis, the average k-factor for each county is used (NRI, 2001).

Residue management is captured by the variables CTIX, STIX, INTC, and INTS variables. Extensive information on residue management and crop types for each county were available from CTIC (2002). The data contains different tillage adoption acres such as no-till, ridge- till, mulch-till, reduced-till, and conventional till for corn and soybean since 1988 to 1998. The level of residue that remains on the fields varies by tillage practice. Conventional tillage is the practice that leaves less than 15% of residue, reduced tillage is the type that leaves between 15-35% of residue, mulch till and ridge till leaves between 35% to 70% residue, and no-till is the type that residue level is more than 70%.

CTIX and STIX variables are calculated as the proportion of weighted average of residue remains to total harvested land for corn and soybean respectively. The next variable INTC and INTS are interaction variables between k-factor and tillage intensity index which is multiplication of two variables. We further test out hypothesis of residue manage impacts on yield level using these interaction variables. We assume that residue management intensity could affect differently on different quality land. This interaction variable could provide additional relation of residue management on yield through different land quality classes. So the coefficient of interaction variables could capture the effects of residue management under given quality of land, k-factor. The last variable T is a time trend variable starting from 1 in 1998 that could capture technical progress and any fundamental changes within 10 years.

The estimation results in Table 2 show expected results overall. Lagged dependent variables on both equations have positive relation but insignificant result for soybean equation. Weather variables show reasonable results that precipitation on growing season such as July has positive impact on yield but precipitation on harvest season in October has negative impacts. January precipitation in corn equation shows significant negative impacts on yield level that could possibly capture the effects of moisture on seeding season in spring. Soil quality variable k-factor shows expected relation on both crop yields because higher number of k-factor is less productive land.

Residue management variable CTIX and STIX show negative impacts on yield level which has been suggested by various studies. Although these variables shows negative impacts of residue management on yield level, it is not clear how it affects on different land types and how much it could impact on the yield. The hypothesis on different impacts of residue management on crop yield could be tested by calculating marginal impacts of residue management. From the OLS regression, the marginal impact of residue management on yield is just the sum of CTIX variable coefficient and the coefficient of INTC and k-factor itself. It could be expressed as following

$$\frac{dYield}{dCTIX} = \beta + \gamma KFACT \qquad (1)$$

, where β is the coefficient of CTIX and γ is the coefficient of INTC. To estimate marginal impacts for the data, it is reordered from lowest to higher k-factor, and the marginal impact is calculated for each observation using equation (1) above. Table 3 shows four different land quality by k-factor percentiles packets and the numbers are average of marginal yield change on both crops. The results suggest that with different land qualities residue management has different effects on yield. Corn yield is more affected in higher land quality. Residue management does not heavily affect yields for lower quality land. Soybean yield, however, is not affected by residue management overall. These findings are used in the dynamic model.

Although higher residue reduces yield, farm profitability may still rise because no-till management could reduce the input costs for fertilizers, fuel for machines, machinery repair cost, and labor costs. Numerous studies investigate how these input costs change with tillage choice (for example, Yoridoe et al., 2000; Katsvairo & Cox, 2000; Sijtsma et al., 1998; Clements et al., 1995; Lines et al., 1990). On average, the total variable costs difference between no-till and conventional till is about $56 per hectare in 2002. As residue management increases, input usage on pesticide and herbicide is increased for treating higher number of insects and microbial activities from higher level of remains. For this study, the cost factors for these inputs are reflected but the carbon impacts by these factors are ignored. Yield response by fertilizer input is estimated from other studies (Vitosh et al., 2002; Munn et al., 1998). It is incorporated with yield level data from USDA NASS (2002) and used in the optimization model.

For the carbon study, it is important to examine crop rotation as well as tillage intensity because carbon dynamics for different rotations are different along tillage choices (Lal et al, 1998). Crop rotation is recommended by numerous reasons such as for higher yield, preventing pathogens built up, weed and insects controls, and for overall lower costs (Beuerlein, 2001). It is also shown from USDA NASS and CTIC data that farmers tend to shift their land usage between corn and soybean in this region. Among various important factors of crop rotation, we focus on the yield change by rotation.

