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Abstract

Growing concern about global climate change has led to an interest in using perennial grasses to generate bio-energy and to sequester organic carbon in agricultural soils. The purpose of this study is to evaluate the extent to which dedicated bioenergy crops can lower the costs of carbon sequestration while also providing bio-energy for electricity generation. We examine the allocation of land between two alternative sequestration friendly land uses, growing perennial grasses and practicing conservation tillage with row crops to achieve given carbon sequestration targets. Additionally, we analyze the implications of alternative assumptions about the dynamics of soil carbon sequestration on the pattern of land use and costs of sequestration. A dynamic micro-economic model is applied at county-level in Illinois to examine cost-effective land use allocation among alternative row crops and two perennial grasses, Switchgrass and Miscanthus, over a 15 year period. A transportation module links power plants to least cost sources of bioenergy. We find that the extent to which biomass crops lower costs of sequestration varies directly but inelastically with the price of bioenergy. Use of a linear carbon accumulation function rather than a negative exponential function leads to earlier switching of land to sequestration friendly uses and this results in significantly higher marginal costs of sequestration. The potential to rely on bio-energy crops and conservation tillage to achieve sequestration targets varies spatially. In particular, bioenergy crops are more likely to be grown in counties that are closer to power plants while increased adoption of conservation-tillage in response to economic incentives is more likely in the northern and southern counties where there is either considerable capacity to sequester carbon or the returns from conservation tillage in the absence of carbon credits are low.

1. Introduction

Carbon sequestration in agricultural soils in the U.S. has the potential to remove considerable amounts of carbon (C) from the atmosphere annually, with estimates ranging from 75 to 208 million metric tones (MMT) annually and representing nearly 8% of total emissions of the U.S. (Lal et al. 1998). Studies show that soil sequestration is competitive with other strategies for carbon mitigation, such as afforestation and C offsets associated with use of biofuels, but the quantity of carbon sequestered will depend on the price for carbon credits (McCarl and Schneider 2001; Antle and McCarl 2002). There are several land use and management practices that can be adopted to increase soil carbon sequestration. These include conversion from conventionally tilled row crops to conservation tillage or to perennial grasses that can be used for forage or for bioenergy production. Two perennial grasses, Switchgrass (*Panicum viragatum*) and Miscanthus (*Miscanthus x giganteus*), have been identified in particular as among the best choices for low input bioenergy production in the U.S (Lewandowski et al. 2003; Heaton et al. 2004). We focus here on use of biomass as a renewable fuel for electricity generation. Several states in the US have established Renewable Portfolio Standards that require electricity providers to obtain a minimum percentage of their power from renewable energy resources by a set deadline.[1] Many utilities have established green pricing program that allow consumers to purchase electricity generated from renewable energy sources by paying a premium above standard electricity rates (Bird and Cardinal 2004).

The purpose of this paper is to examine the costs of carbon sequestration in cropland using alternative management strategies and determine the optimal spatial pattern of land use in a region to achieve given soil carbon sequestration levels. The costs of sequestration depend on the profits foregone and the carbon sequestered by alternative strategies; both of which are expected to vary among strategies, across space and over time. The potential for soil carbon sequestration varies among strategies with perennial grasses having a higher potential to sequester carbon per acre than annual row crops regardless of the tillage applied.[2] The sequestration potential of conservation tillage, on the other hand, is not only smaller than that of perennial grasses but may even be small in absolute terms if measurements are taken at sufficient soil depth (Manley et al. 2005). Soil carbon sequestration is inherently a dynamic process, the amount of sequestration at any point in time being dependent on the amount of carbon already present in the soil (West et al. 2004). The latter tends to vary spatially depending on land use history, and soil and climatic conditions (Tan et al., 2006). Moreover, there is an upper limit on the amount of carbon that can be stored in soil with any particular strategy and the annual sequestration rate is thought to diminish over time as the soil carbon level approaches equilibrium levels established by the land use practice applied (Six et al., 2002). Thus accumulation of soil carbon is a non-linear process. This process is also reversible and asymmetric process, whereby stored carbon can be released back to the atmosphere if land is reverted back to conventional uses; in this case, rates of soil carbon loss are much higher than rates of accumulation (Gilley et al., 1997; Baer et al., 2002).

The profitability of alternative sequestration friendly practices relative to the most profitable land use (in the absence of any sequestration considerations) is also likely to vary both spatially (depending on soil conditions, climate, and location relative to markets) and temporally (depending on the age of the perennial crops). This is particularly important in the case of bio-energy crops since their yield response to specific soil conditions and climate can be very different from that of traditional row crops and varies over their lifetime (McLauchlan et al., 2006). Additionally, transportation costs can be a significant component of the delivered price of bioenergy and lead to variability in the profitability of growing bio-energy crops across locations depending on their distance from the users of bio-energy. In the absence of well-developed markets, the delivered price of bio-energy, for co-firing with coal, received by producers is likely to be determined by the price of the fossil fuels they are substituting for and policies seeking to promote renewable energy use. Assuming that the delivered price is uniform across power plants within a region, the farmgate price of biomass is likely to vary spatially, depending on the location of the field producing the biomass and the power plant to which it is delivered.

We develop a dynamic optimization framework to investigate the socially optimal pattern of land use in a region that seeks to achieve targeted sequestration levels over a finite time horizon at least cost. Carbon sequestration dynamics are incorporated by assuming a negative exponential time path of sequestration with saturation limits determined by land use. This time path implies that annual rates of sequestration depend on the initial time of switching to a sequestration friendly practice. The framework developed here, therefore, incorporates the number of years a land parcel has practiced a sequestration friendly practice to determine the amount of carbon stored in that parcel. Since landowners have the option of switching in and out of various uses, the soil carbon loss due to a switch from a sequestration friendly use to a conventional use is also incorporated. We examine the impact of spatial differences in annual sequestration rates on the pattern of land allocation for conservation tillage and bio-energy crops with alternative carbon sequestration targets. The marginal cost of sequestering various levels of soil carbon is determined endogenously and used to develop supply curves for soil carbon sequestration. We use this framework to examine the implications of alternative prices for bio-energy for the marginal cost of carbon sequestration and the optimal allocation of land. As price and, therefore, profitability of bio-energy increases, the marginal cost of carbon sequestration is expected to decrease. The extent of this decrease will depend on the extent to which bioenergy crops contribute to achievement of the carbon sequestration target. We also compare the implications of alternative prices of bioenergy crops and of alternative targets for carbon sequestration for the spatial pattern of land use allocated to either bioenergy crops or conservation tillage practices. We apply this framework using county level data for Illinois to examine the cost-effective land use allocation among alternative crops, rotations and tillage practices over a 15 year period.

We compare costs of sequestration and pattern of land use with those that would be obtained under the assumption of a linear time path of sequestration, as assumed by several other studies (see for example, Antle et al. 2001, 2003; Pautsch et al. 2001). Even if both time paths eventually achieve the same total level of sequestration, the linear time path implies underestimation of annual sequestration rates achieved during the early years and an overestimate of sequestration rates achieved in later years as compared to the negative exponential time path. We therefore, expect the assumption of a linear time path to lead to a higher cost of switching land into sequestration friendly practices but a lower cost of maintaining land already in those practices as compared to the assumption of an exponential path.

There are several economic studies that examine the sequestration potential and the costs of afforesting marginal agricultural lands (Parks and Hardie 1995; Alig et al. 1997; Plantinga, Mauldin and Miller 1999; Stavins 1999). Other studies use sector level analysis to consider sequestration not only through afforestation but also in the agricultural sector by adjusting land uses, crop choices (including biofuels and forestry) and agricultural management practices (McCarl and Schneider 2001; Lewandrowski et al. 2004). These studies analyze the extent to which soil carbon is sequestered at various exogenously given prices in broadly defined regions in the US. Both studies find that at low carbon payments conservation tillage would be the dominant strategy for carbon sequestration and that afforestation and biofuels would become viable only at higher prices. McCarl and Schneider (2001), however, do not explicitly consider the dynamics of carbon sequestration and the need for payments over an infinite horizon to maintain carbon permanently in the soil. Lewandowski et al. (2004) compares the implications of payment for permanent carbon sequestration and that of payment for only a 15 year period.[3]

They find that the latter leads to more than twice as much carbon sequestration and with significantly higher portion being provided by afforestation.

In contrast to the above studies, Pautsch et al. (2001) and Antle et al. (2003) conduct disaggregated studies that focus specifically on examining the economic potential to sequester soil carbon in cropland at various carbon prices in Iowa and Montana, respectively. These studies focus on sequestration through a change in tillage from conventional to conservation tillage (Pautsch et al. 2001) and by changing cropping systems from crop-fallow to grass or continuous cropping (Antle et al. 2003). These studies use biophysical models to estimate the carbon accumulated over a 20-30 year period due to a change in land use and convert that to an annual basis assuming a linear accumulation function over time. They find that at a price of $190/metric ton of carbon up to 1 million metric ton (MMT) of additional carbon can be sequestered annually in Iowa (Pautsch et al., 2001) and 10.78 MMT of carbon can be stored in 20 years in Montana at a price of $30 per ton of soil carbon (see Antle et al. 2003). While these studies incorporate detailed spatial heterogeneity in costs of sequestration and in sequestration rates they undertake a static analysis of the potential for soil carbon sequestration at exogenously given prices assuming a constant rate of annual sequestration.

Estimates of the extent of carbon sequestered through land use changes, particularly conservation tillage and the returns from conservation tillage differ considerably across studies (Manley et al. 2005). A meta-analysis of results from previous studies analyzing the loss in profits and the carbon sequestered due to a switch from conventional to no-till finds that its potential for carbon sequestration may be very small, particularly if measurements are taken at sufficient depth (Manley et al., 2005). Cost of carbon sequestered through no-till increases with the depth at which carbon is measured. At a 25 cm depth, this cost is estimated to range between $86/per metric ton of carbon for non-wheat crops and $142/per metric ton for wheat.

This framework developed here makes several contributions to this literature. First, it accounts for the spatially and temporally varying carbon sequestration process by including a negative exponential carbon accumulation response function. This function utilizes information about the site-specific existing stock of carbon, the potential for additional soil carbon sequestration and the endogenously determined age structure of the specific landuse at each point of time. Second, it expands the range of land use options for sequestering soil carbon to include perennial grasses that can be used as biofuel source for electricity generation. By including a market for bio-energy crops, it shows that the price of bio-energy crops can affect the costs of carbon sequestration and the location of power plants can affect the spatial pattern of land use allocated to conservation tillage and perennial grasses. Third, it allows us to estimate the marginal costs of sequestration endogenously and to analyze the subsidy payments needed to build soil carbon levels to desired levels at least cost. It also facilitates the investigation of the feedback effects on changes in crop prices, discount rates and bioenergy subsidy on the cost of carbon sequestration.

The remainder of this paper is organized as follows. The next section discusses the dynamic optimization model followed by a description of the data used for the numerical simulation in Section 3 and the results in Section 4. Section 5 concludes with a discussion of the policy implications of the empirical findings.

2. The Land Use Decision Model

We develop a framework to analyze a social planner's land use choices for achieving a predetermined soil sequestration target at the end of a prespecified planning horizon, at least cost. We consider a region that is divided into homogeneous agricultural sub-regions. These sub-regions differ in terms of climate, productivity, relative proximity to market, baseline sequestered carbon level, capacity for carbon sequestration, and profitability of alternative land uses. Each sub-region is assumed to choose from a prespecified set of row crops and perennial crops and alternative management practices (rotation and and tillage practices).

Cost and output prices (therefore net returns) from row crop production are assumed to be fixed over time, but these vary spatially. The number of years a land area is continuously under perennial or conservation tillage practice affects the carbon sequestration rate, which varies across sub-regions as explained below. Finally, returns net of production costs and transportation costs from biomass crops also vary spatially since both costs depend on location. The cost of transportation per ton of biomass to power plant depends on the distance that biomass is shipped Production costs vary across space and time depending on yields. The price of bioenergy paid by all power plants is assumed to be the same and dependent on the energy content of biomass relative to coal. The indices, variables and parameters used in the algebraic model are defined in Tables 1-3. We use lower case letters and greek letters to denote exogeneously given parameters and upper case letters to represent variables which are endogeneous to the model.

