

Sustainability of Corn Stover Harvest for Biomass

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Abstract

Off-farm demand for crop residues is expected to grow as bioenergy policies become effective. Demand for residues will provide farmers with an additional source of revenue but it may also trigger losses in soil organic carbon and increases in fertilizer application. This study develops a dynamic economic model of stover harvest that permits conceptualization and quantification of these potential tradeoffs. We parameterize our model based on publicly available studies of soil biophysical relationships in the Corn Belt. Under these parameter values and 2010 corn and fertilizer prices harvesting stover is not economically convenient at prices below \$53 per dry ton of stover. Results suggest that the rate of stover harvest may be quite sensitive and negatively linked to corn prices, which means that policies favoring the use of stover for biomass may be overridden by further increases in corn price. The negative link between stover harvest and corn prices, while somewhat counterintuitive, is driven by the fact that removal of stover reduces future grain yield (through reductions in soil organic carbon). Results also seem to indicate that, under plausible parameter values, profit maximizing farmers would increase stover supply in response to increases in stover price. However increases in supply are, according to our simulations, associated with (potentially significant) reductions in soil organic carbon (and hence carbon emissions as these are positively linked) and increases in nitrogen application (and potential runoffs). This result suggests that concerns about adverse environmental implications of harvesting stover may be justified, and more precise quantification of environmental tradeoffs should be pursued by future research.

Introduction

Off-farm demand for crop residues is expected to grow as bioenergy policies become effective (e.g. renewable fuel mandates, Biomass Crop Assistance Program, increases in blend wall), and new technologies are developed that make these feedstocks more competitive with respect to fossil energy. As required by the Energy Independence and Security Act of 2007 the U.S. Environmental Protection Agency (EPA) has established new statutory requirements for specific annual volume standards for cellulosic biofuel, biomass-based diesel, advanced biofuel, and total renewable fuel that must be used in transportation fuel. The EPA's final rule (<http://www.epa.gov/oms/renewablefuels/420f10007.pdf>) establishes a 36 billion gallon ethanol equivalent mandate of renewable transportation fuels per year by 2022. Corn stover was identified by EPA and USDA as the third feedstock in importance to meet the annual mandate.¹ Corn stover is expected to provide about 25% of total advanced biofuels supply. Due to high density and yields the bulk of corn residue is expected to come from the Corn Belt.

Demand for residues will provide the farmer with an additional source of revenue but it comes at a cost; their mechanical harvest may modify soil moisture and temperature, and remove nutrients and organic material critical to maintaining soil productivity and hence future grain and residue yields (Wilhelm et al. (2004)). This in turn may reduce future farmers' profitability by increasing production cost of grain and biomass for food and biofuels. Farmers will balance costs and benefits of harvesting stover to determine what (if any) is the most convenient rate of stover harvest from an economic point of view in each year. Stover removal may also decrease net carbon sequestration in soils and increase non point source pollution (through increased fertilizer application and soil erosion from wind and water.) Even though these environmental effects may

¹ USDA Regional Roadmap to Meeting the Biofuels Goals of the Renewable Fuels Standard by 2022 at <http://www.ascension-publishing.com/BIZ/USDA-Biofuels-06232010.pdf>

not influence farmers' profitability and supply, they will affect the environmental sustainability (or "social" cost) of production. The most profitable harvest rate of stover may not coincide with the rate deemed sustainable (i.e. preferred by society as a whole) by scientists and policy makers.

Understanding and anticipating farmers' behavior and its potential environmental implications is of importance to policy makers to estimate the volume and cost-effectiveness of corn stover as an energy feedstock and the societal gains accrued from its support through public policy. Therefore the development of an economic model linking market prices, grain and residue supply, soil carbon, and fertilizer application is crucial for energy and sustainability policy design. Economic analyses of stover supply conducted so far have exogenously assumed fixed stover removal rates at the field level.² Although effective in providing a first approximation to the amount of available stover under "sustainable" removal rates (i.e. rates under which soil erosion will remain below soil loss tolerance) this methodological choice offers no information on the link between prices, policies, and harvest rates. As such they limit our ability to conduct assessment of biomass energy policies. This study attempts to fill that gap. We construct a dynamic economic model depicting corn producers' behavior. Steady state levels (and temporal trajectories to those levels) of soil organic carbon, nitrogen application, grain and residue supply are derived from such a model. This model is then quantified with literature-based values of parameters. Simulations based on these parameters allow recovery of a supply schedule of corn stover, contrast economically optimal levels of residue harvest with those deemed "sustainable" by the agronomic literature, and discuss environmental implications of profit maximizing stover removal.

² Gallagher et al. assumed a 50% harvest rate, Brechbill and Tyner assumed removal rates of 38%, 52% and 70% of available stover per year, Petrolia analyzed 50% rates, and Perrin et al. assumed a 25% rate of removal (50% removal from 50% of the field per year).

An economic model of corn residue supply

Producers will decide how much of available residues to harvest and sale based on a careful balancing of economic cost and benefits of doing so. Benefits to corn growers consist of income from sales of grain and corn residue. In turn the on-farm costs of providing residues to customers are composed of static costs (cost of baling, raking and transport residues to the edge of the field) and intertemporal costs. Intertemporal costs exist because harvesting of residues may adversely affect soil physical attributes and fertility (Larson et al. (1972); Barber (1979); Wilhelm et al. (1986) and (2004); Maskina et al. (1993); Karlen et al. (1994); Huggins et al. (1998); Power et al. (1998); Blanco Canqui et al. (2007) and (2009a, b, c)). The negative impacts of stover removal on fertility may depend on soil characteristics such as clay content, drainage characteristics, slope gradient (Wilhelm et al. (2004)), tillage system, crop grown, management duration and climate zone (Blanco Canqui et al. (2009a)). Negative effects of residue removal on yields (Changere and Lal (1995) and Fahnstock et al. (1995); see Table 1 for a summary) may be outweighed by increased fertilizer application. The intertemporal cost can then be calculated as the forgone income due to reduced future grain sales or the increased cost of fertilizer application necessary to sustain yields.