Experimental science studies show that continuous corn yield level is less than the rotation of corn and soybean (Porter et al., 1997; Stecker et al., 1995). In Ohio, corn yields are generally higher by 5 - 15 % when corn is rotated with soybean, rather than planted continuously (Beuerlein, 2001). For the dynamic crop choice model, we assume that yield level declines the longer an individual maintains land in a single crop type, and that the magnitude of this reduction in yield depends on the land quality. This assumption follows Porter et al (1997), who showed that corn and soybean rotation yields are up to 25% higher than continuous corn in poor production region and up to 15% higher in high production regions.

Carbon accumulation in agricultural soil is affected by many physical, biological and chemical processes (Lal, 2002). We focus on the impacts of residue management on organic carbon in the first 30cm of the soil column. The dynamics of soil organic carbon with respect to residue management are obtained from various studies (Lal et al., 2002 &

personal communication, 2003; West & Post, 2002; West & Marland, 2002; Paustian et al., 1997). Although enhanced residue management accumulates organic carbon in soil, the accumulation slows as carbon reaches a steady state level. In general, soil scientists suggest that for intensive residue management practices, such as no-till (where >90% residue remains on the site) steady state carbon levels are attained in 15 – 20 years. (Dick et al., 1997; Pierce & Fortin, 1997; Vitosh et al, 1997; West & Post, 2002),

DYNAMIC CROP CHOICE MODEL

The dynamic model in this study maximizes the profit of landowners who are facing exogenous crop prices. The choice variables for the problem are land allocation of row crops in corn versus soybean, fertilizer inputs, and residue management intensity. The objective function is in equation (2).

$$\underset{\substack{FC,FS,CS,\\SC,RC,RS}}{Max} \sum_{t=0}^{T}\sum_{i=1}^{I}\gamma^{t}\{P_t^C[Q_{i,t}^C(F^C, X^C, RC)] + P_t^S[Q_{i,t}^S(F, X^S, RS)] - C_t(F^C, F^S, X^C, X^S, RC, RS)\} \tag{2}$$

$$X_{i,t}^{c} = X_{i,t-1}^{c} - CS_{i,t-1} + SC_{i,t-1}$$

$$X_{i,t}^{S} = X_{i,t-1}^{S} + CS_{i,t-1} - SC_{i,t-1} \tag{3}$$

The notation t and i denote time and land class respectively. For the empirical estimates in this study, T is 50 years and I is 3. The equations of motions for corn and soybean land are shown in the equation (3). The functions and variables for this model are explained in table 5.

The first two terms in equation (2) are the revenue from corn and soybean. The function $Q^C(\cdot)$ and $Q^S(\cdot)$ is the yield function for the corn and soybean that depends on the fertilizer input (F^C&F^S), total land of corn (X^C) and soybean (X^S), years in continuous corn or continuous soybean (*YCT & SYT*), and percentage residue (*RC&RS*). The yield function for corn and soybean is in equation (4) and (5).

$$Q^C = [(\alpha_1 + \alpha_2 F^C - \alpha_3 F^{C^2}) \cdot \exp^{(-\alpha_4 RC)} \cdot \exp^{(-\alpha_5 YCT)}] \cdot X^C \tag{4}$$

$$Q^S = [(\beta_1 + \beta_2 F^S - \beta_3 F^{S^2}) \cdot \exp^{(-\beta_4 RS)} \cdot \exp^{(-\beta_5 SYT)}] \cdot X^S \tag{5}$$

Quadratic function of yield response by fertilizer was estimated from other studies (Vitosh et al., 2002; Munn et al., 1998). The estimates of parameters α and β are shown in table 5. The constant terms α_1 and β_1 were estimated from USDA data base (2002) to reflect different yield potential in different land class. The last two terms capture yield effects by residue management and continuous corn and soybean effect. The magnitude of each effect is different with land class (table 5). The negative sign in α_4, α_5, β_4, and β_5 indicate that yield level declines as residue management (*RC* & *RS*) increases and as a parcel of land continues in corn or soybean production without conversion to the other crop type (*YCT* & *SYT*).