Table 1. List of symbols used in the model

Indices	Definition
$Jr = \{jr\}$	set of row crops
$Jp = \{jp\}$	set of perennials
$J = \{j\} = Jr \cup Jp$	set of all crops
$T = \{t\}$	set of time
$I = \{i\}$	set of sub-regions
$m = \{1,2\}$	set of tillage management practices, 1=conservation till, 2=conventional till
$A = \{a\}$	set of age of perennials and conservation tillage
$L = \{\ell\}$	set of power plants

Table 2. List of parameters

Parameters	Definition
$yr_{i,jr}$	Yield of row crop jr in sub-region i in metric tons
$yp_{i,jp,a}$	Yield of perennial crop jp of age a in sub-region i in metric tons
el	Economic life of a perennial crop
$\pi r_{i,j,jr,m}$	Per hectare profit from rowcrop jr followed after crop j in sub-region i with practice m in t
$\pi p_{i,jp,a}$	Per hectare profit from perennial crop jp of age a in sub-region i
$d_{i,l}$	Distance between region i and power plant ℓ in kilometers
tc	Per metric ton per kilometer transportation cost
sc	Per hectare cost of switching from perennials to row crops
$\beta = 1/(1+\rho)$	Discount factor where ρ is the discount rate
$rs_{i,a}$	Cumulative amount of carbon sequestered under conservation till practice after a years in sub-region i
$ps_{i,jp,a}$	Cumulative amount of carbon sequestered by perennial crop jp after a years in sub-region i
$\bar{s}_T$	Amount of cumulative sequestration target at the end of planning horizon T
s_i^0	Amount of carbon stock in the soil in sub-region i in the base period
$s_{i,j,m}^e$	Long run equilibrium level of carbon that can be stored in the soil in sub-region i with crop j and practice m

Table 3. List of Variables

Variables	Definition
$RO_{i,j,jr,m,t}$	Acreage under rowcrop jr following crop j in sub-region i with practice m in year t
$RA_{i,jr,t}$	Total acreage of rowcrop jr in sub-region i in year t
$NT_{i,a,t}$	Acreage under conservation till of age a in sub-region i in period t
$\Delta NT_{i,a,t}$	Acreage of conservation till with age a switching back to conventional till in sub-region i in period t
$\Delta CT_{i,t}$	Acreage converted from conventional till to conservation till rowcrops in sub-region i and period t
$PA_{i,jp,a,t}$	Acreage of perennial crop jp of age a in sub-region i in period t
$\Delta PA_{i,jp,a,t}$	Acreage under perennial crop jp of age a switching to rowcrops in sub-region i and period t
$\Delta RA_{i,jr,t}$	Acreage converted from rowcrop jr to perennials in sub-region i in period t
$SB_{i,\ell,t}$	Amount of biomass shipped from sub-region i to plant ℓ in period t

Using the above notation, the mathematical model representing the social planner's problem is as follows:

$$Maximize\ \sum_{t=1}\beta^{t}\left[\sum_{i}\left\{\sum_{\{j,jr:\delta_{j,jr}=1\},m}\pi r_{i,j,jr,m}.RO_{i,j,jr,m,t}+\sum_{jp,a}\pi p_{i,jp,a}.PA_{i,jp,a,t}-\sum_{\ell}tc.d_{i,\ell}.SB_{i,\ell,t}-\sum_{jp,a}sc.\Delta PA_{i,jp,a,t}\right\}\right]+$$

$$\sum_{t=T+1}^{\infty}\beta^{t}\sum_{i,j,jr,m}\left(\pi r_{i,j,jr,m}.RO_{i,j,jr,m,t}\right)+\sum_{i,jp,a}\left[\sum_{a'>a}^{a'=el}\beta^{(T+a'-1)}\pi p_{i,jp,a,a'}+\sum_{t=T+el-a+1}^{\infty}\beta^{\mathrm{t}}\left(\rho.\sum_{a=1}^{el}\beta^{a}\pi p_{i,jp,a}\right)\right]PA_{i,jp,a,t}$$

$$-\sum_{t=T+1}^{\infty}\beta^{t}\sum_{i.l}tc.d_{i,\ell}.SB_{i,\ell,t}\qquad \exists\, a',a\in A \tag{1}$$

subject to:

$$\sum_{i}\left\{\sum_{a}rs_{i,a}NT_{i,a,T}+\sum_{jp,a}ps_{i,jp,a}PA_{i,jp,a,T}\right\}\geq\overline{s}_{T} \tag{2}$$

$$\sum_{i}SB_{i,l,t}\leq q_{l}\ \ for\ \forall\ l,t \tag{3}$$

$$\sum_{l}SB_{i,l,t}\leq\sum_{jp,a}y_{i,jp,a,t}.PA_{i,jp,a,t}\ for\ \forall\ i,t\ \text{and}\ jp\in\{\text{bioenergy crops}\} \tag{4}$$

$$\sum_{jr,m}RO_{i,j,jr,m,t}.\delta_{j,jr}\leq r\overline{a}_{i,j\in Jr}\,|_{t=1}+RA_{i,j\in Jr,t-1}\,|_{t>1}-\Delta RA_{i,j\in Jr,t}+\sum_{a}\Delta PA_{i,j\in Jp,a-1,t}\ \ \forall\ i,j,t \tag{5}$$

$$RA_{i,jr,t}=\sum_{j,m}RO_{i,j,jr,m,t}.\delta_{j,jr} \tag{6}$$

$$NT_{i,a,t}=n\overline{t}_{i,a-1}\,|_{t=1}+NT_{i,a-1,t-1}\,|_{t>1}+\Delta CT_{i,t}\,|_{a=1}-\Delta NT_{i,a-1,t}\qquad\forall i,a,t \tag{7}$$

$$\sum_{j,jr:\delta_{j,jr}=1}RO_{i,j,jr,m=1,t}=\sum_{a}NT_{i,a,t}\qquad\forall i,t \tag{8}$$

$$\sum_{a}NT_{i,a,t}\leq0.8\times\sum_{\{j,jr:\delta_{j,jr}=1\},m}RO_{i,j,jr,m,t}\forall i,t \tag{9}$$

$$PA_{i,jp,a,t}=p\overline{a}_{i,jp,a-1}\,|_{t=1}+PA_{i,jp,a-1,t-1}\,|_{t>1}-\Delta PA_{i,jp,a-1,t}\ \ \forall i,a>1,jp,t \tag{10}$$

$$\sum_{jp}PA_{i,jp,a=1,t}=\sum_{jr}\Delta RA_{i,jr,t}\qquad\forall i,t \tag{11}$$

$$0.90\times\left(r\overline{a}_{i,j\in Jr}+\sum_{a}p\overline{a}_{i,j\in Jp,a}\right)\leq RA_{i,j\in Jr,t}+\sum_{a}PA_{i,j\in Jp,a,t}\leq1.10\times\left(r\overline{a}_{i,j\in Jr}+\sum_{a}p\overline{a}_{i,j\in Jp,a}\right)\ \forall\ i,j,t \tag{12}$$

$$\sum_{jr}RA_{i,jr,t}+\sum_{a,jp}PA_{i,jp,a,t}=\sum_{jr}r\overline{a}_{i,jr}+\sum_{a,jp}p\overline{a}_{i,jp,a}\ \ \forall\ i,t \tag{13}$$

$$RA_{i,jr,t};\ RO_{i,j,jr,m,t};\ PA_{i,jp,a,t};\ \Delta NT_{i,a,t};\ \Delta CT_{i,t};\ \Delta PA_{i,jp,a,t};\Delta RA_{i,jr,t};SB_{i,\ell,t}\geq0\ \forall\ i,j,a,t \tag{14}$$

The objective function and constraints of the model are explained below. The objective function in (1) allocates land across various crops, rotations and management practices to maximize discounted aggregate profits over a finite planning horizon of *T* years. The first term in parenthesis in (1) represents the discounted net returns from production of both row crops and perennials over *T* years and the term in parenthesis represents the discounted returns in all years beyond the planning horizon. The terminal value of a unit of land at the end of the planning horizon is determined by the return to that land if it were to permanently remain in the land use in which it is in year *T*. In the case of perennials, the terminal condition also reflects the value of standing crop in year *T* for the remaining economic life followed by a return in perpetuity of growing that perennial on that land (as in McCarl et al. 2000).

Equation (2) represents the social planners targeted level of soil organic carbon (SOC) sequestration at the end of the planning horizon $\bar{s}_T$. Carbon sequesteration is achieved by switching to conservation tillage with row crops or to perennial grasses. The term $rs_{i,a}$ and $ps_{i,jp,a}$ represent the cumulative amount of carbon stored by row crops under conservation tillage and by perennial crops, respectively in *a* years:

$$rs_{i,a} = \left(s_{i,m}^{e} - s_{i}^{0}\right)\left(1 - e^{-ka}\right) \text{ for } \forall \;\; i, a$$

$$ps_{i,jp,a} = \left(s_{i,jp}^{e} - s_{i}^{0}\right)\left(1 - e^{-ka}\right) \text{ for } \forall \;\; i, jp, a$$

As the above expression suggests, carbon accumulation depends on each region's site specific characteristics, specifically the existing level of soil carbon, the long-run equilibrium level of soil carbon and the natural growth rate of carbon accumulation (denoted by *k*) (as in INRA, 2002). We assume that the equilibrium level of sequestration under conservation till is the same for all row crops (thus no crop index is used in the first expression). We also assume that the carbon accumulation over time increases at a diminishing rate and asymptotically approaches an upperbound^4. The left hand side of constraint (2) represents the total amount of soil carbon stored by all sub-regions and all land uses. Note that equation (2) implicitly accounts for losses of all previously accumulated SOC if land switches back to conventional uses from sequestration friendly uses. Thus, any carbon accumulated on land that switches out of a sequestration practice prior to year T is assumed to be lost and does not contribute to the achievement of the targeted sequestration.

The carbon sequestration constraint in (2) does not take into account the time value of carbon to account for declining future marginal social value of sequestered carbon (Stavins 1999). We examine the implications of discounting the soil carbon sequestration that occurs in later years by replacing equation (2) by equation (2.1) which discounts carbon using the same social discount rate as in (1) and thereby incorporates a time preference for early sequestration as in Plantinga et al. (1999), Stavins (1999) and Richards (1997).

$$\sum_t \beta^t \left(s_t - s_{t-1}\right) \geq \overline{s}_T \tag{2.1}$$

$$s_t = \sum_i \left\{ \sum_a rs_{i,a} NT_{i,a,t} + \sum_{jp,a} ps_{i,jp,a,t} PA_{i,jp,a,t} \right\} \tag{2.2}$$

where s_t is the amount of cumulative carbon sequestered in period t.

Since the carbon constraint is to be met by time T, the shadow price of the carbon sequestration constraint in (2) λ_T is the discounted present value of foregone profits over period T to achieve the last unit of sequestered carbon at time T and to maintain that permanently in the soil. The shadow price of carbon ($\tilde{\lambda}_T$) associated with equation (2.1) is the discounted present value of forgone profits over period T to achieve the last unit of discounted sequestered carbon at time T and to maintain that permanently in the soil. By solving the model repeatedly with different sequestration targets, the shadow prices associated with these targets can be used to construct a supply function of soil carbon sequestration. The product of the shadow value of carbon and the amount of carbon sequestered by a particular land area (metric tons per hectare) gives the subsidy payment per hectare to that land area. Although the shadow price of carbon and thus the marginal cost of carbon sequestration is uniform over space and time, per hectare payments for carbon will vary temporally and spatially due to non-linearity in the carbon accumulation function and spatial heterogeneity in the sequestration rate per hectare.

Equations (3) and (4) represent the bioenergy demand and supply constraints. We assume that the market for biomass is constrained by the technical capacity of a coal-based electricity generating plants. Specifically, each power plant can cofire biomass upto a certain fraction of its capacity to generate electricity[5]. Equation (3) restricts the capacity of each power plant to use biomass input. Power plants have the flexibility to acquire biomass from any sub-region. Incorporation of the biomass transportation costs in the objective function implies that each power plant will acquire its biomass input in the least expensive way subject to the sub-regions' biomass supplies. Equation (4) indicates that the total supply of biomass by each sub-region to all power plants cannot exceed the total production of biomass in that sub-region.

Equations (5) and (6) govern dynamic changes in the acreage of row crops resulting from conversion of land across different tillage options, row crops and perennial crops. Constraint (5) limits the land available for row crop *jr* in period *t* based on the land planted in period *t-1* for crops that can precede *jr* given the allowable crop rotation possibilities, plus the land converted from perennials, minus the acreage that switches to perennials. Equation (6) is an accounting equation that relates the total acres of each row crop (by sub-region and period) to the rotation activities producing that crop in that year.

Equation (7) reflects the dynamics of total acreage under conservation till practice. It states that in each sub-region the current year's allocation of land for conservation till for each age category is equal to the previous year's land under conservation tillage (that was one year younger) plus the land converted from conventional till to conservation till minus the amount of land that switches from conservation till to conventional till. Equation (8) is an accounting equation that relates the total land under conservation till to the rotation activities that can use this tillage option.

Equation (9) limits the total acreage under conservation till (in each sub-region and period) to a specified maximum (here 80%) of the total acreage under row crops. Analogous to equation (7), constraints (10) and (11) govern the dynamics of land conversion between perennials and row crops. These two equations jointly state that the current year allocation of land to each perennial crop of a given age group is equal to the previous year's land allocation of the same perennial crop (of one year younger age group) plus the acreage that switches from row crops to perennials minus the acreage that switches from perennial crops to row crops.

To prevent large scale and abrupt changes in land use, we incorporate lower and upper bounds for land allocation to each row crop and perennial crop that are consistent with farmers' historically observed behavior. Equation (12) reflects these bounds and states that the allocation of land to a particular crop in a sub-region should not exceed 10% or fall below 90% of the initial allocation of land to that crop in that sub-region.

Equation (13) ensures that total allocation of land between different land use choices should not exceed the total availability of land in the initial period. Finally, equation (14) states non-negativity conditions for the endogenous variables. The simulation is run in annual time steps for the 15 year period, 2003-2017.

3. Data Description

The framework described above is applied at the county level for the state of Illinois. The crop choices included are four row crops (corn, soybeans, wheat, sorghum) grown using either conventional or conservation-tillage practice and three perennial grasses, pasture, a forage crop, and Switchgrass and Miscanthus, as two bio-energy crops that can be co-fired with coal to generate electricity at existing electricity-generating plants in Illinois. We consider 34 different rotation possibilities among the row crops (Table 4). Pasture involves a five year rotation consisting of four years of continuous alfalfa for hay and a year of corn for silage. Switchgrass is assumed to have a productive stand life of 10 years while Miscanthus is assumed to have a life of 20 years. Five types of data are compiled for these crop choices for each of the 102 counties that comprise approximately 23 million acres of cropland in Illinois (USDA 2003). These include data on crop yields, rotation- and tillage-specific costs of production for row crops, age-specific costs of production for perennials, location and capacity of coal-fired power plants and annual sequestration rates for soil carbon with conservation tillage and each of the perennial grasses. These data are described in more detail below.