Previous studies on the economics of stover removal (Gallagher et al. (2003); Brechbill et al. (2008); Petrolia (2008); Perrin et al. (2010)) although static in nature approximated the intertemporal cost of removing stover by the cost of replacing nutrients removed with every ton (dry matter) of plant residue. Hereby we refer to this method as the replacement cost approach. This approach may be somewhat incomplete from an agronomic perspective. Removing plant residue from the field not only reduces nutrients but may adversely affect soil physical properties. In contrast to the loss of nutrients that can be replenished by applying fertilizers,

adverse changes in soil physical quality cannot be easily restored by routine soil management options (Lal (1998)). Therefore economic and environmental assessment of removing stover for biomass requires modeling the broader and long run effects of this management practice on soil health and productivity. The dynamic approach followed here permits modeling of these effects.

There are different indicators that can be used to represent soil health and productivity. In this study I use soil organic carbon (SOC) as an indicator of soil productivity. Soil organic carbon constitutes a good indicator of soil fertility because it is a driver of or is correlated to many physical attributes of the soil such as depth (positively linked to SOC), nutrient retention (greater SOC is associated with greater nutrient availability), bulk density (negatively linked to SOC), water holding capacity (positively linked to SOC), and cation exchange (positively linked to SOC) (Reeves (1997), Wilhelm et al. (2004), and Blanco Canqui et al. (2009a)).

We model farmers' production possibilities by the following grain yield function:

$$g_t = g_0 + a \ln S_t + b \ln x_t \quad (1)$$

Where S_t denotes the level of SOC concentration in the soil (megagrams per foot-acre) at time t , x_t denotes nitrogen application rate (pounds per acre) at time t , a denotes the semi-elasticity of yield with respect to SOC, and b is the semi-elasticity of yield with respect to fertilizer. Other variable inputs (e.g. labor, capital, seeds) used in production are considered fixed and absorbed by the parameter g_0 which will be calibrated along with other parameters in the model. This function implies that fertilizer may substitute for soil organic carbon and maintain productivity. However fertilizer application displays diminishing returns as indicated by existing evidence in the Corn Belt (Sawyer et al. (2006) and Paulson et al. (2010)).

To model the dynamics of SOC we use the following equation proposed by Parton et al. (1996) (Wilhelm et al. 2004):

$$\dot{S}_t = -cS_t + dA_t \quad (2)$$

Where S_t is the SOC stock in the soil (Mg per foot-ac), \dot{S}_t is the change in time of the SOC pool, c is the rate of decay of relic or stable SOC (i.e. $c < 0$), A_t denotes carbon input, d is the proportion of stover added to the soil that actually becomes soil organic carbon.

Equation (2) describes the dynamics of SOC as a function of existing levels of SOC and carbon additions. Additions to the carbon stock in the soil come from plant biomass produced and returned to the soil. Parameters c and d are functions of weather and climate but we treat them as constants here for simplicity.³ The tillage system, weather, and fertilization influence SOC retention (Allmaras et al. (2000)) and hence the linearity of SOC dynamics with respect to biomass returned is not guaranteed. However since there is some consensus over the fact that, given soil management, changes in SOC are proportional to the amount of crop residue returned to the soil (Larson et al. (1972) and Willhelm et al. (2004)) we will impose linearity on the SOC dynamics equation:

$$\dot{S}_t = cS_t + d(g_0 + a \ln S_t + b \ln x_t)(1 - h_t) \quad (3)$$

Where the term A_t in equation (2) has been replaced by the amount of stover returned to the soil; $(g_0 + a \ln S_t + b \ln x_t)(1 - h_t)$. The factor $(g_0 + a \ln S_t + b \ln x_t)$ represents yields and is, thus, measured in bushels per acre. A fraction $(1 - h_t)$ of that biomass is returned to the soil (h_t is the rate of stover harvest). The amount of stover returned is modeled as a fraction of grain yield because it is assumed that stover yields are the same as grain yields (1:1 ratio of grain and

³ To simplify the analysis further we assume a “short-memory” dynamic process; i.e. only the current level of SOC and biomass returned affect SOC rate of change.

biomass) which is standard in the literature (Wilhelm et al. (2004); Brechbill et al. (2008); Petrolia (1998); Perrin et al. (2010)).

Farmers will choose the rate of stover removal and fertilizer application that maximizes the present value of future stream of profits (in continuous time) subject to production possibilities (equation 1) and soil carbon dynamics (equation 3):⁴

$$\text{Max}_{(h,x)} \int_0^{\infty} e^{-rt} \left((g_0 + a \ln S + b \ln x) p_y + \left[0.0238 (g_0 + a \ln S + b \ln x) h \left(\frac{p_h - c_h^b}{0.0238} \right) - c_h^a \right] - x p_x \right) dt$$

s.t. (1) and (3)

Where r is the (constant in time) interest rate, p_y is the price of corn (\$ per bushel), p_x is the price of nitrogen (\$ per pound), and p_h is the price of stover (\$ per bushel). There are two components to the cost of harvesting stover. The first component can be expressed on a per bushel (or converted to bales or tons) basis, c_h^b , and it involves the cost of stalk shredding, baling, and moving bales to the edge of the field. The second component involves raking and is expressed on a per acre basis, c_h^a . Bushels of stover are converted to dry tons by multiplying them by 0.0238 (i.e. $0.85 \cdot (56/2000)$). The price of stover (p_h) and per bushel cost (c_h^b) are also converted to dry tons (divided by 0.0238). We will denote this “net” price by p_h^n ; i.e.

$$p_h^n = \frac{p_h - c_h^b}{0.0238}.$$

The profit-maximizing combination of stover harvest (h) and fertilizer application (x) solves the following current value Hamiltonian:

$$H = (g_0 + a \ln S + b \ln x) p_y + 0.0238 (g_0 + a \ln S + b \ln x) h p_h^n - c_h^a - x p_x + \lambda [cS + d(g_0 + a \ln S + b \ln x)(1 - h)]$$

⁴ I hereby drop the time subscripts for notational ease.