Let the notation k and i be suppressed and the equation (2) and (3) could be expressed as discrete current value Hamiltonian,

$$H = V - C + \gamma\lambda(-CS + SC) + \gamma\delta(CS - SC) \tag{6}$$

In equation (6), V function is the value function of the first two brackets in equation (2), which is the sum of revenue in corn and soybean, C is the cost function consists of input costs such as fertilizer, fixed costs for corn and soybean, and , λ , and δ are costate variables. To maximize the problem, following conditions should be satisfied.

$$\begin{aligned} &\frac{\partial H}{\partial CS}; V_{CS} - C_{CS} - \gamma\lambda + \gamma\delta = 0 \\ &\frac{\partial V}{\partial SC}; V_{SC} - C_{SC} + \gamma\lambda - \gamma\delta = 0 \end{aligned} \quad (7)$$

$$\begin{aligned} &-\frac{\partial H}{\partial X^{C}} = \gamma\lambda - \lambda \\ &-\frac{\partial H}{\partial X^{S}} = \gamma\delta - \delta \end{aligned} \quad (8)$$

$$\begin{aligned} &\frac{\partial H}{\partial \gamma\lambda} = X_t^C - X_{t-1}^C \\ &\frac{\partial H}{\partial \gamma\delta} = X_t^S - X_{t-1}^S \end{aligned} \quad (9)$$

From conditions in equation (7), the optimal choice of land transfer between corn and soybean occurs according to the following condition.

$$\left\{\begin{matrix} CS = \overline{CS} \ \& \ SC = \underline{SC} \\ CS = \underline{CS} \ \& \ SC = \overline{SC} \\ CS \in \left[\underline{CS}, \overline{CS}\right] \& \ SC \in [\underline{SC}, \overline{SC}] \end{matrix}\right\} \quad \text{if} \ \left\{\begin{matrix} \lambda < \delta \\ \lambda > \delta \\ \lambda = \delta \end{matrix}\right\} \quad (10)$$

Equation (10) indicates that land shifts occur between corn and soybean as the marginal value of land in corn and soybean changes. For the baseline case, it is assumed that the price of corn and soybean both increase at 5 percent annually, so there is no change in the relative value of corn and soybeans. Land still shifts between the two crops because yields fall off the longer land remains in one crop or the other.

For the empirical analysis, baseline estimates of crop choices and carbon storage first developed. Then, estimates of carbon sequestration costs are obtained by implementing carbon policy that pays carbon rental per ton per year for different carbon prices, following Sohngen and Mendelsohn (2003). The objective function when augmented with carbon rental is shown in equation (11):

$$\underset{\substack{FC,FS,CS,\\SC,RC,RS}}{Max} \sum_{t=0}^{T}\sum_{i=1}^{I}\gamma^{t}\{P_t^C[Q_{i,t}^C(F^C,X^C,RC)]+P_t^S[Q_{i,t}^S(F,X^S,RS)]$$
$$+R_C\cdot K_t(RC,RS,X^C,X^S)-C_t(F^C,F^S,X^C,X^S,RC,RS)\} \qquad (11)$$

R_C is the carbon rental rate and K is the total carbon stock stored in agriculture soil. The total carbon is the function of residue management and land area in corn and soybean. For the scenarios considered in this analysis, only constant carbon prices are considered. Thus, if the carbon prices is given as $\$P_C$ in dollars per ton, the carbon rental rate is $R_C = r*P_C$, where r is the interest rate. Carbon prices explored in this analysis are \$3, \$10, and \$40 per ton, leading to annual rental values for a ton-year of carbon storage of \$0.15, \$0.5, and \$2 per ton per year. The models are solved using GAMS.

RESULTS

The results are shown in table 6 and figures 1-2. Several scenarios are considered. First, there are three crop price projections, including a base project where both corn and soybean prices rise at 5% per year, one scenario where corn prices rise slightly more rapidly, and one where soybean prices rise slightly more rapidly. For each of these crop price projections, three different constant carbon price scenarios are considered. Table 6 presents land use for the county in corn and soybean, total carbon storage, and residue management intensity in percent, and total average values for the entire 50 year time period. As shown in figures 1 – 2, the actual area of land in different crops, residue management, and total carbon storage varies substantially from year-to-year, but the average annual values presented in table 6 provide an indication of general trends in land use, residue management, and total carbon under the alternative scenarios considered.