3.1. Crop Choices and Yields

The perennial grasses considered here, Switchgrass (*Panicum viragatum*) and Miscanthus (*Miscanthus x giganteus*), are warm season herbaceous crops that have a tolerance for the cool temperatures in the Midwest and can be grown on a broad quality of land types with relatively low need for water and fertilizer inputs using conventional farming practices. The U.S. Department of Energy identified Switchgrass as a “model” crop among 18 other herbaceous crops (not including Miscanthus) and there has been extensive field research on Switchgrass in the U.S. since 1992 (McLaughlin and Kszos 2005). Miscanthus is a perennial rhizomatous grass that is a native of East Asia and remarkably adaptable to a range of climatic conditions. A sterile hybrid genotype *Miscanthus x giganteus* has been extensively studied through field trials in several European countries and shown to have high yields, low fertilizer and pesticide requirements and high nutrient and water use efficiency. Field trials in Europe since 1983 show that yields can range between 4 to 44 t/ha per year (Lewandowski et al. 2003). Research on Miscanthus in Illinois was initiated recently with the establishment of field trials of Miscanthus and Switchgrass at three University of Illinois Agricultural Research and Education Centers in 2002 (Heaton, Voigt and Long 2006).

In the absence of long term observed yield for Miscanthus in Illinois, we simulate its yield using a process-based crop productivity simulation model, MISCANMOD (Clifton-Brown, Stampfl and Jones 2004). Simulated yields of Miscanthus in Illinois range between 30-42 dry t/ha with an average yield of 35.76 dry t/ha. Counties in the north have yields of 28-30 dry t/ha, in the central region of 31-36 dry t/ha, in the southern and southwestern regions of 37-42 dry t/ha. (see Khanna, Dhungana and Clifton-Brown 2006). In the absence of a crop productivity model for Switchgrass, we use the results of field experiments with Switchgrass in Iowa and Illinois to assume that the average yield per hectare in Illinois is 9.42 dry t/ha (see Khanna, Dhungana and Clifton-Brown 2006). This is 26.4% of the average yield for Miscanthus predicted by MISCANMOD. The corresponding ratio of Switchgrass yields to Miscanthus yields when the two were grown side by side at three locations in Illinois ranges from 8% to 37% (Heaton, Voigt and Long 2006). We assume that the ratio of Switchgrass yield per hectare to Miscanthus yield per hectare remains 26.4% at every location and use that to obtain the county level yields for Switchgrass for Illinois. Perennial grasses typically take a year to be established; with no harvestable yield in the first year. In the second year, yield is assumed to be 67% of the maximum yield of Switchgrass (Ugarte et al. 2003) and 50% of the maximum yield of Miscanthus (Khanna, Dhungana, and Clifton-Brown 2006). From the third year onwards, yields are assumed to remain constant through the remaining life of the plant.

Yields for all row crops and pasture for each county are proxied by their five year (1998-

2002) historical averages obtained from NASS/USDA. Five-year averages are used to smooth the temporary shocks from weather and other random factors that may affect productivity in particular years. We assume that yields do not vary with tillage practice but that corn yields with a continuous corn rotation are 12% lower than with a corn-soybean rotation.[6]

3.2. Costs and Revenues from Crop Production

The costs of production include costs of inputs such as, chemicals, fertilizers and seeds, costs of equipment for land preparation and harvest operations, costs of drying and costs of crop insurance for row crops, and costs of storage and transportation in the case of bio-energy crops. The cost items included for alfalfa are similar to those for row crops but exclude the costs of drying and crop insurance. For all crops, we include interest payments based on a 7% interest rate on all variable input costs. We assume that application levels for nitrogen, phosphorus, potassium and seed for row crops and alfalfa are yield-based and differ across counties in Illinois. Other costs of producing row crops are assumed to be fixed per hectare and the same across counties. Costs of producing perennial grasses (including alfalfa) in the establishment year differ from those in subsequent years because they include the costs of seeds/rhizomes and land preparation but no harvesting, storage or transportation. The latter differ for Switchgrass and Miscanthus between year 2 and subsequent years due to the yield that can be harvested.

Input application rates under conventional tillage for each crop and under each rotation are based on recommendations provided in by UI Extension (Schnitkey 2003). Costs of machinery include costs of repair and maintenance, fuel and lube, labor hire, depreciation and interest on investment. These were obtained from crop budgets for each crop under each rotation grown using conventional tillage prepared by FBFM (Schnitkey, Lattz and Siemens 2003).

Costs of fertilizer, chemicals and machinery under conservation tillage are expected to differ from those under conventional tillage. Fertilizer and machinery costs of production under each of the alternative types of conservation-tillage (ridge till, mulch till and no-till) and each type of conventional tillage (reduced till and intensive till) for various corn and soybean crop rotation possibilities for Illinois were obtained from the cropping practice survey (CPS) of the USDA (Wu et al. 2004). An area-weighted average fertilizer cost (and similarly machinery cost) with conservation tillage for each crop rotation was estimated using the ratio of the area under each type of conservation tillage practice to the total area under all types of conservation tillage used as weights. Similarly, an area-weighted average fertilizer cost (and machinery cost) with various conventional tillage practices was estimated for each crop rotation using CPS data. The ratio of these averages was then applied to the county-specific, rotation-specific costs under conventional tillage to obtain corresponding fertilizer and machinery costs under conservation tillage. The CPS data shows that machinery costs under conservation tillage are approximately 23%-35% lower than those under conventional tillage for most crop-rotation choices. However, fertilizer costs are lower for some crops/rotations and higher for others. For example, these costs are 39% lower for a hay-corn rotation but 80% higher for a corn-soybean rotation with conservation till as compared to conventional till. Additionally, we assume that chemical costs under conservation till are 33% higher than those under conventional till since more frequent herbicide spraying is needed to control weeds under conservation till.[7] These ratios were used to obtain county-specific and rotation-specific costs of production under conservation till for each of the row crops.

In the case of perennials, costs and revenues are age-specific. In the first year there are costs of establishment and no revenue. In subsequent years, there are annual maintenance costs and revenues. Since there are no recommendations for input application rates for perennials, we assume rates based on an extensive review of the existing literature on costs of producing

Switchgrass and Miscanthus with particular focus on studies for the Midwest (a detailed description of these studies and assumptions made for this study are discussed in Khanna, Dhungana and Clifton-Brown 2006). A large component of the cost of production during the first year is the cost of seed/rhizomes which is a fixed cost per hectare, while in subsequent years it is primarily the costs of harvesting (mowing, raking, baling) and storage. We assume that harvesting can be done by conventional hay harvesters and balers (Duffy and Nanhou 2001). We assume the costs of mowing/conditioning and raking are fixed per hectare, as in the case of hay, and the costs of making square bales vary with yield. After baling is completed and the bales are staged they are loaded on a truck/semi trailer and transported to an on-farm storage facility. Bales are stored on the farm and then reloaded on a truck and hauled to the power plant. We include the costs of renting a tractor, loading it on the field, transporting the bales to the storage area, unloading and stacking and then reloading the truck/semi-trailer for the final hauling to the power plant.

The per acre costs of land, overhead (such as farm insurance and utilities), building repair and depreciation and farmer's labor, are not included in the costs of perennials or row crops since they are assumed to be the same for all crops and do not affect the choice among alternative crops. Costs of fertilizer, chemicals and seeds in 2003 prices are assumed as follows: \$0.44/kg for nitrogen, \$0.49/kg for phosphorus, \$0.31/kg for potassium, \$12.67/t for lime, \$15.84/kg of live Switchgrass seed, and \$0.032 per propagule of Miscanthus (Lewandowski et al. 2003)[8] Transportation costs are calculated from each county center to each of the 24 coal-fired power plants in Illinois using the great circle distance method and geo-referenced data on location of county centers and power plants (Sinnott 1984)[9]. Lastly, we include a cost of switching land from perennials to row crops using a herbicide to kill the grass (as in Duffy and Nanhou 2001).[10]

We use the loan rates for each county for corn, soybean, wheat and sorghum to estimate the expected revenues from these crops.[11]. When market prices are low, farmers can receive the difference between the price designated as the loan rate and the market price per bushel sold as a direct payment from the government; these prices, therefore, serve as a price floor. These support prices play a major role in corn and soybean acreage decisions (Young and Westcott 2000) and have been found to be better proxies for expected future cash prices than futures prices in the presence of government programs (Chavas, Pope and Kao 1983).[12] Other farm subsides are in the form of direct payments that are essentially decoupled from crop and acreage decisions and are assumed to be paid to farmers even if they switch some of their acreage to perennial grasses (FBFM 2002). These include the direct government payment for corn, soybeans, wheat and sorghum for each county. For each crop in a county, the direct payment equals 85 % of the 2002 base year acreage times the crop-specific direct payment rate times the average yield for 1998-2002. The direct payment rates based on the 2002 Farm Bill are \$0.28, \$0.44, \$0.52, and \$0.35 per bushel for corn, soybeans, wheat and grain sorghum respectively (FSA/USDA 2003). These payments are based on the historical acres under each of these crops and are assumed to continue irrespective of current acreage allocation decision. The price of Alfalfa is assumed to be the uniform across Illinois and set at the average price reported for Illinois in 2003 by NASS/USDA[13]**.** Since corn silage is typically not marketed, we determine its implicit price by estimating the foregone revenue per acre by growing corn silage instead of corn and the additional cost of fertilizer replacement that is needed for corn silage, using the method in FBFM (Schnitkey, Lattz and Siemens 2003).

For perennial grasses used for bio-energy production, we assume that the price a power plant would be willing to pay for co-firing grasses with coal to produce electricity in Illinois would depend on the cost of coal and the energy content of these grasses. The energy content of

Switchgrass and Miscanthus is assumed to be 18 GJ per ton (McLaughlin et al. 1996) which is equivalent to 17.08 MBTU/ metric ton. The average price of coal in Illinois in 2002 was \$1.185 per million BTU and its heat content was 20.17 million BTU per ton of coal (EIA 2004).[14] The coal equivalent price that a power plant would be willing to pay for bio-energy is, therefore, \$20.22 per delivered dry metric ton (EIA 2004). In practice, this price could be lower if the power plant has to make investments in retrofitting equipment to co-fire grasses or if there is a loss in boiler efficiency with co-firing of grasses. Alternatively this price could be higher if the government was to subsidize power plants to induce switching to renewable energy or if power plants recouped value for savings due to avoided costs of sulfur dioxide permits, nitrogen oxide permits and carbon permits that result from the substitution of these grasses for coal which reduces these emissions. We examine the effect of alternative levels of these prices for bioenergy on the incentives to produce bio-energy crops and on the marginal costs of carbon sequestration. We assume that use of perennial grasses by power plants is constrained to a maximum of 5% of their fuel use which is determined by their capacity for electricity generation.

3.3. Carbon Sequestration Parameters

To determine the annual sequestration rates for each crop and tillage practice, we first needed to estimate the existing stock of carbon in each county. We obtained estimates of the percentage of soil organic matter (SOM) for each major soil series and hectares in that soil series in each county (including both agricultural and non-agricultural land) in Illinois from Alexander and Darmody (1991). We obtained data on average cropland acreage in each county for 1998-2002 from USDA's NASS database and assigned SOM and acreage under each SOM in descending order till the cropland acres were exhausted. Implicit in this is the assumption that land with the lowest SOM was not suitable for agriculture and was being used for other purposes. We then computed a weighted average of the percentage of SOM in the cropland in each county. This weighted average of percentage SOM was then converted to the amount of average soil organic carbon (SOC) (in metric tons per hectare), represented by $s^o{}_i$ for each county i, by assuming that there is 0.52% of SOC in each 1% of SOM and that there are 2.25 million kilogram of surface soil (to a depth of 30 cm) per hectare (VandenBygaart and Angers, 2006). We assume that 40% of SOC might have been lost on currently farmed agricultural land during the last century (Mann 1985; Flach, Barnwell and Crosson 1997; Paustian, Collins and Paul 1997; Unger 2001)[15] and, therefore, $s^o{}_i$ is 60% of the theoretical maximum capacity of the soil to be completely saturated by carbon. This maximum capacity is not always achievable because of climatological constraints. The technically achievable maximum level of SOC, referred to here as the long-run equilibrium level of SOC ($s^e{}_{i,j,m}$), is assumed to vary with specific perennial crops, tillage practices, climate, soil types and past land use history (Paustian, Collins and Paul 1997; Six et al. 2002). We assume that conservation-till and pasture can achieve 70% and 75% of the maximum capacity, respectively. Switchgrass and Miscanthus are expected to sequester 83% and 88% of the maximum capacity respectively.

To update the county-specific carbon stock from the level in 1991 estimated by (Alexander and Darmody 1991) to the level in 2003 due to conservation tillage and pasture, we combined data on cropland and pasture from NASS/USDA and on acreage under conservation tillage from the Conservation Tillage Information Center[16] to determine the acreage under conventional tillage, conservation tillage in each county in each year between 1992 and 2002. We assumed that it is only on these acres that carbon stocks will be likely to have changed between 1992 and 2002. Since the extent of carbon accumulated is dependent on the number of years the land has been continuously under conservation tillage (or pasture), we assume that the minimum acreage under conservation tillage over the period 1992-2002 had been under that practice for ten years. The remaining acres in conservation tillage are allocated equi-proportionately to each of the ages 1 through 9. A similar exercise is conducted to allocate duration of time under pasture to the pasture acreage in 2002.

We determine annual sequestration rates for each land use by assuming that carbon accumulation occurs in a non-linear manner with rapid increase in soil carbon in the first 10 years and then a gradual leveling off (Ismail, Blevins and Frye 1994; Liu, Liu and Loveland 2004; Prueger et al. 2004; West et al. 2004). We derive the value of k as equal to 0.12 in carbon accumulation function discussed in section 3.2 by assuming that 70% of the sequestration potential can be achieved within the first 10-year period under all land use choices. Although k is the same across all land use choices and counties, the annual sequestration rate differs, due to differences in the sequestration potential, across land uses and counties. Annual accumulation rates under the linear carbon accumulation function are obtained by dividing the sequestration potential associated with given uses of land in a sub-region by 20 to get the constant rate of annual sequestration. These assumptions imply that annual carbon sequestration rates are higher in a region with higher sequestration potential than in a region with lower sequestration potential. Finally, we assume that discontinuation of a particular sequestration friendly land use results in a loss of all the accumulated carbon. Our derived rates under the constant path assumption and total accumulation under the exponential path assumption fall within the range of sequestration rates used in other studies, as shown in Table 5.