The solution based on this Hamiltonian (see Appendix for details) yields the following system of equations:

$$x^* = b \left(\frac{P_y + 0.0238 p_h^n}{P_x} \right) \quad (4)$$

$$S^* = \frac{ad}{r-c} \left(1 + \frac{P_y}{0.0238 p_h^n} \right) \quad (5)$$

$$\dot{S} = cS + d(g_0 + a \ln S + b \ln x)(1-h) \quad (6)$$

Note that the level of SOC from equation (5) is always positive as $c < 0$, $a > 0$, and $d > 0$. The system of equations (4)-(6) reveals that while the nitrogen application rate and the rate of stover harvest do not change over time the level of SOC in the soil does. The optimal nitrogen application rate is fully described by equation (4). The optimal rate of stover harvest, on the other hand, is obtained by inserting equations (4) and (5) into (6), and assuming steady state ($\dot{S} = 0$):

$$h^* = 1 + \frac{ca}{(r-c)g} \left(1 + \frac{P_y}{0.0238 p_h^n} \right) \quad (7)$$

$$\text{Where } g = \left(g_0 + a \ln \left[\frac{ad}{r-c} \left(1 + \frac{P_y}{0.0238 p_h^n} \right) \right] + b \ln \left[b \left(\frac{P_y + 0.0238 p_h^n}{P_x} \right) \right] \right). \text{ Equation (7)}$$

depicts the optimal rate of stover harvest as a function of prices, interest rate, and parameters.

This is not only the steady state level of h but the optimal level of h at any point in time as discussed further below. Since $c < 0$ and the rest of the parameters are positive the second term on the right hand side of (7) is always negative. Therefore $h^* < 1$.⁵ In addition the second term on the right hand side can be lower than -1. Since it is not, in general, economically interesting to

⁵ There are certain engineering aspects of stover removal that may impose upper bounds to this rate that are even lower than 1. Montross et al. (2003) have found that shredding, raking, and baling will result in 64 to 75 percent collection. Lang (2002) estimates that shredding, raking, and baling may result in as much as 80 percent collection.

harvest a negative fraction (i.e. adding stover brought from other fields) we will denote the optimal stover harvest rate as follows:

$$h^* = \begin{cases} (7) & \text{if } \frac{ca}{(r-c)g} \left(1 + \frac{P_y}{0.0238 p_h^n}\right) \geq -1 \\ 0 & \text{otherwise} \end{cases} \quad (7')$$

We will now analyze the properties (trajectories and stability) of the dynamic system described by equations (4), (5), (6), and (7').

Dynamic System, Steady State, and Stability

Inserting equation (4) into (6) and assuming steady state ($\dot{S} = 0$) yields:

$$h = 1 + \frac{cS}{dg(S)} \quad (8)$$

Where $g(S) = \left(g_0 + a \ln S + b \ln \left[b \left(\frac{P_y + 0.0238 p_h^n}{P_x} \right) \right] \right)$. Equation (8) depicts the rate of

stover harvest as a function of SOC in the soil. Since $c < 0$, equation (8) is negatively (positively) sloped and convex (concave) if and only if $g(S) > (<)a$.⁶ Provided that $g(S)$ represents grain yields in bushels per acre and a is the semi-elasticity of yields with respect to SOC then the more plausible scenario (and one confirmed by our parameterization in the following section) is $g(S) > a$.

Equations (5) and (8) depict the dynamic system of this problem. This system is graphed in Figure 1. For the reasons just discussed, Figure 1 depicts the case where $g(S) > a$ (i.e. equation

⁶ The derivative of the harvest rate with respect to SOC from equation (7) is $\frac{c}{d} \left[\frac{g(S)-a}{g(S)^2} \right]$ and the second order derivative is $\frac{c}{d} \frac{a}{S} \left[\frac{a-g(S)}{g(S)^3} \right]$.

(8) is negatively sloped and convex). Stability of the dynamical system (the system converges to the steady state equilibrium) implies that there are no explosive paths describing the behavior of SOC and stover harvest. This, in turn, means that under profitable conditions for stover removal, SOC is not completely depleted. The phase diagram is recovered by taking the derivative of \dot{S} with respect to h ; i.e. $d\dot{S}/dh = -d(g_0 + a \ln S + b \ln x) < 0$. Since this derivative is negative SOC is increasing (decreasing) for all combinations of SOC and harvest rate below (above) the curve depicting $\dot{S} = 0$.

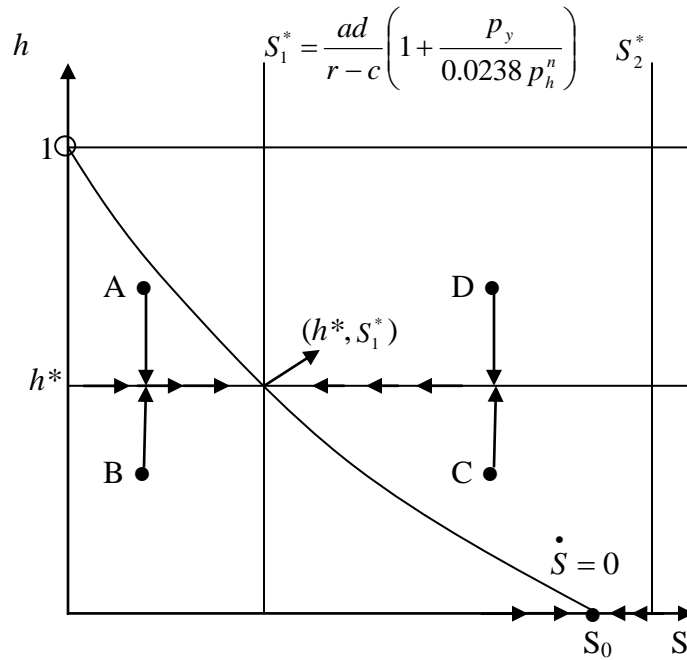


Figure 1. Dynamical System and Stability

The optimal rate of stover harvest in steady state is determined by the intersection of S_1^* (from equation (5)) and $\dot{S} = 0$, depicted by h^* . Since the system does not yield a dynamic equation for h (i.e. \dot{h}) there will be an immediate adjustment of the rate of stover harvest to h^* . This implies that starting from some combination of (h, S) such as points A-D in Figure 1 there

is a jump to h^* . Since the system is globally stable ($d\dot{S}/dh < 0$) it will then converge to (h^*, S_1^*) as indicated by the directional arrows along h^* . The rate (years) and pattern (monotonic or oscillatory) of convergence will be discussed after parameterization of the model.

Moreover depending on prices and parameter values the vertical line S^* could be located to the right of S_0 as exemplified by S_2^* . In this case the intersection of the two curves would occur on the negative orthant of h . Since the optimal harvest rate h^* cannot be negative (as imposed by equation (7')) it will be zero until SOC converges to S_0 where the system will be at rest as indicated by the directional arrows along the horizontal axis. This denotes a situation where removing no stover from the field is found optimal by the farmer. Therefore the steady state level of SOC will be the minimum of S^* (from equation (5)) and S_0 which can be (implicitly) calculated by imposing $h^*=0$ in equation (8):

$$S^{SS} = \min \left[S^* \text{ from equation (5)}, S_0 = \left\{ S : h - 1 - \frac{cS}{dg(S)} = 0 \right\} \right] \quad (9)$$

Where $g(S)$ has been defined in equation (8).