For the baseline, the results suggest that small carbon prices of $3 - $10 per ton lead to relatively small changes in carbon sequestration. Total storage of carbon in the baseline is 847,151 tons, or 1,231 tons per hectare. Under the $3 and $10 carbon prices, this is 909,113 and 1,048,044 tons, or 1,321 and 1,523 tons per hectare respectively. On average, the per hectare carbon gains are 90 tons for the $3 price, 291 tons for $10 price, and 682 tons for the $40 price. The gains differ by crop, however, with most carbon accumulation for low carbon prices occurring in corn. As carbon prices rise, soybean hectares accumulate the most carbon. For $3 per ton, the gain for corn is 145 tons per hectare and only 13 tons per hectare for soybeans. For $10 per ton, the gain is 471 tons per hectare and 48 tons per hectare for corn and soybeans respectively, and for $40 per ton, the gain is 614 tons per hectare and 776 tons per hectare for corn and soybeans respectively. While the effect of residue management on yields is smaller for soybeans than for corn, small increments to residue management in corn can have a large effect on overall carbon storage.

For the carbon rental prices investigated here, there is little incentive to shift more land into soybeans. The results indicate small to no changes in the hectares of land devoted to each crop under the alternative carbon price scenarios. An implication of this result is that, despite the larger yield losses for residue management on corn acres than soybean acres, policy-makers need not worry about whether or not incentives for carbon would raise the percentage of land in soybeans. Of course, the specific incentive in this study distinguishes carbon quantities across corn and soybean acres. Thus, it also suggests that policies that fail to raise residue management on corn acres may also fail to increase carbon storage in agricultural lands.

The alternative crop price projections show that shifts in relative price levels, which lead to shifts in relative land areas devoted to the two crops could have important consequences for carbon sequestration and policy effectiveness. Note that while crop prices are specifically considered here, government incentives that cause general shifts in land allocation could also have implications for residue management and consequently carbon. Not surprisingly, if soybean prices are higher relatively than corn prices, soybean hectares rise relative to corn hectares. As shown in figure 2, average carbon storage rises for the baseline case (without carbon prices). This occurs because fewer acres per year are shifted to corn, and shifting acres to corn leads to some carbon emissions due to the generally lower residue levels with corn. Although baseline carbon rises relative to the initial output price scenario, carbon gains with carbon prices are 13 – 23% smaller. For example, there is a 167 and 20 ton per hectare carbon gain for corn and soybeans respectively for the $3 carbon price, a 334 and 143 ton per hectare carbon gain for corn and soybeans for the $10 carbon price, and a 432 and 586 ton per hectare carbon gain for corn and soybeans for the $40 carbon price. While the gains for corn are slightly larger, the gains for soybeans are smaller, and when aggregated across the larger proportion of hectares, this reduces the average gain in carbon by 13 – 26% for the county.

The higher corn price scenario not surprisingly, shifts more land into corn. In this scenario, average residue levels decline, and carbon storage declines. Corn land provides 44 tons of additional carbon per hectare under $3 carbon price, 318 tons per hectare under $10, and 524 tons per hectare with $40 carbon price. For soybean land, 55 tons per hectare with $3 carbon price, 211 tons per hectare with $10 carbon price, and 554 tons per hectare with $40 carbon price. Thus, carbon incentives are more costly the larger the proportion of crop land in corn.

These results indicate the difficulties associated with attempting to increase carbon storage across the types of crops typically managed in the same farming system. On the one hand, more land in soybeans raises the overall level of carbon in soils because lands tend to be managed at higher residue levels on average. However, by raising the overall carbon stored in soils in the baseline (i.e the scenario without carbon prices), there are only small increments in carbon available when carbon payments are provided. That is, land is initially closer to the steady state level of carbon, and hence accumulation rates are lower. On the other hand, if more land is in corn, it is also costly to obtain improvements in sequestration because corn is the most susceptible to yield losses from higher levels of residue management. This is particularly true on the relatively high land qualities farmed in Henry County, Ohio.

CONCLUSION

This study develops a dynamic model of land, crop, and residue management choices in a typical Midwestern farm region. They dynamic model is developed and implemented for a single county in Ohio, using parameters estimated from data and also parameters obtained from the literature. The effects of alternative crop price projections and carbon prices on the potential sequestration of carbon in this one county region are explored.

To develop the dynamic model, a regression model relating residue management to corn and soybean yield in Ohio was first estimated. The results show that higher residue management tends to reduce crop yield on average, but the effects differ depending on crop type and land quality. For both corn and soybean, high quality land is more adversely affected by residue management than lower quality land. Although we explore a relatively limited range of land qualities in this study, continuing research efforts will explore how carbon sequestration differs across a broader region with substantive variations in land quality.