4. Results

The optimization model described above was solved for various prices of bio-energy ranging from \$1.185/MMBTU to \$3.785/MMBTU in \$0.20/MMBTU increments for each carbon sequestration target that ranged from an addition of 1 MMT to 19 MMT in 3 MMT increments to the baseline level by the 15th year. Results in Table 6 are reported for two soil carbon targets, 10MMT and 19MMT and for two bio-energy prices, \$2.985/MBTU and \$3.385/MBTU. The base scenario assumes that there is no bio-energy subsidy or constraint on soil carbon levels. It projects the stock of carbon from its level in 1992 to that at the start of 2003 based on the simulated profit maximizing land use and the amount of age-specific land under conservation tillage and pasture in 2002. Carbon stock for land assumed to be under conservation tillage for some duration since 1992 is projected to have increased using the negative exponential carbon accumulation function described above. Carbon accumulated on land on which conservation tillage may have been practiced prior to 2003 but not in 2003 (if conservation tillage is not the profit maximizing land use predicted by the model) is assumed to be released back to the atmosphere; carbon stock levels on such land thus revert back to their level in 1992. Baseline carbon stocks at the start of 2003 vary considerably across counties, ranging from 23 to 71 MT per hectare, and are typically higher in the north-eastern and central regions of Illinois (Figure 1). The aggregate baseline carbon stock in 2003 is estimated to be 16 MMT.

4.1. Baseline Scenario and Bio-Energy Production in the Absence of Sequestration Targets

The baseline results in column 1, Table 6, show that in the absence of any carbon targets or bio-energy subsidy, 45% of the 9.4 million hectares of cropland in Illinois would be under conservation till, less than 3% under pasture and the rest under conventional tillage by the 15th year (2017). As a result of conservation tillage and pasture, the soil carbon level increases by 16 MMT by 2017; 93% of this increase is due to use of conservation tillage.

We find that the minimum price of bio-energy needed to make it profitable for landowners to produce Miscanthus is \$2.485/MBTU; at this price only 660 hectares of Miscanthus and no Switchgrass would be planted. This implies the need for a minimum subsidy of $1.30/MBTU, if power plants are only willing to pay a coal heating value equivalent price for bio-energy. The price that landowners receive for producing bio-energy would have to increase to $2.985/MMBTU and to $3.385/MMBTU for the Miscanthus production to increase to the level needed to generate 2.5% and 4%, respectively, of electricity in Illinois. At the lower of these two prices, the per unit cost of electricity generation would be twice as high as that with coal and the discounted present value of subsidies needed to induce power plants to use bio-energy over 15 years would amount to $515 million and $944 million, respectively. Figure 3 shows the supply and acreage response of Miscanthus biomass to bioenergy prices. As price of bioenergy increases from $2.985/MBTU to $3.385/MBTU, the acreage under Miscanthus increases from 0.8% to 1.2% of cropland and production increases from 2MMT to 3MMT with marginal reductions in acreage under row crops with both types of tillage practices and under pasture. Carbon sequestered in 15 years increases by 1.5 MMT (if the price of bio-energy is $3.385/MBTU) relative to the level in 2017 with no bio-energy subsidy. The contribution of Miscanthus to total sequestration in 15 years would be 11%.

Focusing on the spatial distribution of Miscanthus production we find that it would be profitable to grow it only in counties that have a power plant in close proximity. As the price of bioenergy increases, the maximum distance to which a county would be willing to deliver biomass increases. At a price of $2.985/MBTU this distance is 53 km but it increases to 83 km if the bioenergy price is $3.385/MBTU. As shown in Fig 5, cropland allocated to Miscanthus ranges from 1000 ha to 6000 ha with most of the land located in southwestern Illinois. However, it would be profitable to produce some Miscanthus even in the central and north-eastern counties of Illinois, despite the relatively low yield of Miscanthus and the high opportunity cost of land there, because of the demand for bio-energy by those plants and the low transportation costs for counties in that area. Location of power plants and their capacity to utilize bioenergy can offset some of the yield advantage of counties in southern Illinois and provide incentives to grow Miscanthus elsewhere. Figure 7 shows that land under conservation tillage ranges from 0 to 57% of the county cropland. Counties in central and north-eastern regions of Illinois have a relatively high percentage of land under conservation tillage even in the absence of any carbon subsidy.

4.2. Alternative Soil Carbon Sequestration Targets

4.2.1 Negative Exponential Carbon Accumulation Function

In Table 6, we report the results of imposing two levels of soil carbon sequestration targets, 10 MMT and 19MMT above the baseline level. The costs of meeting these targets and their land use implications differ depending on the price of bio-energy. We consider three alternative bio-energy prices, less than \$2.485/MBTU (at which there is no biomass production), \$2.985/MBTU and \$3.385/MBTU. We find that a carbon subsidy alone does not create incentives for biomass production. For any bio-energy price less than \$2.485/MBTU, there is no incentive to produce biomass even if the carbon subsidy is \$130 per metric ton. At the price of \$2.985/MBTU, the imposition of 10MMT and 19MMT carbon sequestration targets increase the share of cropland under Miscanthus from 0.77% to 1.02% and 1.5%, respectively. It also increases the share of cropland under conservation tillage from 45% to 58% and 77% respectively. The contribution of Miscanthus to these sequestration targets (at the \$2.985/MBTU price) is 6-7% while that of conservation tillage is about 87%. This is because of two main reasons. The first is the demand constraint with 5% limit for cofiring biomass with coal that is constraining the use of biomass for some power plants even though it may be profitable to grow it in the vicinity of those power plants at \$2.985/MBTU. The second reason is that there exists a low opportunity cost for converting row crops with conventional tillage to conservation tillage practice for sequestering carbon in many counties. Thus small carbon payments can lead large land areas to switch from conventional to conservation tillage.

An increase in the price of bio-energy to \$3.385/MBTU even with a 19MMT sequestration target does not lead to any increase in the land area under Miscanthus as compared to that under 10MMT carbon target, presumably because of limited capacity of power plants to use the biomass; thus the contribution of biomass to the 19MMT sequestration target declines to 5%. Despite the bio-energy subsidy, conservation tillage remains the dominant contributor to the achievement of the soil carbon sequestration target.

Areas where there is a change in the acreage under Miscanthus and conservation tillage are shown in Figures 5 to 8. The carbon subsidy provides incentives to expand the area under Miscanthus in central and north-eastern Illinois by expanding the distance from which biomass is transported (Figures 5-6)[17]. These are areas where power plants have unutilized capacity to use bio-energy in the absence of carbon constraints. The carbon subsidy also creates incentives to increase the area under conservation tillage and as shown in Figure 8, much of this increase occurs in counties in north-eastern and southern Illinois. These are the counties where it was otherwise unprofitable to undertake conservation tillage and as a result there is more capacity to sequester carbon in the soil. In three counties, we find that there is a decline in the area under conservation tillage and land allocation shifts in favor of Miscanthus production in response to the carbon subsidy.

The marginal cost curve of carbon sequestration in the absence of any biomass production (Figure 4) shows that 4 MMT of carbon can be sequestered by the 15th year at a fairly low price of \$40/ ton of soil carbon. The marginal cost rises steeply till a target of 7MMT, then more gradually till a target of 16MMT is achieved and steeply thereafter; this suggests that low cost opportunities for carbon sequestration through conservation tillage are available but limited.

The relatively elastic cost curve between carbon prices of $120/metric ton to $140/metric ton suggest that there is considerable potential for soil carbon sequestration through conservation tillage when prices are in that range.

The marginal cost of carbon sequestration depends not only on the sequestration target, but also (among other things) on the price of bio-energy (Figure 9). The potential to grow biomass crops, if the price of bio-energy is high enough, lowers the marginal cost of sequestering 10MMT of soil carbon from $131/metric ton, in the absence of any biomass production to $124/metric ton if bio-energy price is $3.385/MBTU. The marginal cost of achieving a 19MMT target would increase from $160/metric ton, with bio-energy priced at $2.985/MBTU to $185/metric ton in the absence of biomass production. Thus, the benefit of using biomass crops to lower the cost of carbon sequestration is either at low sequestration targets (4 MMT) but with very high bio-energy subsidies (bio-energy price of $2.985/MBTU and above) or at very high sequestration targets (19MMT) and a moderate bio-energy subsidy (bio-energy price of $2.985/MBTU). In the former case, high bio-energy subsidy is needed to make biomass production competitive with conservation tillage while in the latter case costs of further sequestration through conservation tillage are rising steeply, making biomass production a preferred alternative.

The negative relationship between the marginal cost of carbon sequestration and the price of bio-energy is fairly flat at low prices of bio-energy, steeper at moderately higher prices of bio-energy and then flat as bio-energy price exceeds $3.385/MBTU or the sequestration target increases to 10MMT. This suggests that there is a limited amount of cropland that producers would find it profitable to switch to Miscanthus production if bio-energy prices range between $2.985/MMBTU and $3.385/MMBTU and there is a carbon subsidy. The profitability of Miscanthus on other cropland is so low relative to conventional uses; hence there is no incentive for it to switch to Miscanthus despite increases in bio-energy prices and/or in the carbon subsidy.

The land use implications of carbon sequestration targets and bio-energy prices can be seen in Figure 10. Conservation till acres increase almost linearly as the carbon sequestration target increases. As the bio-energy price increases, some conservation till acreage is converted to Miscanthus production. At the 10 MMT carbon sequestration target, the share of cropland under conservation till declines by 3% from 61% in the absence of biomass production to 58% with Miscanthus production at a bio-energy price of $3.385/MBTU. At the 19MMT target the corresponding decline is by 5%. Nevertheless, conservation tillage remains the dominant land use strategy for soil carbon sequestration. At any given bio-energy price, the imposition of a carbon sequestration target positively impacts the land area under Miscanthus. At the $2.985/MBTU bio-energy price, this area increases fairly steeply, particularly as the carbon sequestration target increases beyond 16MMT. At the $3.385/MBTU bio-energy price, this area levels out after the 10MMT target; suggesting that relatively low cost conversion to Miscanthus is feasible on 1.5% of the cropland; beyond that it is too costly to convert from conventional land uses to Miscanthus, even with high bio-energy and carbon subsidies.

The discounted value of the carbon subsidy required to meet the 10MMT sequestration target is $1306 M in the absence of any subsidy for bio-energy and $1274 M with biomass crops; with most of this subsidy paid to land under conservation tillage. However, total subsidy payments for the 10MMT target are substantially higher in the presence of biomass production than otherwise. This is because the bioenergy subsidy increases production of Miscanthus by much more than it reduces the marginal cost of sequestration or the amount of sequestration. At the 19 MT sequestration target, increasing the bioenergy subsidy from $2.985/MBTU to $3.385/MBTU does not have any impact on the marginal cost of sequestration and simply increases the total subsidy payments from $3978 M to $4184 M.

4.2.2. Carbon discounting

In Figure 11, we depict the shadow value of carbon resulting from carbon discounting and compare it with the value in the absence of carbon discounting. The figure shows that the costs of meeting the given sequestration target with equivalent amount of time discounted carbon would be 17%-25% higher compared with that of undiscounted carbon constraint case. This is mainly because the higher value attached to carbon sequestered in early periods than in later periods induces earlier switching of land to conservarion tillage practices (Figure 12). With carbon discounting meeting a discounted carbon sequestration target equivalent to 10MMT in 15 years requires approximately 5.3 million hectares of land to be allocated to conservation tillage as early as 203. This level remains almost constant until the end of 15th year. On the other hand, in the absence of carbon discounting, about 4.9 million hectares of row crops are allocated under conservation tillage initially which gradually increase to 5.4 million hectares by the end of 5th year and remains at that level until the end of 15th year.

4.2.3. Linear Carbon Accumulation Response Function

As illustrated in Figure 2, there can be considerable difference in the annual rates of sequestration obtained using a negative exponential carbon accumulation and a linear carbon accumulation function. In the early years after land is converted from a conventional use to a sequestration friendly use, the linear function underestimates the amount of sequestration, while in latter years this approach overestimates the amount of sequestration relative to that predicted by the exponential function. Overall, the linear function assumes a higher total amount of carbon sequestration in 20 years as compared to the exponential function which predicts saturation will result in 40 to 50 years. We examine the impact of these alternative assumptions about the carbon accumulation path on costs of carbon sequestration (Table 7). Figure 4 shows that the marginal cost of carbon sequestration is lower with the linear path assumption for relatively low sequestration targets such as 4 MMT and 7MMT (with bio-energy priced at $2.985/MBTU). These targets are essentially met by maintaining land that has been under conservation tillage prior to 2003 in that tillage practice (this land shifts out of conservation tillage in the absence of soil carbon targets). Since this land has already accumulated a considerable amount of soil carbon, its annual sequestration rate under the linear path assumption is higher than that under the exponential path assumption.

However, as sequestration targets increase beyond 7 MMT target, the cost of sequestration under the exponential path is considerably lower than that under the linear path assumption. The higher initial sequestration rates under the negative exponential path assumption result in lower marginal costs of carbon sequestration as compared to those with the linear rate. At the 10MMT soil carbon target, the linear path assumption leads to a 12% increase in the marginal cost of sequestration while at the 19MMT soil carbon target this approach leads to an increase of 16% in the marginal cost of sequestration, relative to the costs with a negative exponential accumulation function. The path of aggregate carbon accumulation over the 15 year period is more gradual with the non-linear path assumption as compared with that under the linear sequestration path assumption because existing soil carbon levels are already quite high and additional sequestration grows slowly in the former case. The amount of land allocated to conservation tillage and to miscanthus in earlier years of the 15 year period is larger under the linear assumption than under the non-linear soil carbon sequestration path assumption; this leads to a higher discounted cost of carbon sequestration. By the end of the 15 year period, both carbon sequestration paths converge. The spatial pattern of land use under both types of sequestration paths is very similar since the relative opportunity cost of sequestration with different practices does not change much across counties.