As S^* is pushed to the left (e.g. from S_2^* to S_1^*) by increases in the price of stover or reductions in corn price (holding everything else constant), the rate of stover harvest will converge to 1 but never actually reach 1 as indicated in our discussion of equation (7).

We now parameterize our model based on available evidence and analyze, quantitatively, plausible dynamics of the system and the steady state supply of corn stover in the Corn Belt.

Parameterization

Parameter d in the soil dynamic equation has been estimated by many studies under a rather wide range of soil characteristics and management practices. A positive relationship

between residue return and SOC pool in the soil has been consistently found across the Corn Belt (Wilhelm et al. (1986); Maskina et al. (1993); Power et al. (1998); Barber (1979); Larson et al. (1972); Linden et al. (2000); Clapp et al. (2000); Blanco Canqui et al. (2007), (2009 a-c); Blanco Canqui (2010)) found.⁷ It was also found that tillage tends to reduce SOC retention and that fertilization with residue return tends to increase it (through both increases in biomass yield and carbon input and through reduction in relic SOC decomposition). Finally there is also accumulated evidence of a positive relationship between SOC and plant productivity (Sparling et al. (2006)).⁸

To sum up, considerable evidence seems to have built up suggesting a positive linear relationship between residue return and SOC ($d > 0$) and, all else constant, SOC and yields ($a > 0$). However point estimates of these parameters are hard to obtain. Given the lack of publicly available data that would permit econometric estimation of corn yields including SOC as input to production I parameterize the model using results from field experiments in a region considered somewhat representative of the broader Corn Belt. Field experiments in Iowa conducted by Larson et al. (1972) and Robinson et al. (1996) provide enough information to calculate both parameters of the soil equation. Robinson et al. (1996), based on experiments in three different sites in Iowa, reported that an increase in the residue application rate by 1 Mg ha⁻¹ increased SOC by an amount ranging from 0.26 to 0.57 g kg⁻¹. Estimation based on pooled data from all three experiments yielded a slope of 0.30 which means that an increase in stover return of 1 Mg ha⁻¹ increased SOC by 0.3 g kg⁻¹ or, in other words, an increase in stover return of 1

⁷ These results are also consistent with validated simulations conducted by Paustian et al. 1992, with the CENTURY software.

⁸ According to Sparling et al. (2006) this positive link is driven by greater water retention and availability, higher cation exchange capacity, the ability to retain nutrients within the root zone, greater buffering capacity against pH change, the ability to chelate and complex ions, contribute to soil structure and form stable aggregates, and sustain biological activity and biodiversity by providing food and habitat for soil animals and microorganisms.

bushel ac^{-1} increases SOC by $0.034 \text{ Mg foot-ac}^{-1}$. Since we measure stover return in bushels our parameter d is 0.034. In addition, based on experiments in Iowa, Larson et al. (1972) estimated that in soils with a SOC pool of 18 g kg^{-1} ($32.4 \text{ Mg foot-ac}^{-1}$), 6 Mg ha^{-1} ($95.64 \text{ bu. ac}^{-1}$) were needed to maintain soil organic carbon at baseline levels. In the context of our equation (3)

Larson et al.'s finding implies that $0 = c(32.4) + d(95.64)$. Hence $(-c) = \left(\frac{95.64}{32.4}\right)0.034 \cong -0.1$.

Therefore equation (3) becomes:

$$\dot{S} = -0.1S + 0.034(a \ln S + b \ln x)(1-h) \quad (10)$$

We now proceed to calculating technological parameters a and b . Equation (4) is used to calibrate parameter b using quantity and price data from Iowa. In particular solving equation (4) for b yields:

$$b = \left(\frac{P_x}{P_y + P_h} \right) x^* \quad (11)$$

Data on fertilizer application rates in Iowa are available from NASS Agricultural Chemical Usage (1994-2005). In 2005 the nitrogen⁹ application rate in Iowa was 141 pounds per acre (i.e. $x^* = 141$). The current price of stover in 2005 is assumed to be zero. Prices of fertilizer and corn in 2005 were \$0.21 per pound and \$2 per bushel respectively (Agricultural Prices, National Agricultural Statistics Service, USDA). Using these data, b is calculated to be 14.8. Since b is a semi-elasticity, the elasticity of yield with respect to nitrogen evaluated at yields corresponding to 2005 is approximately 0.09.¹⁰ This means that an increase in 1% in nitrogen application (i.e.

⁹ We are only considering nitrogen here due to difficulties to construct an index of total fertilizer including nitrogen, phosphorus, and potassium.

¹⁰ $\frac{d \ln y}{d \ln x} = \frac{dy}{d \ln x} \frac{1}{y} \Rightarrow \frac{d \ln y}{d \ln x} = \frac{14.8}{141} \cong 0.09$. This estimation is about half of the 0.19 point estimate obtained by Huffman et al. (1974) for the Corn Belt.

an increase in 1.41 pounds per acre) would increase yields by approximately 0.09% (i.e. almost 0.15 bushels per acre).

Parameter a represents the semi-elasticity of yields with respect to SOC. To my knowledge there are only a handful of publicly available estimates of the SOC-yield relationship that can be used to calculate parameter a . Studies estimating the marginal effect of increases in the SOC pool on corn yields in the US Corn Belt are summarized in Table 1. We use a simple average of these estimates to calibrate our model. Therefore the parameter a in our yield equation (1) is calculated to be 14.4.

Table 1. SOC-Corn yield relationship

| Study | Linear Effect of SOC (% of soil) on Corn Yield (Mg/ha) | Linear Effect of SOC (% of soil) on Corn Yield (Mg/ha) ⁽¹⁾ | Semi-elasticity of Corn Yield (bu/ac) with respect to SOC (Mg/ac); i.e. parameter a ⁽²⁾ |
|-------------------------------------|--|---|--|
| Gollany et al. (1992); South Dakota | 0 | 0 | 0 |
| Changere and Lal (1995); Ohio | 1.48 | 1.31 | 42.5 |
| | 1.7 | 1.51 | 48.8 |
| | 1.64 | 1.45 | 47 |
| | 2.79 | 2.47 | 80 |
| Fahnestock et al. (1995); Ohio | 0 | 0 | 0 |
| | 0 | 0 | 0 |
| | -9.02 | -7.97 | -258 |
| | 6.41 | 5.68 | 184 |
| Blanco Canqui et al. 2008; Ohio | 0 | 0 | 0 |
| Average | | | 14.4 |

⁽¹⁾Numbers in this column are obtained multiplying numbers in the second column by 0.885 which expresses the SOC-yield relationship in terms of Mg/ac of SOC to corn yield in bu/ac.