Several interesting results emerge. First, the proportion of crop choice between corn and soybean within a scenario does not appear to be sensitive to carbon prices. This is helpful for policy makers, because it suggests that a policy that rents carbon in soils will be price neutral. Second, although this model treats crop prices as exogenous, shifts in relative prices are explored and their effects on carbon sequestration are shown. The results suggest that residue management choices and carbon storage do depend on crop choices, and hence on crop prices. The total carbon stored in soil is the greatest when more land is maintained in soybeans (i.e. soybean prices rise relative to corn prices). Third, raising the proportion of land in soybeans raises the costs of sequestration because soils initially have higher levels of carbon in them, and accumulation rates starting from this baseline are lower. Unfortunately, raising the proportion of land in corn also raises the costs of sequestration because corn acres experience larger yield losses with increases in residue management.

The results suggest that the $3 per ton carbon price leads to a 4 – 7% increase in carbon storage per hectare, the $10 per ton carbon prices leads to a 13 – 23% increase in carbon storage per hectare, and the $40 per ton carbon price leads to a 31 – 55% increase in carbon storage per hectare. Payments under the $3, $10, and $40 per ton carbon price would amount to annual payments of $4, $15, and $76 per hectare ($1.60, $6, and $31 per acre). Other studies have suggested that $ 5 per ton payment results in 2 to 4 tons of carbon and cost per ton of carbon ranges $5 to $70 (Antle et al., 2001), $20 per ton of carbon depending on the target (Pautsch, et al, 2001), and $0 to $50 per ton (Schneider, 2002).

This study has several important limitations. First, the model needs to assess the effects of sequestration on different land qualities. The region modeled has relatively good land quality, and it would be useful to consider alternative qualities of land. Second, the model should allow prices to be endogenous. That is, crop prices should depend on land use choices within the region, rather than allowing these choices to be entirely exogenous. Future analyses will incorporate these important considerations.

Table1. Variables in crop yield estimation

Dependent variable: Corn(bu/ac)		***Dependent variable: Soybean(bu/ac)***	
Variables	definition	Variables	definition
Const	constant	Const	constant
CLAG	lag of corn yield	SLAG	lag of soybean yield
JANP	precipitation in January	JANP	precipitation in January
APRP	precipitation in April	APRP	precipitation in April
JULP	precipitation in July	JULP	precipitation in July
OCTP	precipitation in October	OCTP	precipitation in October
KFACT	k-factor	KFACT	k-factor
CTIX	Index of residue management intensity	STIX	index of residue management intensity
INTC	Interaction variable of k-factor and conservation	INTC	Interaction variable of K-factor and conservation
T	time trend	T	time trend

Table2. Estimation result of crop yield function

Corn equation(Bu/ac)			Soybean equation		
Variable	Coefficient	t	Variable	Coefficient	t
Const	132.91	11.11	Const	42.56	12.09
CLAG	0.04	3.35	SLAG	0.01	1.33
JANP	-4.01	-4.69	JANP	-0.54	-2.1
APRP	0.62	1.33	APRP	-0.57	-4.04
JULP	4.25	14.15	JULP	0.5	5.63
OCTP	-1.81	-3.97	OCTP	-0.32	-2.33
KFACT	-111.23	-3.23	KFACT	-23.92	-2.33
CTIX	-65.26	-2.14	STIX	-11.11	-1.45
INTC	173.18	1.9	INTS	40.98	1.79
T	3.01	12.53	T	0.88	10.81

Table3. Marginal impacts of residue management on yield by land quality

k-factors	Corn(bu/ac)	Soybean(bu/ac)
Upper 25% percentile(Highest quality)	-17.4	0.0
Between 50% and upper 25%	-7.5	1.4
Between 50% and lower 25%	-4.4	1.9
Lower 25% percentile (Lowest quality)	-0.9	2.3

Table4. Dynamic model variables and functions

Notation	Definition
r	Discount factor
P^C, P^S	Price for corn and soybean
$Q^C(\cdot),Q^S(\cdot)$	Yield function of corn and soybean
$C(\cdot)$	Cost function
F^{C*},F^{S*}	Fertilizer input for corn and soybean
X^C,X^S	Total land area of corn and soybean (ha)
RC^*, RS^*	Residue management intensity for corn & soybean
CS^*	Land transfer from corn to soybean
SC^*	Land transfer from soybean to corn
t	time
i	Index of land class
YCT	Year in corn
SYT	Year in soybean