4.3 Sensitivity Analysis

The sensitivity of our results to various assumptions underlying the results in Table 6 is examined in Table 8 keeping bio-energy price at \$2.985/MBTU and the carbon sequestration target at 10MMT. An increase in the capacity of power plants to utilize bio-energy from 5% to 8% would increase the land area planted under Miscanthus from 1% to 1.4% but have a very negligible impact on the marginal cost of sequestering 10MMT. A 25% increase or a 25% decrease in the costs of producing Miscanthus would have a small impact on the land area under Miscanthus (decreasing it to 0.04% or increasing it to 1.55%, respectively) and a small impact on the marginal cost of sequestration. An increase in yields of all row crops would increase the cost of relying on biomass crops to achieve the sequestration target and reduce their contribution to the target while increasing the marginal cost of carbon sequestration by 9%. Similarly, allowing greater flexibility in land use changes has a negligible impact on the marginal cost of sequestration.

Assumptions about the discount rate used by landowners and the inclusion of terminal returns to the land in making land use decisions have the largest impact on the cost of sequestration. An increase in the discount rate from 4% to 8% affects the marginal cost of sequestration in two ways; with the latter effect more dominant in this case. First, it leads landowners to prefer annual returns from row crop production to perennials which have a two year lag in providing returns. As a result, land under Miscanthus decreases and 89% of the 10MMT carbon target is now met by conservation tillage; this tends to increase the marginal cost of sequestration. Second, future costs of land use changes to meet the sequestration target in the 15th year are discounted more heavily and this decreases the discounted present value of the marginal cost of the sequestration. Exclusion of the terminal returns to land also reduces incentives for landowners to plant a perennial such as Miscanthus, whose economic life is longer than the planning horizon of the landowner. Additionally, it lowers costs of sequestration, since land returns to its most profitable use after the 15th year, reducing the length of time costly land use changes have to be maintained in order to achieve the 10 MMT carbon target. The marginal cost of sequestration of 10MMT for 15 years falls to $33/ton.

5. Conclusions

This paper analyzes the costs of soil carbon sequestration in Illinois using dynamic optimization and incorporating a non-linear carbon accumulation function. It considers the potential of both conservation tillage and perennial grasses to sequester carbon. While perennial grasses have a larger potential to sequester soil carbon than conservation tillage, they also lead to higher foregone profits than conservation tillage. The magnitude of these foregone profits depends on the price of bio-energy, leading to a trade-off between a bio-energy subsidy to power plants and a carbon subsidy to landowners. Our main findings are as follows. First, at the current coal-based energy price considerably large bio-energy subsidies would be needed to make it profitable for landowners to grow Miscanthus. Even with these subsidies, the contribution of Miscanthus to the soil carbon sequestered in 15 years remains less than 11% and conservation tillage continues to be the primary cost-effective mechanism for soil carbon sequestration. Production of Miscanthus is heavily constrained by location of production sources relative to power plants and by the capacity of the power plants to cofire bioenergy. Second, the costs of carbon sequestration increase fairly rapidly as sequestration targets increase, particularly up to the 10MMT level, and then more gradually after that. The magnitudes of these costs are higher with a linear accumulation path, particularly at larger carbon sequestration targets.

Third, we find that biomass crops can lower the costs of carbon sequestration by up to 8% but mainly at very high carbon sequestration targets and with considerably large bio-energy subsidies. Results are very sensitive to the assumed discount rate and whether sequestration is a temporary or a permanent strategy for mitigating climate change.

The estimates for costs of sequestration over a 15 year period obtained here are not directly comparable with those obtained by Pautsch et al. (2001) or Antle et al. (2003), due to differences in the treatment of permanence of carbon sequestration, in the sequestration targets and the length of time during which the target is to be met. While Pautsch et al. (2001) provide an estimate for the annual cost of carbon sequestration, Antle et al. (2003) estimate the marginal cost of sequestering carbon in six agro-ecozones over a period of 20 years. Antle et al. (2002) compare their estimate of the cost of carbon sequestration with that of Pautsch et al. (2001) by converting their estimate of 10.71 MMT of carbon sequestered over 20 years to about 0.5 MMT of carbon sequestered annually at a cost of $30 per ton. They find that 0.5 tons of carbon can be sequestered at a price of $30 per ton in Montana and $80 per ton in Iowa. As sequestration levels increase, the cost in Montana rises steeply as compared to Iowa due to limitations on available land. In contrast to these studies our study estimates the costs of sequestering 10MMT in 15 years either permanently or for 15 years only. This implies that annual sequestration of 0.66 ton for a 15 year period can be achieved in Illinois at a price of $33 per ton. Of course, the difference in assumptions about the timing of sequestration, within one year in the case of Pautsch et al. (2001) while over a 20 year period in Antle et al. (2003) and over a 15 year period in this study make it difficult to compare the three studies precisely. The lower costs of sequestration in this study and in Antle et al (2003) could be because of the greater flexibility that landowners have in the timing of sequestration, over a 15 or 20 year period. In contrast in Pautsch et al (2001) landowners are required to meet the 1MMT carbon constraint in one year. Additionally, they only consider one sequestration friendly option, namely conservation tillage, as compared to the other two studies, which might explain the higher costs of meeting a given carbon target in a short period of time.

Our results have several policy implications. They show that with low coal prices market incentives to divert land from traditional row crops to biomass crops in Illinois, even if one accounts for the carbon sequestration benefits of biomass crops, are likely to be limited, at least under the present technology and market conditions. Large bio-energy subsidies per unit of energy to power plants and carbon subsidies per ton of carbon sequestered to landowners will be needed to induce landowners to switch even 1% to 2% of cropland to biomass crops that can be used to produce 3% to 5% of electricity generated in Illinois. The magnitude of the carbon subsidy is sensitive to the assumption about the carbon accumulation path, especially as carbon sequestration targets increase, and to the discount rate used by landowners. Moreover, we find that soil carbon sequestration may be more viable as a short run strategy for mitigating climate change rather than as a strategy for permanent reduction in carbon. This paper focused only on one of the sequestration benefits provided by perennial grasses. Further research that incorporates the potential for carbon mitigation and air pollution reduction by using bio-energy to displace coal in power plants is needed to examine the extent to which the price of bio-energy should diverge from the level justified by its coal equivalent heating value. Our results show the extent to which policy makers can promote carbon sequestration by raising the price of perennial grasses by subsidizing power plants that use bio-energy and/or by providing “green payments” to landowners that switch to sequestration friendly practices. These payments can take the form of subsidies for conservation tillage on working lands or payments to retire land from crop production and use it for growing perennial grasses. Our results show the role that energy policy, conservation policy for working lands and land retirement policies can play in achieving given sequestration goals cost-effectively and its implications for government payments.

Table 4: Crop Rotation Possibilities

	Current Crop						
Previous Crop	Corn	Soybeans	Wheat	Sorghum	Pasture	Miscanthus	Switchgrass
Corn	1	1	0	1	1	1	1
Soybeans	1	1	1	1	1	1	1
Wheat	1	0	1	1	1	1	1
Sorghum	0	1	0	1	1	1	1
Pasture	1	0	0	1	0		
Miscanthus	1	1	1	1	0		
Switchgrass	1	1	1	1	0		

Note: 1= yes, 0=no. Example: The first row shows that corn after corn is possible but wheat after corn is not possible. Empty cells shows no rotation is defined for perennials.

Table 5. Carbon Sequestration Rates

Land Use	This Study[1]			Previous studies[2]		
	Annual C (MT/ha) Linear path	Total C in 20 years (Mt/ha) Linear path	Total C in 20 years (MT/ha) Expo-nential path	Annual C (MT/ha)	Total C in 20 years (MT/ha)	References
Conservation till	0.20-0.57	3.81-11.47	3.46-10.43	0.30-0.49	5.93-9.88	Wander et al. 1998; Dick et al. 1998; Robertson et al. 2000; Eve et al. 2002; Puget et al. 2005
Pasture	0.30-0.86	5.71-17.20	5.19-15.64	0.40-1.24	7.91-24.71	Robertson et al. 2000; Eve et al. 2002, Puget et al. 2005
Switchgrass	0.44-1.31	8.72-26.37	7.93-23.99	0.69-1.11	13.84-22.24	Gebhart et al. 1994; McLaughlin et al. 2002
Miscanthus	1.25-1.61	10.63-32.10	9.69-29.21	0.94-1.38	18.78-27.68	Beuch et al. 2000; Kahle et al. 2001; Matthews and Grogan 2001

[1] This is the range of estimates across the different counties in Illinois

[2] This is the range of estimates found across the studies cited.

Table 6: Implications of Carbon Sequestration Targets with a Negative Exponential Carbon Accumulation Function

Carbon Sequestration Target	**None**			**10 MMT**			**19MMT**		
Bio-Energy Price per MBTU	**< $2.485**	**$2.985**	**$3.385**	**< $2.485**	**$2.985**	**$3.385**	**< $2.45**	**$2.985**	**$3.385**
Carbon Sequestration Level in 2003 (Million Metric Tons)	15.96	16.86	17.44	25.96	25.96	25.96	34.96	34.96	34.96
By Conservation till (%)	92.95	86.92	82.99	93.46	87.42	83.84	95.14	87.83	87.83
By Pasture (%)	7.03	6.69	6.34	6.53	6.51	6.51	4.85	4.82	4.82
By Miscanthus (%)	0.00	6.37	10.65	0.00	6.06	9.64	0.00	7.33	7.34
Land under conservation till (%)	45.07	44.61	44.29	61.04	58.52	57.25	75.15	70.77	70.77
Land under conventional till (%)	52.29	51.98	51.90	36.33	37.83	38.63	22.22	25.08	25.09
Land under pasture (%)	2.64	2.64	2.63	2.64	2.63	2.63	2.64	2.63	2.63
Land under Miscanthus (%)	0	0.77	1.19	0	1.02	1.49	0	1.51	1.51
Biomass Supply (MMT with 15% moisture)	0	1.96	2.94	0	2.56	3.62	0	3.67	3.67
Electricity generated with bio-energy (%)	0	2.5	3.8	0	3.3	4.7	0	4.8	4.8
Maximum distance for transportation of biomass (miles)	0	32.94	52.32	0	37.85	52.32	0	80.75	80.75
Marginal cost of carbon sequestration ($/metric ton)	0	0	0	130.60	127.39	123.87	185.07	160.47	160.47
Discounted present value of carbon subsidy to Miscanthus ($M)				0	200.53	309.92	0	411.49	411.49
Discounted present value of carbon subsidy to conservation till acres ($M)				1231.25	1001.17	858.60	3410.40	2547.13	2546.86
Discounted present value of carbon subsidy to pasture acres ($M)				74.72	72.22	70.22	105.89	90.50	90.50
Discounted present value of bio-energy subsidy ($M)		515.21	943.83	0	647.38	1120.47	0	928.92	1135.35
Total Subsidy ($M)		515.21	943.83	1305.97	1921.30	2359.21	3516.29	3978.04	4184.20

Table 7. Implications of Carbon Sequestration Targets with a Linear Carbon Accumulation Function

Carbon Sequestration Target	**None**			**10 MMT**			**19 MMT**		
Bio-Energy Price per MBTU	**< $2.485**	**$2.985**	**$3.385**	**< $2.485**	**$2.985**	**$3.385**	**< $2.45**	**$2.985**	**$3.385**
Carbon Sequestration Level in 15 years (Million Metric Tons)	21.33	22.07	22.59	31.33	31.33	31.33	40.33	40.33	40.33
By Conservation till (%)	93.17	90.03	87.25	93.20	88.70	86.04	94.72	90.55	89.01
By Pasture (%)	6.83	5.60	5.37	6.80	6.80	6.79	5.28	5.27	5.27
By Miscanthus (%)	0.00	4.37	7.38	0.00	4.50	7.17	0.00	4.18	5.72
Land under conservation till (%)	45.07	44.61	44.29	60.19	57.91	56.73	75.38	71.89	70.75
Land under conventional till (%)	52.29	51.98	51.90	37.18	38.44	39.16	21.98	24.30	25.10
Land under pasture (%)	2.64	2.64	2.63	2.64	2.63	2.63	2.64	2.63	2.63
Land under Miscanthus (%)	0.00	0.77	1.19	0.00	1.02	1.49	0.00	1.18	1.52
Biomass Supply (MMT with 15% moisture)	0.00	1.96	2.94	0.00	2.55	3.62	0.00	2.92	3.68
Electricity generated with bio-energy (%)	0.00	2.5	3.8	0.00	3.3	4.7	0.00	3.8	4.8
Maximum distance for transportation of biomass (miles)	0.00	32.94	52.32	0.00	37.85	52.32	0.00	37.85	80.75
Marginal cost of carbon sequestration ($/metric ton)	0.00	0.00		147.32	142.89	139.76	215.59	186.87	185.10
Discounted present value of carbon subsidy to Miscanthus ($M)				0.00	201.61	313.88	0.00	314.78	426.72
Discounted present value of carbon subsidy to conservation till acres ($M)				1373.78	1131.19	990.10	3950.69	3110.57	2966.42
Discounted present value of carbon subsidy to pasture acres ($M)				99.41	96.10	93.62	145.48	125.17	123.76
Discounted present value of bio-energy subsidy ($M)		496.30	909.20	0.00	646.60	1120.47	0.00	739.53	1137.29
Total Subsidy (M)		496.30	909.20	1473.19	2075.50	2518.07	4096.17	4290.05	4654.19