⁽²⁾This number is obtained multiplying the linear effects in column 3 by the baseline level of SOC, 32.4 Mg/ac to convert it to a semi-elasticity; $\frac{dy}{d \ln S} = \frac{dy}{dS} S$.

The parameter g_0 can now be calibrated based on the estimated parameters a and b , and data on fertilizer application, SOC, and yields. In 2005 yields in Iowa were 173 bushels per acre

(State average) and 141 pounds of nitrogen were applied per acre (State average). No data is available on SOC levels in 2005 but we use publicly available estimates as an approximation to our baseline SOC values. Larson et al. and Robinson measured SOC levels at different sites in Iowa in 1972 and 1992 respectively. The stocks ranged from 18 g per kg (32.4 Mg per foot-acre) to 25.3 g per kg (45.54 Mg per foot-acre). As a conservative estimate we use the lower limit of this range; i.e. 32.4 Mg per foot-acre. Under estimated parameters a and b , 32.4 Mg foot-acre⁻¹ of SOC, and 141 pounds of nitrogen per acre, an intercept of 49.54 would be required to achieve a yield of 173 bushels per acre.

On farm costs of harvesting stover are calculated and presented in Table 2. The on farm cost component denoted by c_h^b is calculated as the sum of shredding, baling, and moving bales to the edge of the farm (\$29.52/dry ton). The second component of on farm costs, denoted by c_h^a , involves raking and is calculated to be \$5.75/acre.

Table 2. On farm cost of stover collection

| | \$/acre | \$/ton |
|-----------------------------------|---------|--------|
| Stalk shredding (b) | | 2.54 |
| Raking (a) | 5.75 | |
| Baling, large round w/netwrap (a) | | 21.94 |
| Moving bales to edge of farm (a) | | 5.03 |
| Total | 5.75 | 29.52 |

(a) 2010 Iowa Farm Custom Rate

(b) Edwards et al. (2008)

Finally the interest rate is assumed to be 5%; i.e. $r=0.05$. A summary of parameter values in our model is displayed in Table 3. Based on these parameter values we can now, through simulation, recover the (per acre) stover supply function, conduct assessment of potential environmental trade-offs involved in harvesting stover for biomass, and conduct sensitivity analysis of supply behavior.

Table 3. Parameter Values

| Model Parameter | a | b | g_0 (bushels) | c | d | c_h^b (\$/dry ton) | c_h^a (\$/acre) | r (rate) | Baseline SOC (Mg/foot-acre) |
|-----------------|------|------|--------------------|--------|-------|-------------------------|----------------------|---------------|--------------------------------|
| Value | 14.4 | 14.8 | 49.5 | -0.056 | 0.019 | 29.52 | 5.75 | 0.05 | 32.4 |

Optimal Rate of Stover Harvest and Supply

Steady levels of SOC in the soil (equation (5)), nitrogen application (equation (4)), and stover harvest rate (equation (7')) are calculated for a range of stover prices (\$/dry ton) based on parameters in Table 2, and 2010 prices of corn (\$5.25/bushel) and nitrogen (\$0.5/ton) according to USDA data. Figure 2 denotes the steady state levels of both the fraction of stover harvested and the total amount of biomass (tons/acre) as a function of stover prices (\$/ton). According to Figure 2 no stover is harvested at prices below \$53 per ton. This is because at prices below \$53 the benefits of harvesting stover (income from selling stover) do not compensate for its costs. Costs of harvesting stover are composed of current costs associated with on-farm collection and transportation to the edge of the field and intertemporal costs associated with reductions in SOC and soil productivity resulting from residue removal from the field.

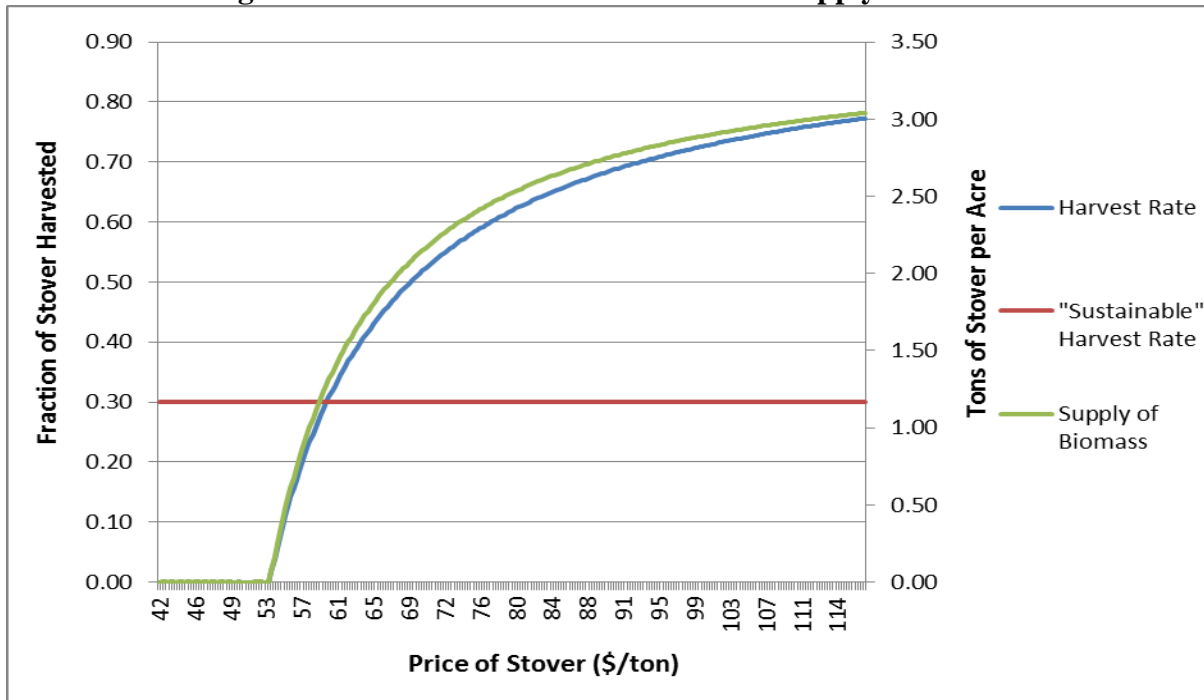
We can compare the results of our dynamic model with the static approximation to intertemporal costs applied by the replacement cost approach. The replacement cost approach includes cost of replenishing nitrogen and phosphorus (Brechbill et al. (2008); Perrin et al. (2008)). Since we only consider nitrogen in our dynamic analysis we will compute the cost of replenishing nitrogen for comparison.¹¹ Applying an average of nitrogen replacement estimates in the literature¹² (15.9 pounds required per ton of dry matter removed) to the 2010 nitrogen