*; Choice variables the dynamic model

Table5. Parameters for dynamic model

Corn yield parameters					
Land class	α1	α2	α3	α4	α5
1	256	0.7167†	0.001†	-0.056	-0.167
2	200	-	-	-0.043	-0.071
3	176	-	-	-0.036	-0.031
Soybean yield parameters					
Land class	β1	β2	β3	β4	β5
1	25.375	2.6667†	0.0169†	-0.01	-0.061
2	19.5	-	-	0.01	-0.01
3	14	-	-	0.03	0.074

†: Same for all land class

Table6. Results for the 50 year time period for the base model for three different carbon prices, and for two alternative assumptions about future corn and soybean prices.

Base Model

	Baseline		*$ 3 per ton carbon price*		*$10 per ton carbon price*		*$40 per ton carbon price*	
	corn	soybean	corn	soybean	corn	soybean	corn	soybean
Average land use (ha)	397	291	398	290	397	291	397	291
Total carbon (tons)	543123	304029	602642	306471	730112	317932	787005	529860
Average carbon per hectare (tons/ha)	1368	1045	1514	1057	1839	1092	1982	1821
Residue (%)	36%	39%	38%	39%	42%	39%	44%	45%

Soybean Prices higher (Soybean prices rise at 6%, Corn prices rise at 5%)

	Baseline		*$ 3 per ton carbon price*		*$10 per ton carbon price*		*$40 per ton carbon price*	
	corn	soybean	corn	soybean	corn	soybean	corn	soybean
Average land use (ha)	268	420	267	421	268	420	268	420
Total carbon (tons)	387662	746056	430187	756971	477276	805944	503563	991945
Average carbon per hectare (tons/ha)	1445	1778	1612	1798	1779	1920	1877	2364
Residue (%)	36%	45%	38%	45%	39%	46%	40%	48%

Corn prices higher (Soybean prices rise at 5%, Corn prices rise at 6%)

	Baseline		*$ 3 per ton carbon price*		*$10 per ton carbon price*		*$40 per ton carbon price*	
	corn	soybean	corn	soybean	corn	soybean	corn	soybean
Average land use (ha)	460	228	463	225	460	228	460	228
Total carbon (tons)	524634	294111	547694	303420	670810	342127	765597	420283
Average carbon per hectare (tons/ha)	1140	1291	1184	1347	1458	1502	1664	1845
Residue (%)	29%	29%	30%	29%	34%	29%	36%	33%