Table 8. Sensitivity Analysis[1]

	Increase in Power Plant Capacity for Bio-Energy from 5% to 8%	25% Increase in Biomass Production Cost	25% Decrease in Biomass Production Cost	10% Increase in Crop Yields	25% Increase in Crop Prices	Increase in Flexibility of Land Use Changes[2]	Increase in discount rate to 8%	Exclusion of Terminal Returns to Land
Carbon Sequestration Level in 15 years (Million Metric Tons)	25.96	25.96	25.96	25.96	25.96	25.96	25.96	25.96
By Conservation till (%)	85.44	93.15	83.38	88.85	91.63	86.02	88.93	89.35
By Pasture (%)	6.50	6.53	6.50	6.53	6.53	6.92	6.53	6.53
By Miscanthus (%)	8.05	0.31	10.11	4.62	1.83	7.05	4.53	4.11
Land under conservation till (%)	57.67	60.91	57.09	59.09	60.31	58.27	60.49	74.22
Land under conventional till (%)	38.30	36.41	38.74	37.46	36.67	37.82	36.05	22.39
Land under pasture (%)	2.63	2.64	2.63	2.64	2.64	2.75	2.64	2.64
Land under Miscanthus (%)	1.40	0.04	1.55	0.81	0.38	1.16	0.83	0.76
Biomass Supply (MMT with 15% moisture)	3.54	0.11	3.75	2.25	1.02	2.87	2.10	1.94
Electricity generated with bio-energy (%)	4.6	0.1	4.8	2.9	1.3	3.7	2.7	2.5
Maximum distance for transportation of biomass (miles)	38.78	10.56	80.75	35.32	26.33	37.85	32.94	32.94
Marginal cost of carbon sequestration ($/metric ton)	126.19	130.60	123.87	139.21	129.53	123.87	51.65	32.69

[1] Bio-energy price: $2.985/MBTU; carbon sequestration target: 10 MMT; negative exponential carbon accumulation function

[2] land use changes are limited to +/- 15% of those in 2003 instead of to +/-10% of those in 2003 as in Tables 6 and 7.

	Exponential Sequestration Function	Linear Sequestration Function	Cofiring Capacity of Power Plant 8%	Inclusion of Carbon Emission Displacement
Carbon Mitigation in 15 years	10MMT			
Carbon Sequestration (%)	100%	100%	100%	53%
Carbon Displacement	-	-	-	47%
Land under conservation till (%)	58.52	57.91	57.67	54%
Land under Miscanthus (%)	1.02	1.02	1.40	0.43%
Biomass Supply (MMT with 15% moisture)	2.56	2.55	3.54	1.06
Electricity generated with bio-energy (%)	3.3	3.3	4.6	1.4%
Maximum distance for transportation of biomass (miles)	37.85	37.85	38.78	26,4
Marginal cost of carbon sequestration ($/metric ton)	127.39	142.89	126.19	52.7

Figure 1: Baseline Level of Soil Organic Carbon

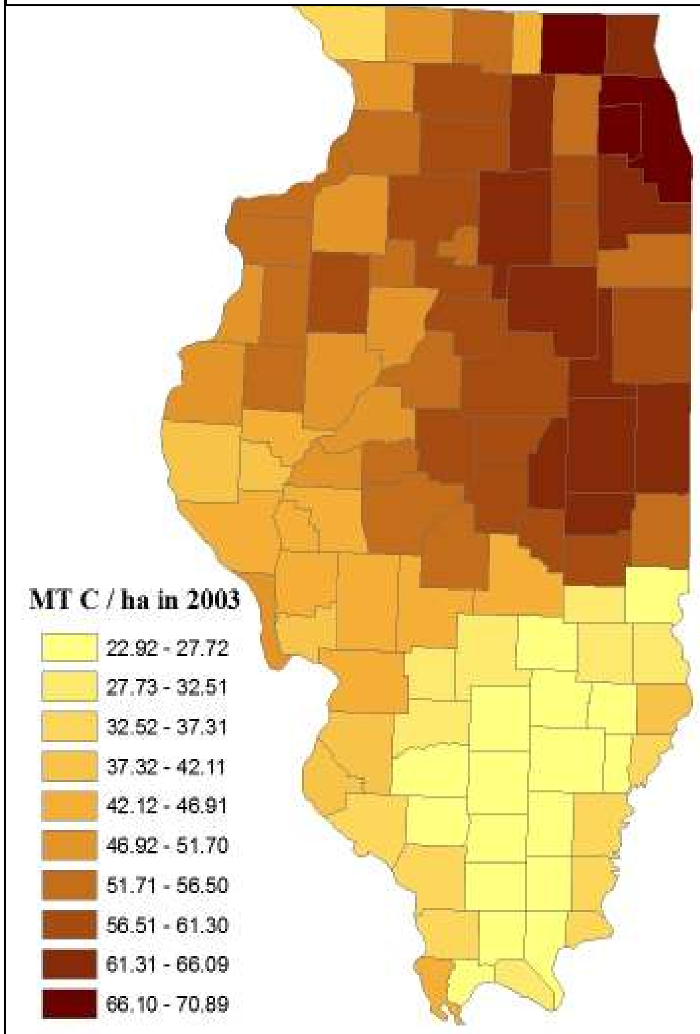


Figure 2. Accumulation Response Functions with Various Uses of Land in Christian County: Linear Versus Negative Exponential

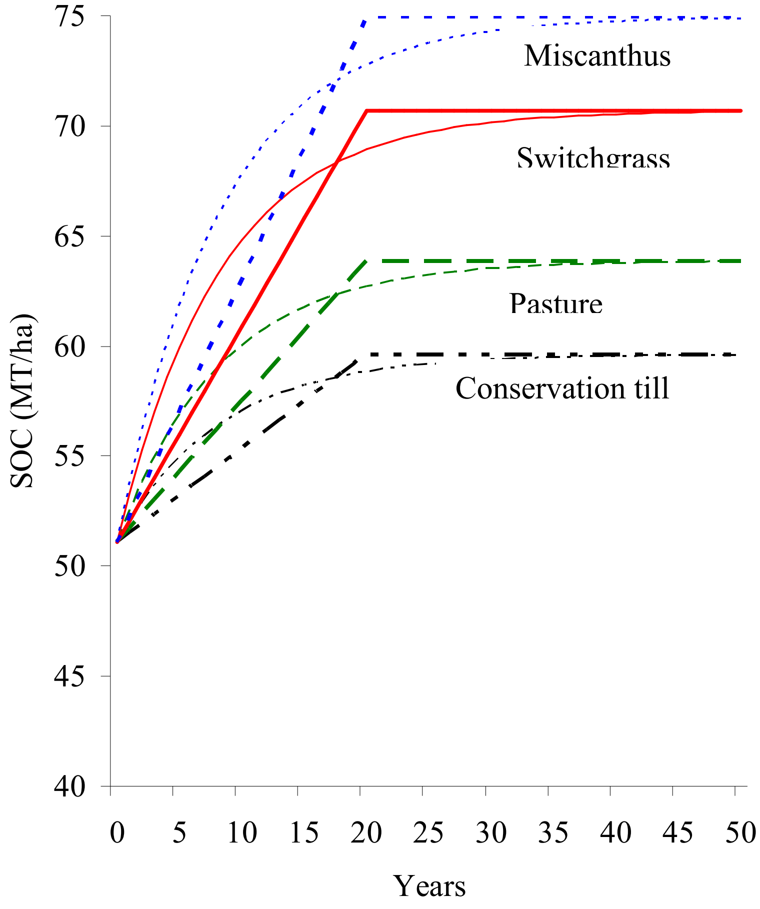


Figure 3: Miscanthus Acreage and Supply

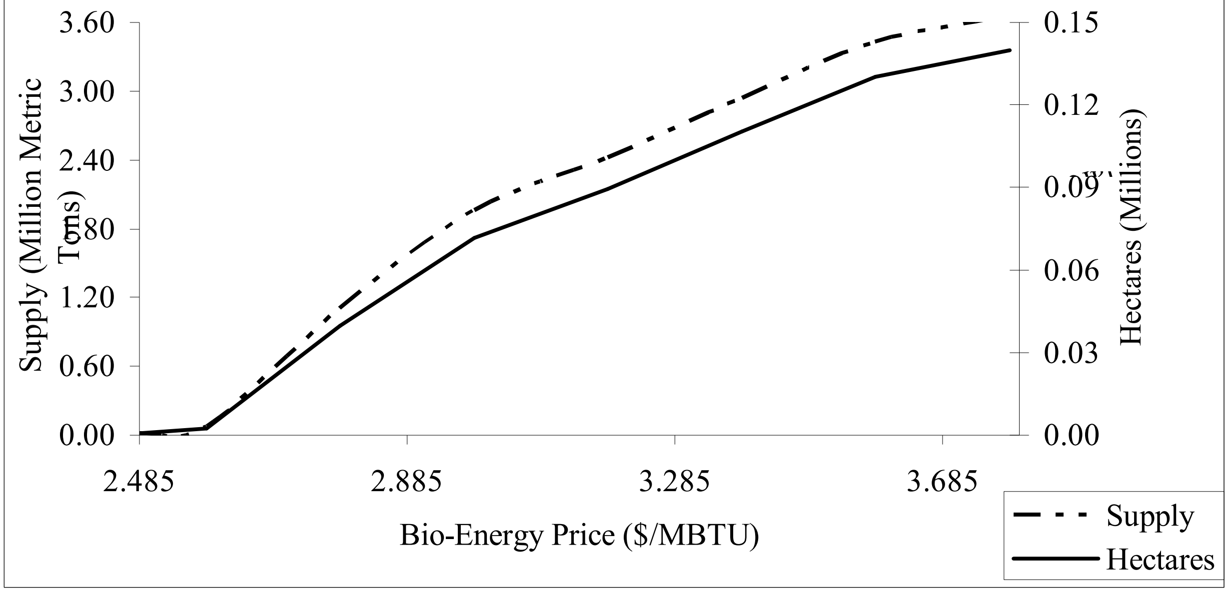


Figure 4: Marginal Cost of Sequestering Soil Carbon

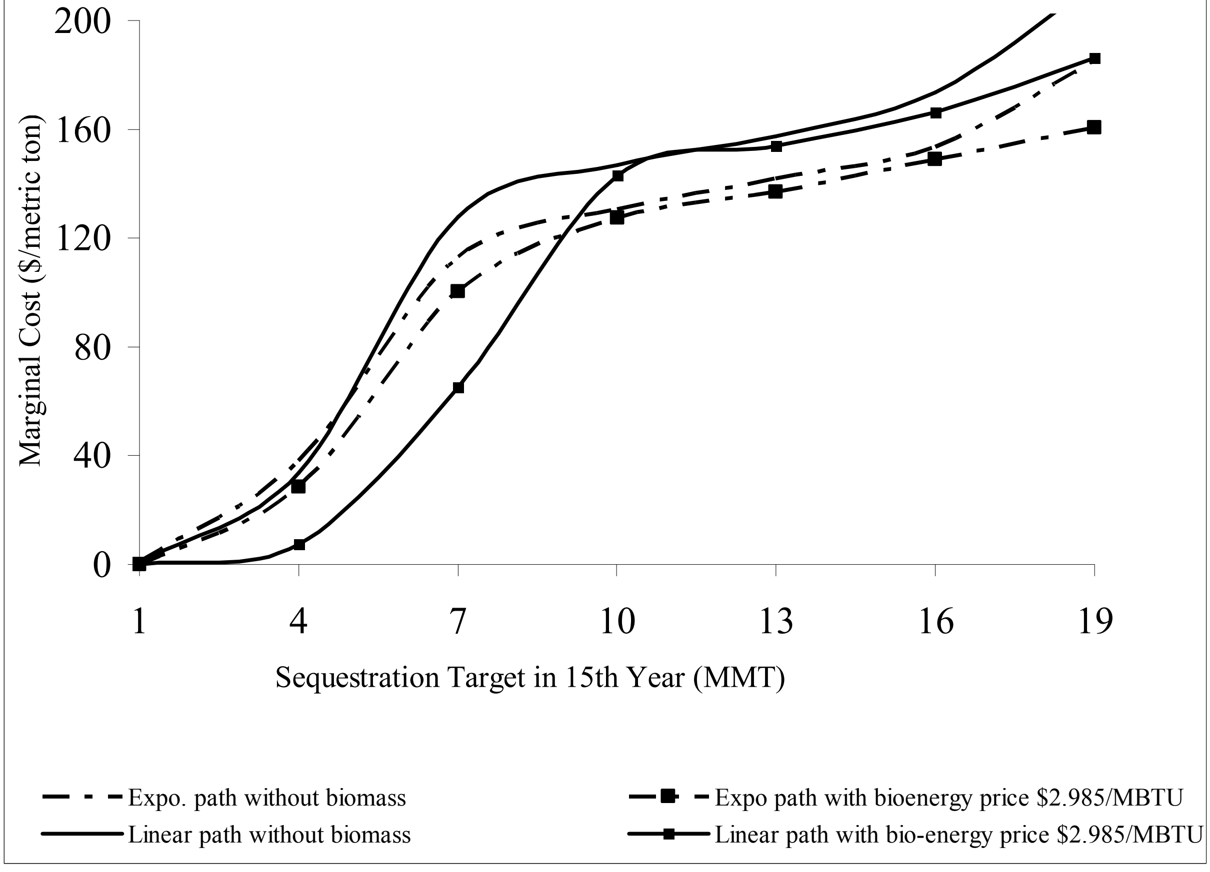


Fig. 5: Area under Miscanthus Production with Bio-Energy Price of $2.985/MBTU and No Carbon Constraint