¹¹ This is still a reasonable good approximation to the overall cost of replenishing nutrients as the cost of nitrogen constitutes about 70% of total replacement cost.

¹² Replacement estimates were applied by Nielsen (1995) (13.6 lbs/ton); Lang (2002) (15 lbs/ton); Fixen (2007) (19 lbs/ton); Brechbill et al. (2008) (15.9 lbs/ton); Perrin et al (2010) (16 lbs/ton).

prices (\$0.5/ton of nitrogen) considered here results in an intercept of \$43 per ton; i.e. no stover is harvested below \$43 per ton of stover. What the dynamic nature of this study reveals is that using the replacement cost approach to approximate intertemporal costs may result in underestimation of these costs and, hence, underestimation of the intercept (i.e. price at which harvesting stover becomes profitable). A dynamic approach like the one followed here considers a broader role of SOC in soil fertility than the mere provision of nutrients to plants. This broader role is embodied in parameter a . Parameter a captures attributes of soil that are driven by or correlated to SOC such as the aforementioned soil depth, water holding capacity, bulk density, cation exchange and nutrient retention.

Figure 2. Stover Harvest Rate and Stover Supply Function



One of the environmental concerns surrounding the harvesting of corn residue for bioenergy is the potential impact of this practice on soil erosion and associated runoffs and water quality

implications. An index of tolerable soil loss¹³ is used to establish an upper bound to soil erosion against which actual erosion can be compared and a “sustainable” rate of stover harvest can be identified. The Soil Conservation Service (SCS) of the U.S. Department of Agriculture requires that 30% of the *surface area* of the field be covered in the spring (Soil Conservation Service 1991). Lindstrom (1986) found that 30% removal usually keeps soil loss below tolerable levels. Gallagher (2003) finds that 50% removal of stover does not, under different types of soils, violate tolerable soil loss. Perrin et al. assumed that 25% of stover could be safely removed from the field. We compare profit maximizing rates of stover harvest calculated in this study against a “sustainable” harvest rate of 30%. As indicated in Figure 2, once harvesting stover becomes profitable (\$51/ton) the “sustainable” rate of stover harvest is exceeded very quickly (it is surpassed at a price of \$56/ton). This result suggests that concerns about rates of harvest causing soil erosion beyond tolerable levels are well justified. However further increases in harvest rates require higher price increments due to the concave nature of the stover harvest curve. The rate of stover harvest converges to 0.80 at a price of \$116 per ton.¹⁴

Figure 2 also depicts the supply of stover on a per acre basis (axis on the right). The supply of stover in tons per acre results from $h^* g(S^{SS}, x^*)$, where x^* , S^{SS} , and h^* are functions of the price of stover as depicted by (4), (5), and (7) respectively. At the rate of stover harvest deemed “sustainable” about 1.2 tons of stover is produced per acre by a profit maximizing farmer given assumed agronomic conditions. The supply of stover is concave in stover prices and converges to 3.2 tons per acre at a price of \$116 per ton.

¹³ Tolerable soil loss is defined as maximum amount of soil loss due to erosion by water or wind that can be allowed without causing adverse effects on soil and water resources” (Miller, et al., 1999).

¹⁴ As noted by Montross et al. (2003) this rate, although economically optimal, may not be feasible given engineering constraints to stover collection.

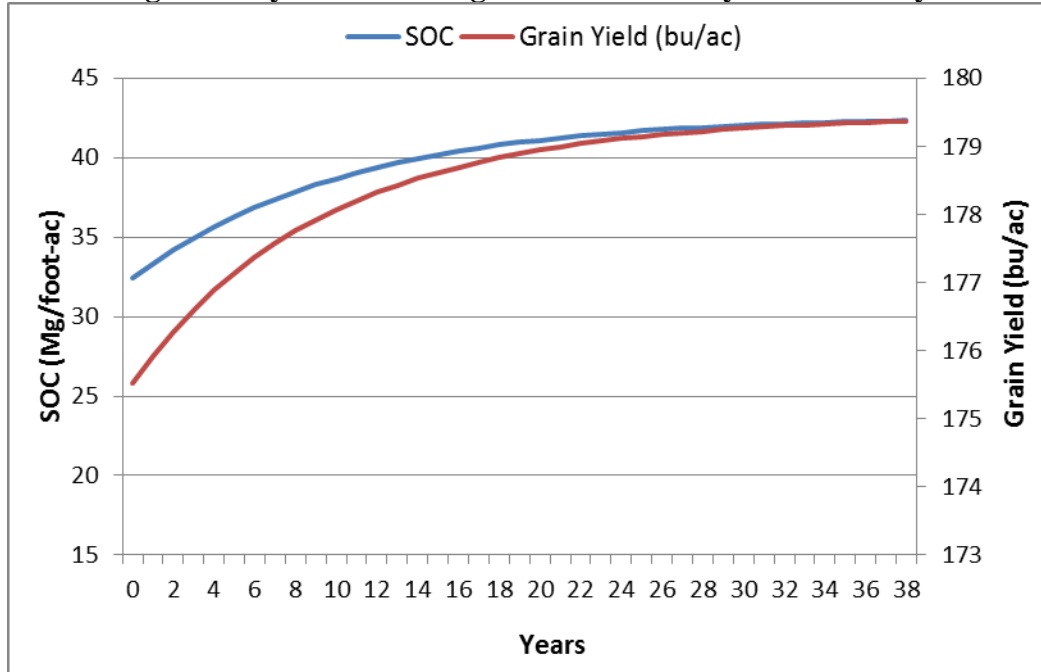
Dynamics and Convergence to Steady State