Figure1. Carbon accumulation by carbon policy

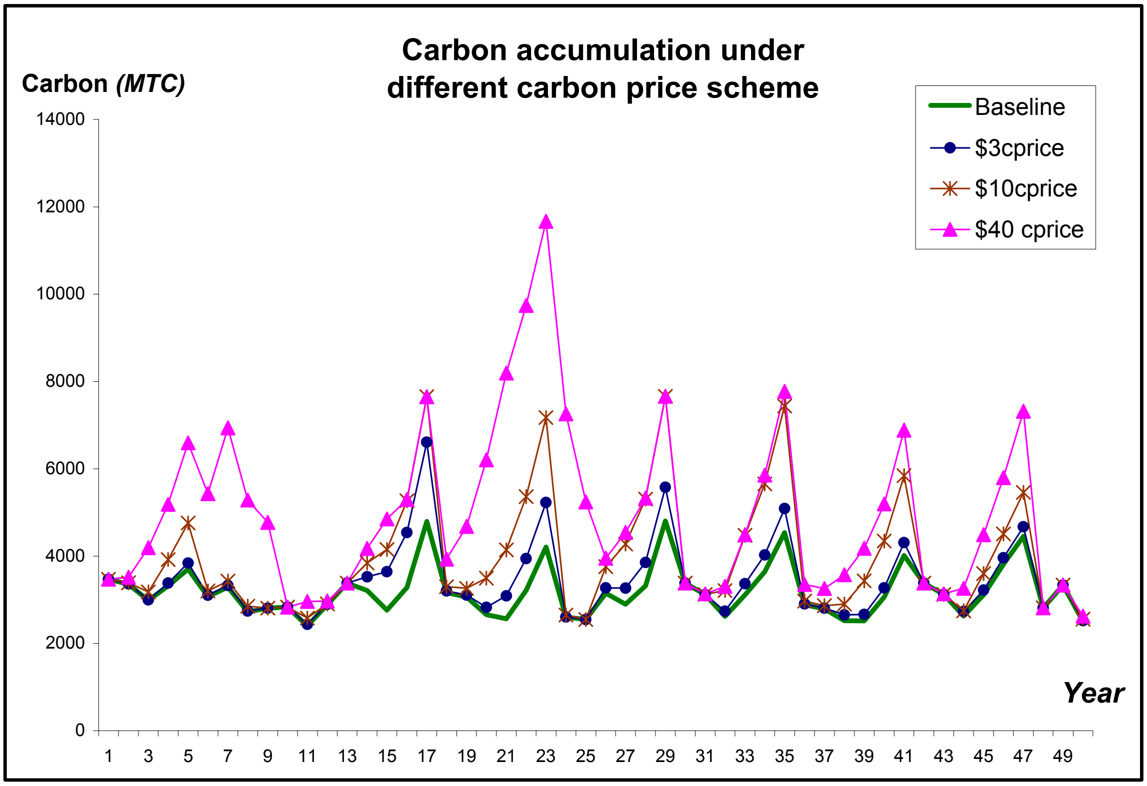
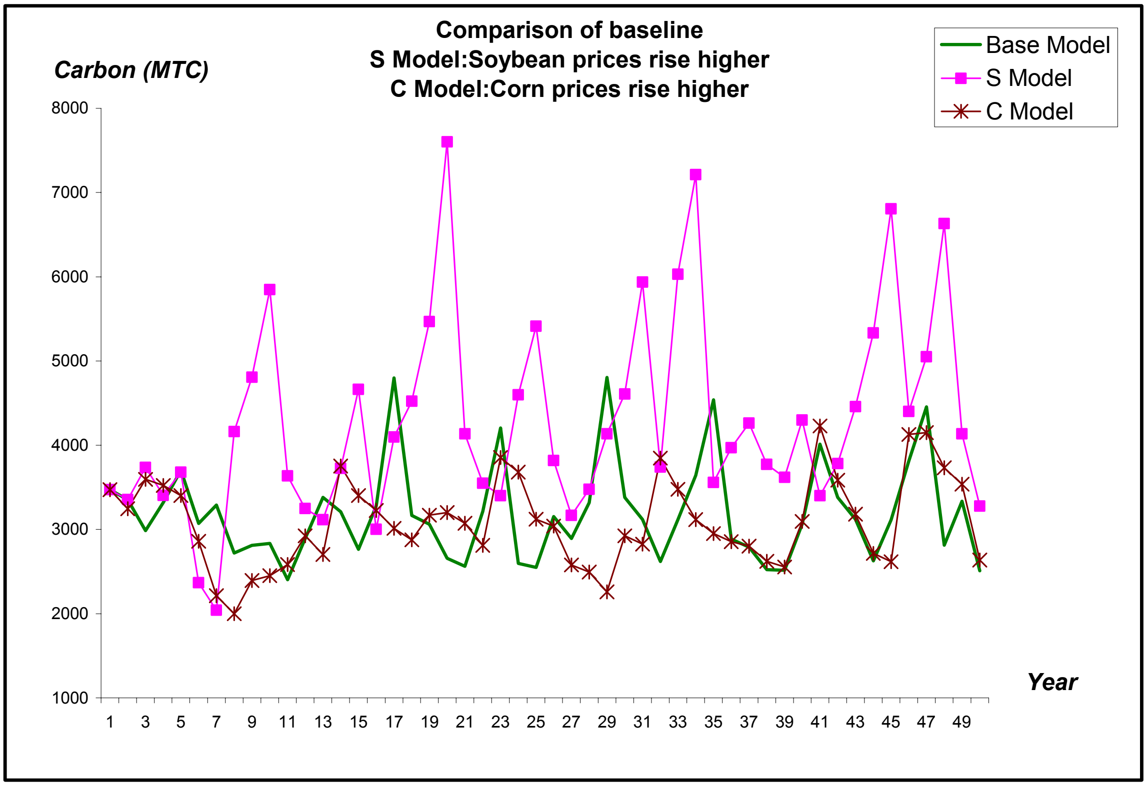


Figure2. Baseline comparison under different crop price assumption



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