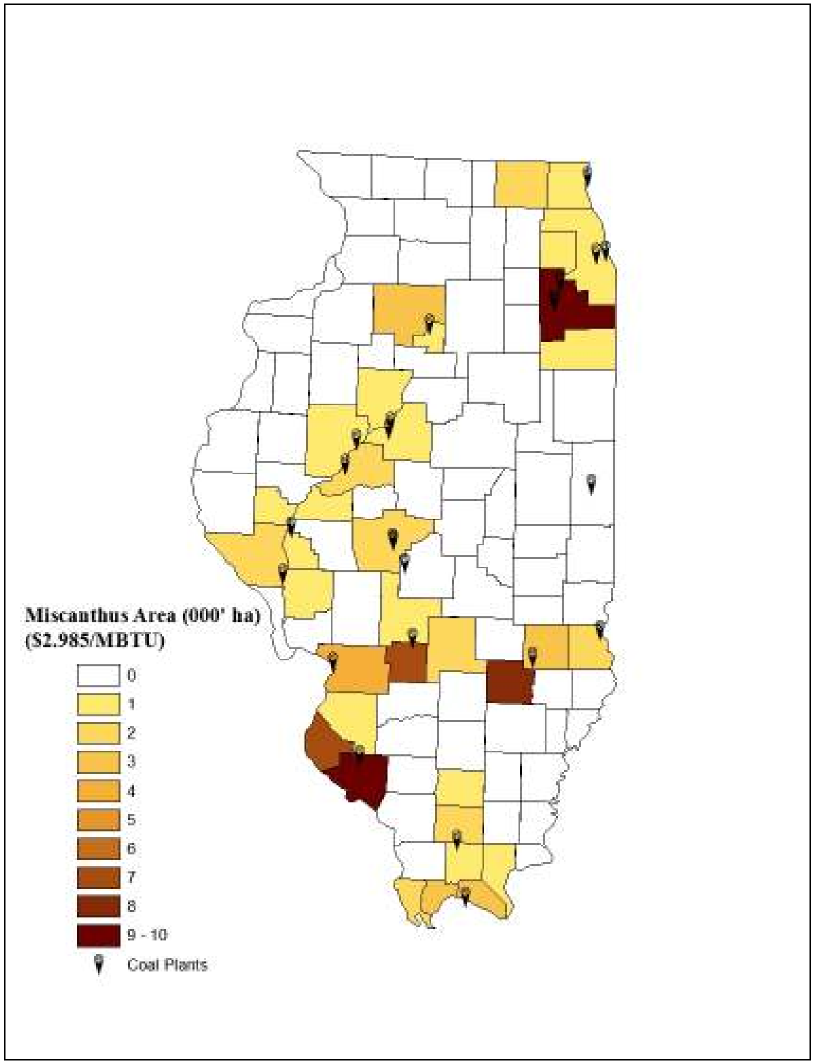


Fig. 6: Area under Miscanthus Production with Bio-Energy Price of $2.985/MBTU and 10 MMT Carbon

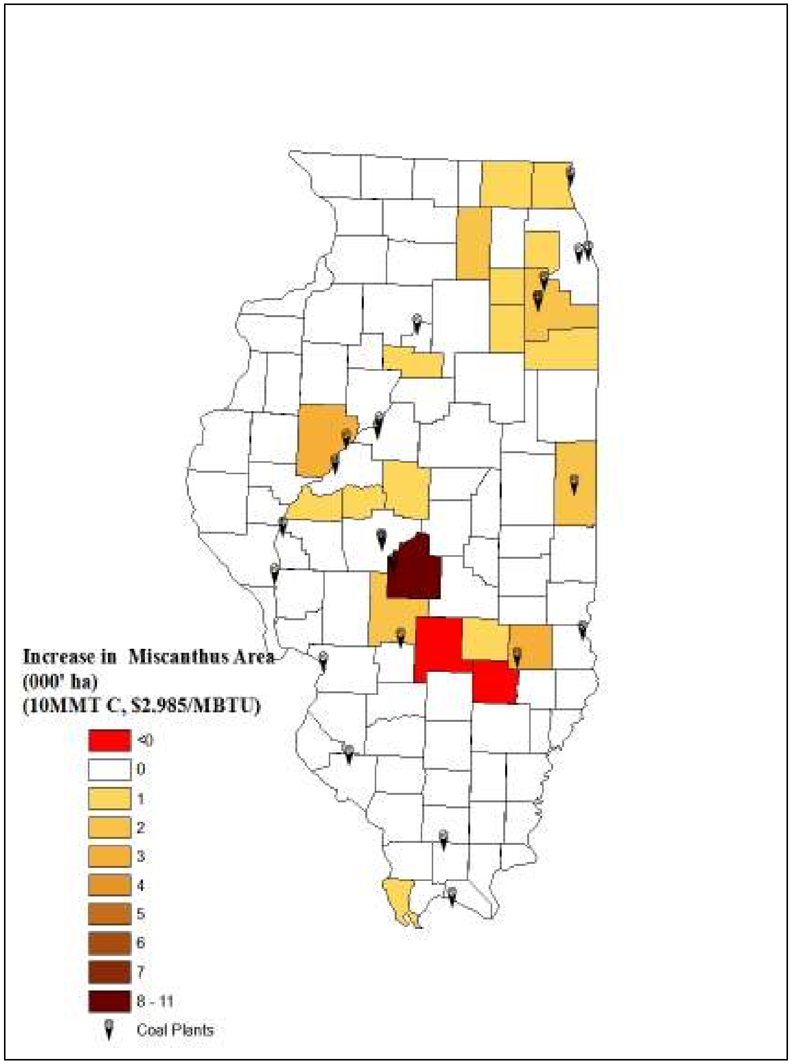


Fig. 7: Percentage Cropland under Conservation Tillage with no Carbon Constraint

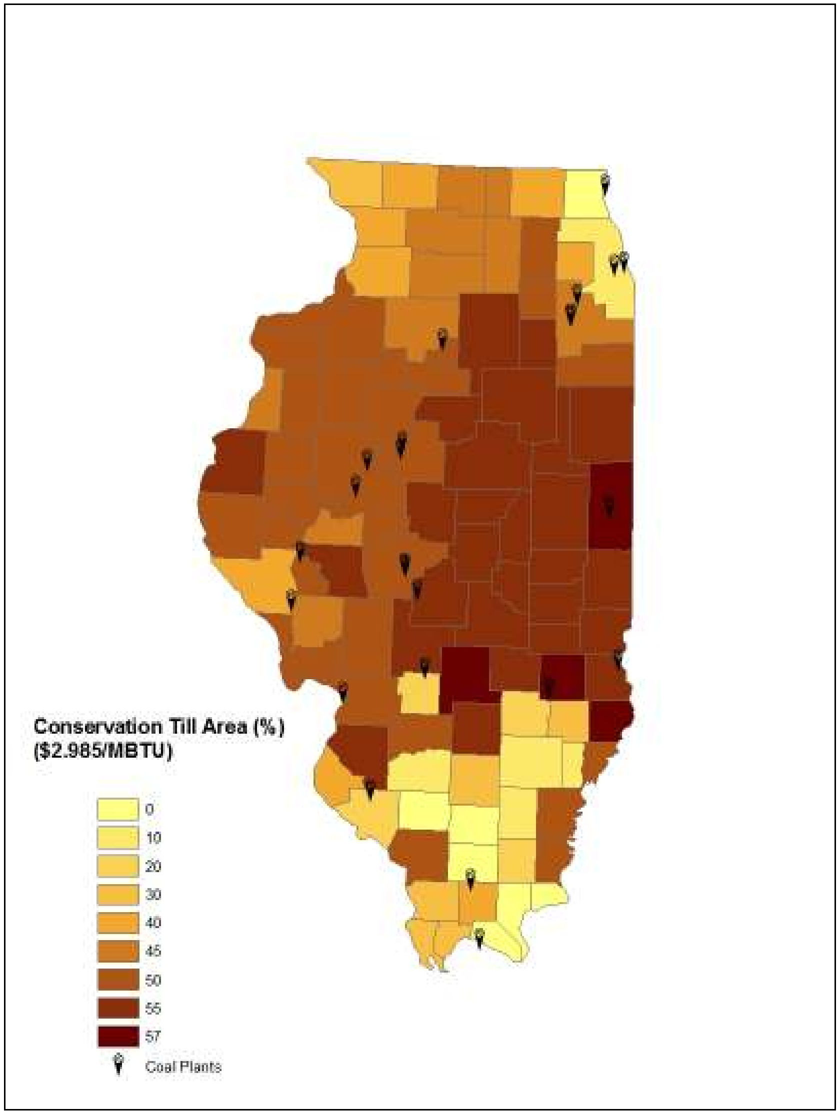


Fig. 8: Percentage Cropland under Conservation Tillage with 10 MMT Carbon Constraint