Figure 3 displays the evolution of SOC in time when the so called “sustainable” harvest rate of 30% is implemented. This rate would be profit maximizing at a price of \$60 per ton. As revealed by Figure 3 the level of SOC in the soil converges monotonically to the steady state level determined by equation (5). At this price and associated harvest rate it takes about 40 years for soil SOC to converge to the steady state level though the bulk of the adjustment takes place in the first 20 years. While this result suggests that, under plausible parameter values, adjustments of SOC may take a long time to unfold, a significant change can already be observed in the first 10-15 years. Finally the steady state level of SOC is 42 Mg/foot-acre which is 30% higher than initial SOC (32.4 Mg/foot-acre). Therefore a portion higher than 30% may be harvestable in the sense that it would result in increases in soil SOC. In fact the harvest rate that would maintain SOC at its baseline level (32.4 Mg/foot-acre) under these parameters is 0.45 which is consistent with a price of about \$66 per ton of stover.

Grain yields are a function of SOC and nitrogen application. The profit maximizing nitrogen application rate does not change in time but is rather immediately determined by prices as described in equation (4). On the other hand the level of SOC in the soil follows a slow adjustment path as displayed in Figure 3. The combination of these two facts result in yields that evolve in time following the evolution of SOC. This path is calculated and displayed in Figure 3. Under a harvest rate of 30% yields increase by approximately 2% to the new steady state. Once again it takes 40 years until yields converge to steady state levels but the bulk of the adjustment occurs in the early stages of the process. These results, however, are potentially severely limited by the assumption of a constant intercept in the yield equation. The intercept may change in time due to innovations in genetics, technology, and soil management. Technological change

embodied by growth in the intercept of our yield equation are bound to be significant in the time frame considered here.

Figure 3. Dynamic convergence of SOC and yields to steady state



Harvest rate and corn price

I have conducted a sensitivity analysis of the schedule of profit maximizing rates of stover harvest with respect to corn prices. Results from this analysis are displayed in Figure 4. Increases in corn price reduce stover harvest at any given stover price. This is because increases in corn price increase the value of accumulating SOC in the soil capable of enhancing corn yields.

Returning more residue to the soil is, based on these results, a “cheap” way of achieving that.

Results in Figure 4 suggest that stover harvest schedules maybe quantitatively sensitive to corn prices. First, increases in corn prices increase the intercept of the stover harvest curve; a \$3 increase in corn price increases the minimum price at which stover harvest becomes profitable by about \$6. In addition reductions in profit maximizing rates of stover harvest caused by increases

in corn price seem to be more ample at lower stover prices. In fact at a stover price of, for instance, \$60/ton removed stover would amount to 0%, 30%, and 62% if corn prices were \$2.25/bu, \$5.25/bu, and \$8.25/bu respectively. On the other hand at a stover price of \$116/ton removed stover would amount to 70%, 77%, and 85% if corn prices were \$2.25/bu, \$5.25/bu, and \$8.25/bu respectively. The sensitivity of economically optimal stover harvest rates to corn prices suggests that policies to boost the use of corn stover as biomass may be overridden by increases in corn prices such as the ones observed in the 2008-2010 period.

Figure 4. Stover Harvest Rate and Corn Price



Environmental trade offs associated with stover removal

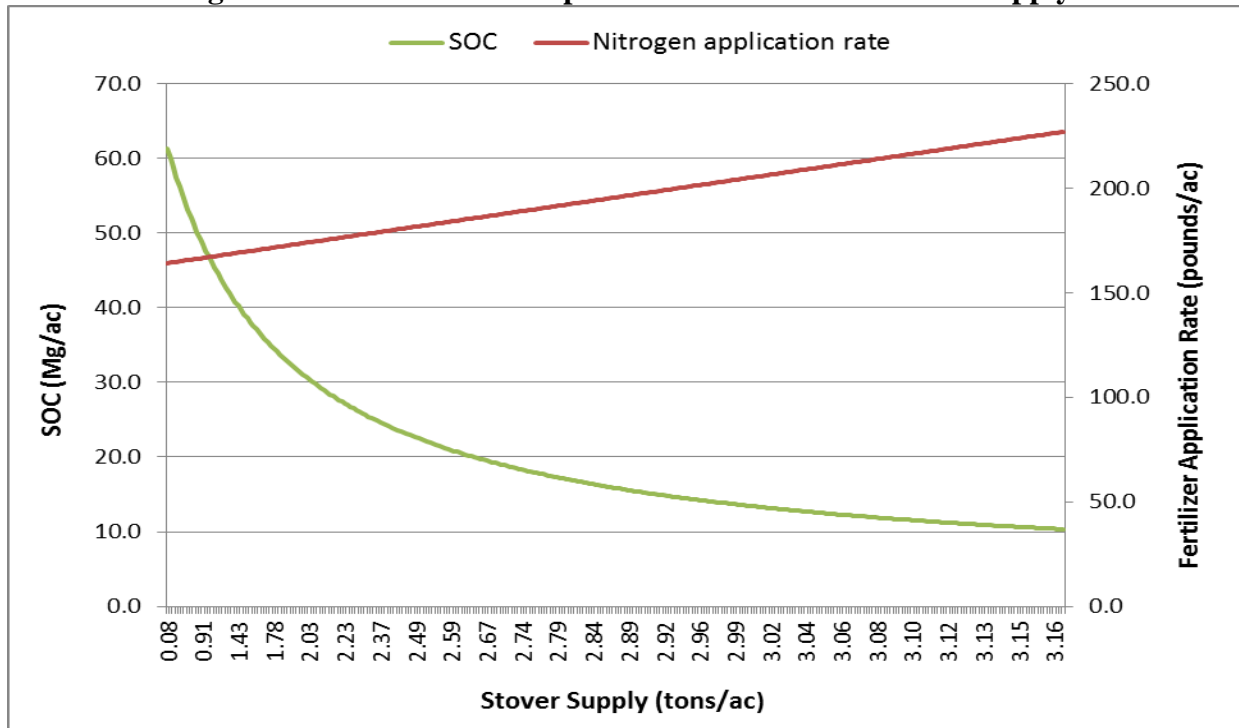
Many stakeholders interested in the use of corn residue for biomass have expressed concerns about potential negative environmental implications associated with its removal from the field. If corn stover, instead of being harvested for biomass, is left on the field at least part of its carbon content would be sequestered and stored by the soil as opposed to being recycled to the atmosphere when burnt for energy. Therefore the evolution of SOC as a result of different

rates of stover harvest indicates whether and to what extent this practice results in release or sequestration of carbon to or from the atmosphere relative to a baseline management practice. Furthermore reductions in SOC associated with harvesting of corn stover may reduce soil productivity resulting in (if it's economically profitable for farmers to do so) increased application of fertilizer. Therefore increases in supply of corn stover may entail increases in fertilizer application and, potentially, with increased water pollution through runoffs.

Our goal in this section is to quantify the link between stover supply for biomass, SOC, and nitrogen application rates under plausible conditions in the Corn Belt. The dynamics of SOC will be driven by the level of stover removal and supply. Under profit maximization farmers' decision on stover supply will in turn, as shown in Figure 2, be determined by prices. Nitrogen application rates will also be determined by prices. Therefore based on a surface of biophysically feasible combinations of stover, SOC, and nitrogen (summarized by the yield function and the dynamic soil equation) our economic model pinpoints (through equations (4), (9), and (7')) the combination that, for a given set of prices, will be chosen by a profit-maximizing farmer.

Economically optimal combinations of stover supply, nitrogen application rates, and SOC are depicted in Figure 5 for stover prices ranging from \$50/ton to \$116/ton. This figure reveals that increases in stover supply driven by increases in stover prices (keeping all other prices constant) are associated with increased nitrogen application (and, possibly, increased water pollution) and reductions in SOC (i.e. increase in carbon emissions relative to the baseline). Under these parameter values, an increase in stover price from \$54/ton to \$116/ton causes a reduction in steady state SOC in the order of 80% and an increase in nitrogen application of 20%.

Figure 5. Environmental Implications of Increased Stover Supply



Conclusions

Previous economic analyses of stover collection for biomass have exogenously assumed a rate of stover harvest and calculated the economic cost of collecting and transporting corn stover on a per ton basis. A direct implication of this approach is that the only source of additional biomass is the extensive margin; additional stover is brought from a wider radius around processing plants. But at higher stover prices additional quantities of biomass are likely to come from the intensive margin as well; i.e. farmers may decide to increase the percentage of stover to be harvested in their fields. This may increase the supply of stover within a given radius (which may in turn reduce transportation costs to the plant) but on the other hand it may intensify environmental problems in that area. Therefore the assumption of a fixed stover collection rate somewhat handicaps the economic and environmental assessment of stover harvesting for biomass.

This study is, to my knowledge, the first in building a model capable of calculating the profit maximizing rate of stover harvest subject to agronomic constraints (embodied by a grain/stover yield equation and a dynamic soil organic carbon equation). This model was simulated based on plausible parameters for the Corn Belt. Simulations allowed recovering of a stover supply schedule (tons of dry matter/ac) and tracing of environmental implications. Results suggest that at prices at or above \$60 per ton of stover farmers may choose harvest rates that surpass “sustainable” rates (i.e. rates that would maintain soil loss below tolerable levels). Under parameter values used here the profit maximizing harvest rate and supply of stover seem to be quite sensitive to both stover and corn prices.

Results from simulations also suggest that increases in the price of stover relative to corn rise stover supply per acre which, in turn, is associated with both losses in soil carbon (or increased emissions) and increases in nitrogen application. Parameters used in these simulations revealed that carbon losses and incremental nitrogen application may be significant. Adjustments in soil SOC may take several decades to unfold but the bulk of this adjustment may occur quickly after the change in management practice (zero removal to positive removal). This result suggests that net reductions in carbon emissions expected to be obtained from this practice are not guaranteed and, ultimately, a statistical question.

This study is a first step towards the development of a decision tool capturing both short-run and longer-term effects of harvesting corn stover for biomass. This decision tool may assist farmers and policy makers involved in the use of stover for biomass in going beyond crude rules of thumb used so far (e.g. removal of up to 30% of stover in the field). This study has many limitations, however. Parameters of the soil equation were taken from experiments in Iowa. In contrast the link between SOC and yields was quantified based on experiments conducted in

Ohio and South Dakota. While these places are somewhat representative of agronomic conditions in the Corn Belt calibrating the model based on experiments in diverse agro-ecological zones creates a spatial inconsistency. A more precise estimation of stover supply and its environmental implications requires a long-term, spatially consistent data set on SOC, stover removal, and yields.

Finally several research efforts should be undertaken if a scientific assessment of the economics and environmental implication of using corn stover for biomass is to be conducted. A non-exhaustive list of such efforts would include estimation of yield and soil equations under residue removal, coupling of more complex biophysical models with economic models of intertemporal profit maximization, and economic (market or non-market) valuation of increased fertilizer application for specific agro-ecological zones.

Appendix.

The current value Hamiltonian of the problem is:

$$H = (g_0 + a \ln S + b \ln x)p_y + 0.028(g_0 + a \ln S + b \ln x)h p_h^n - c_h^a - xp_x + \lambda[cS + d(g_0 + a \ln S + b \ln x)(1-h)]$$

First order conditions:

$$H_h = 0.028(g_0 + a \ln S + b \ln x) p_h^n - \lambda d(g_0 + a \ln S + b \ln x) = 0 \quad (\text{A1})$$

$$H_x = \frac{b}{x} p_y + \frac{b}{x} 0.028 h p_h^n - p_x + \lambda \frac{b}{x} d(1-h) = 0 \quad (\text{A2})$$

$$H_S = \frac{a}{S} p_y + \frac{a}{S} 0.028 h p_h^n + \lambda \left[c + d \frac{a}{S} (1-h) \right] = -\dot{\lambda} + r\lambda \quad (\text{A3})$$

$$H_\lambda = cS + d(g_0 + a \ln S + b \ln x)(1-h) = \dot{S} \quad (\text{A4})$$

$$\lim_{T \rightarrow \infty} \lambda_T \dot{S}_T = 0 \text{ (transversality condition with steady state; Okumura et al. (2009))} \quad (\text{A5})$$

Equation (A1) implies that $\lambda = \frac{0.028 p_h^n}{d}$. Plugging this value in (A2) yields equation (4). The

solution $\lambda = \frac{0.028 p_h^n}{d}$ implies that $\dot{\lambda} = 0$. Plugging these into (A3) and solving for S yields

equation (5). Equation (A4) is equivalent to (6).

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