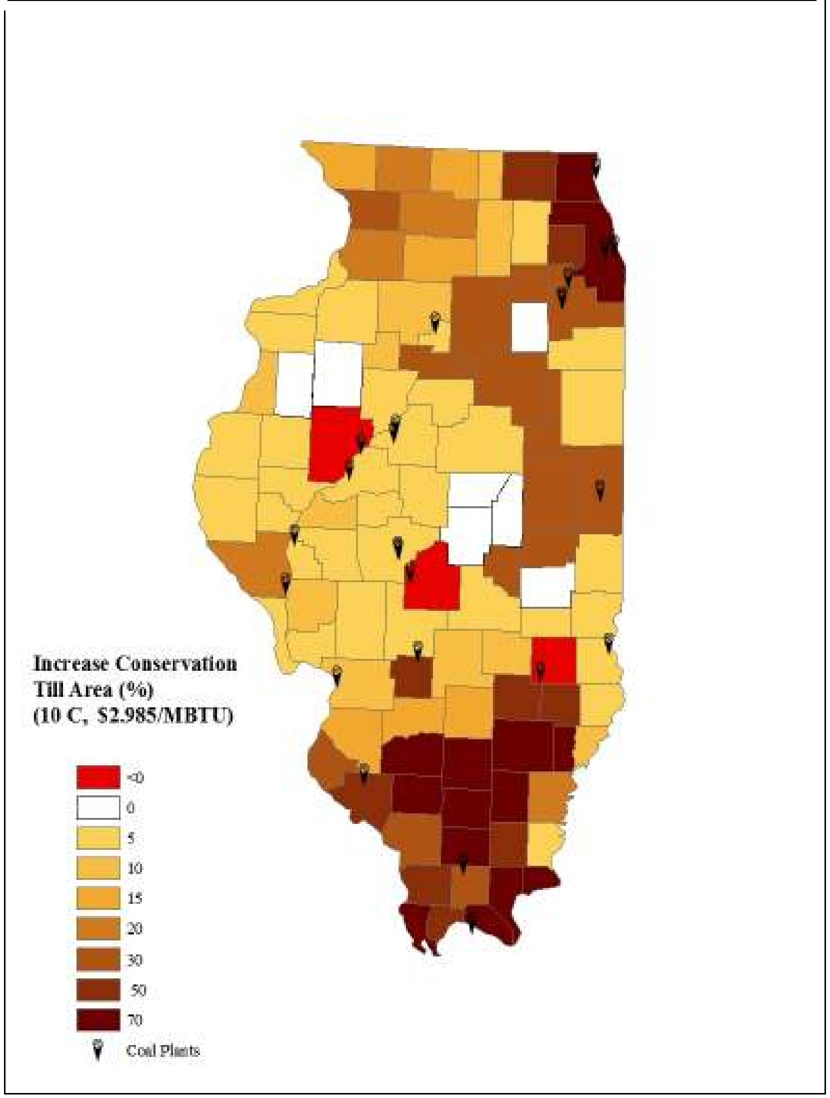


Figure 9: Effect of Bio-Energy Price on Marginal Cost of Carbon Sequestration

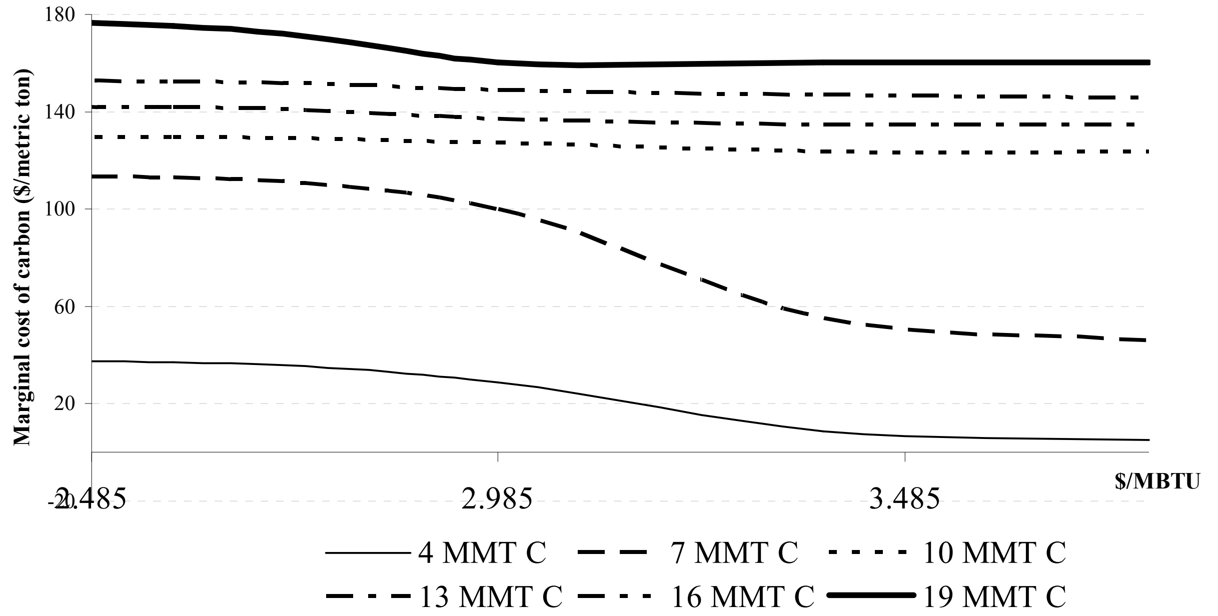


Figure 10: Area Under Conservation Tillage and Miscanthus

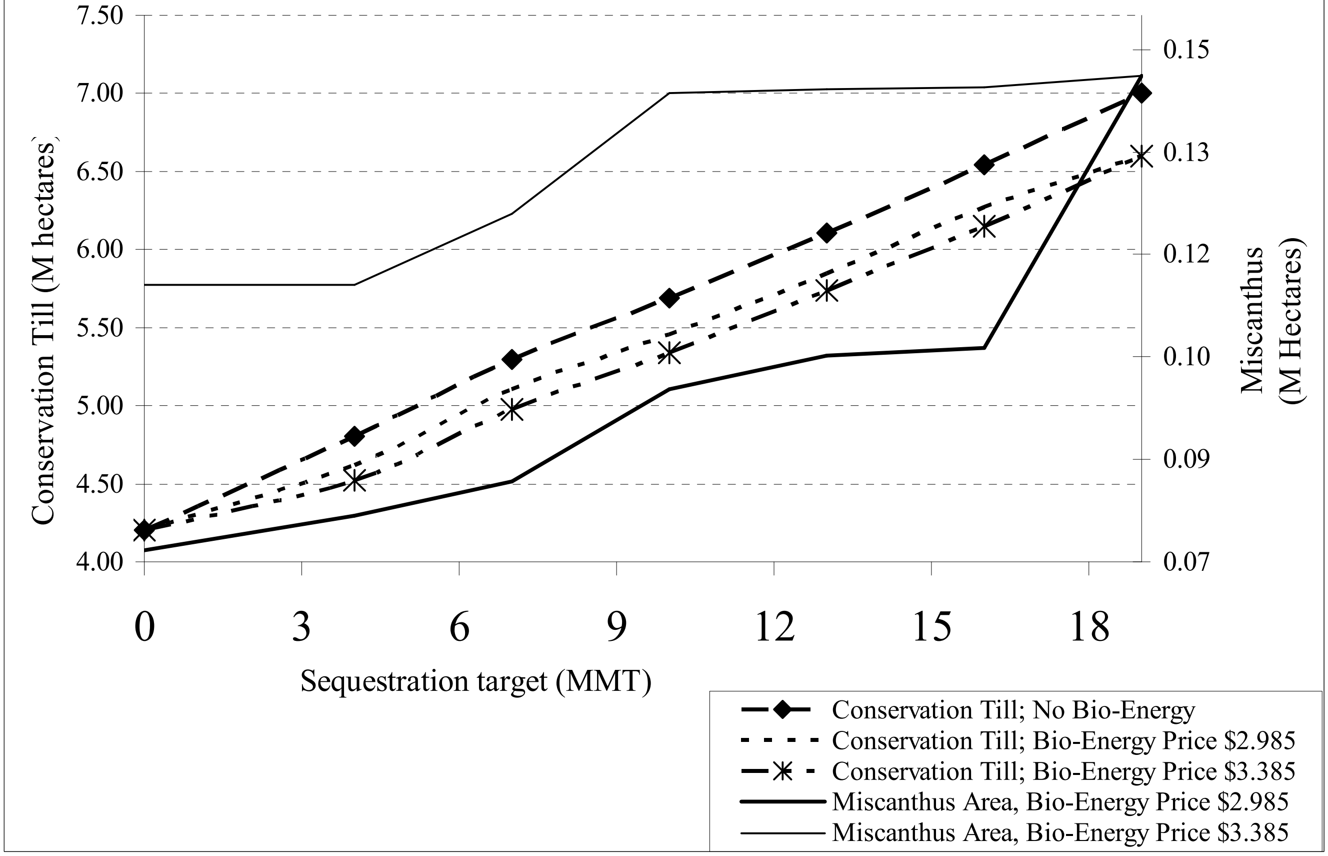


Figure11. Effect of Discounting Soil Carbon on Marginal Cost of Sequestration

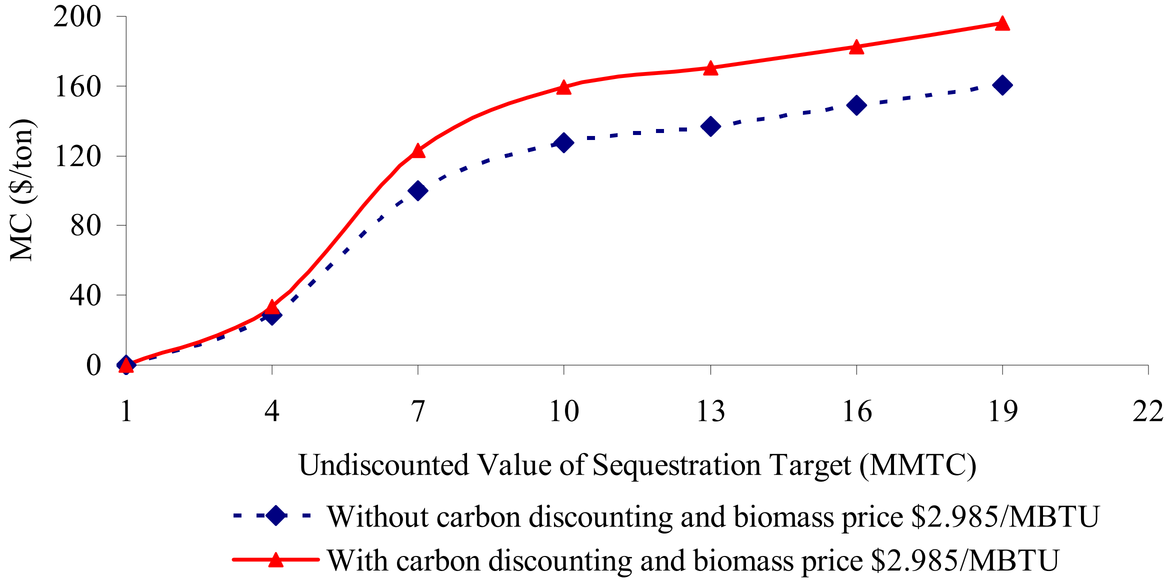
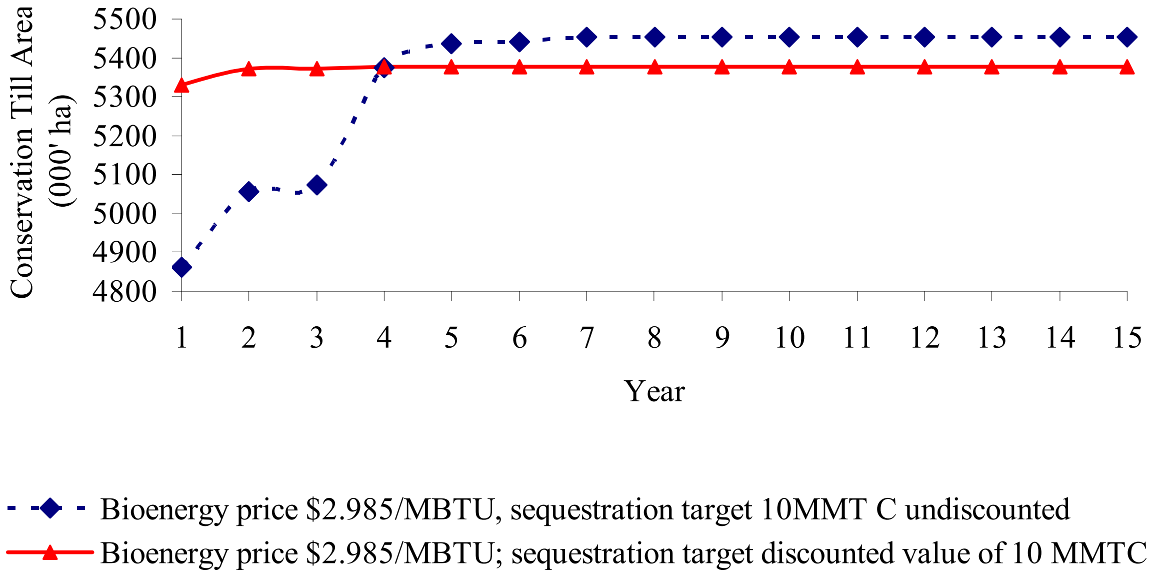


Figure 12. Time Path of Land Allocation Under Conservation Tillage With and Without Carbon Discounting



References:

Alexander, J. D., and R. G. Darmody. 1991. "Extent and Organic Matter Content of Soils in Illinois Soil Associations and Counties." University of Illinois, Urbana, IL.

Alig, R., D. Adams, B. McCarl, J.M. Callaway, and S. Winnett 1997. "Assessing Effects of Mitigation Strategies for Global Climate Change with an Intertemporal Model of the U.S. Forest and Agriculture Sectors." *Environmental and Resource Economics* 9:259-274.

Antle, J.M., S.M. Capalbo, S. Mooney, E.T. Elliot, and K.H. Paustin 2001. "Economic Analysis of Agricultural Soil Carbon Sequestration: An Integrated Assessment Approach." *Journal of Agricultural and Resource Economics* 26(2):344-367

Antle, J.M., S.M. Capalbo, S. Mooney, E.T. Elliot, and K.H. Paustin 2002. "A Comparative Examination of the Efficiency of Sequestering Carbon in U.S. Agricultural Soil." American *Journal of Alternative Agriculture* 17(3):109-115

Antle, J.M., and B.A. McCarl 2002 "The Economics of Carbon Sequestration in Agricultural Soils." In T. Tietenberg, and H. Folmer, ed. *The International Yearbook of Environmental and Resource Economics 2002/2003: A Survey of Current Issues*. Northampton, MA: Edward Elgar, pp. 278-310.

Antle, John, Susan Capalbo, Sian Mooney, Edward Elliot, and Keith Paustian. 2003. "Spatial Heterogeneity, Contract Design, and the Efficiency of Carbon Sequestration Policies for Agriculture." *Journal of Environmental Economics and Management* 46:231-250.

Baer, S.G.; D.J. Kitchen; J.M. Blair; C.W. Rice, 2002. "Change in Ecosystem Structure and Function along a Chronosequence of Restored Grasslands." *Ecological Applications*, 12(6): 1688-1701

Beuch, S., B. Boelcke, and L. Belau. 2000. "Effect of Organic Residues of Miscanthus x Giganteus on the Soil Organic Matter Level of Arable Soils." *Journal of Agronomy and Crop Science* 183:111-119.

Bird, L., and K. Cardinal.2004. "Trends in Utility Green Pricing Programs (2003)." Technical Report. National Renewable Energy Laboratory, Golden, Colarado, September 2004

Brooke, A., D. Kendrick, and A.Meeraus. 1988. *Gams: A User's Guide*. Redwood City, California: The Scientific Press.

Chavas, Jean-Paul, and Matthew T. Holt. 1990. "Acreage Decisions under Risk: The Case of Corn and Soybeans." *American Journal of Agricultural Economics* 72:529-538.

Chavas, Jean-Paul, R.D. Pope, and R.S. Kao. 1983. "An Analysis of the Role of Future Prices, Cash Prices and Government Programs in Acreage Response." *Western Journal of Agricultural Economics* 8:27-33.

Clifton-Brown, J.C., P.F. Stampfl, and M.B. Jones 2004. "Miscanthus Biomass Production for Energy in Europe and Its Potential Contribution to Decreasing Fossil Fuel Carbon Emissions." *Global Change Biology* 10(4):509 -518.

Dick, W.A., R.L. Belvins, W.W. Frye, S.E. Peters, D.R. Christenson, F.J. Pierce, M.L. Vitosh, 1998. "Impacts of Agricultural Management Practices on C Sequestration in Forest - Derived Soils of the Eastern Corn Belt." *Soil and Tillage Research*, 47 (3-4): 235-244.

Donigian, A.S.J., A.S. Oatwardhan, R.V. Chinnaswamy, and T.O. Barnwell. 1998 "Modeling Soil Carbon and Agricultural Practices in the Central U.S.: An Update of Preliminary Study Results." In R. Lal, J. M. Kimble, R. F. Follett, and B. A. Stewart, ed. *Soil Processes and the Carbon Cycle.* Boca Raton, Florida: CRC Press, pp. 499-518.

Duffy, M.D., and V.Y. Nanhou 2001. "Costs of Producing Switchgrass for Biomass in Iowa". Revised April Edition, PM 1866. Ames: Iowa State University, University Extension.

EIA 2004. "State Electricity Profiles 2004." Energy Information Administration. www.eia.doe.gov/cneaf/electricity/st_profiles/illinois.pdf

Eve, M.D., M. Sperow, K. Paustian, and R.F. Follett. 2002. "National-scale Estimate of Changes in Soil Carbon Stocks on Agricultural Lands." *Environmental Pollution*, 116:431-438.

FBFM 2002. Updating Acres and Yields under the Farm Security and Rural Investment Act of 2002.: Farm Business Management, Department of Agricultural and Consumer Economics, UIUC.

Flach, K.W., T.O. Barnwell, and P. Crosson 1997 "Impacts of Agriculture on Atmospheric Carbon Dioxide." In E. A. Paul, K. Pasutian, E. T. Elliot, and C. V. Cole, ed. *Soil Organic Matter in Temperature Agroecosystems*. Boca Raton, FL: CRC Press.

FSA/USDA 2003. Direct and Counter-Cyclical Payment Program: Farm Service Agency, U.S. Department of Agriculture.

Gardner, Bruce L. 1976. "Futures Prices in Supply Analysis." *American Journal of Agricultural Economics* 58:81-84.

Gebhart, D.L., H.B. Johnson, H.S. Mayeux, and H.W. Polley. 1994. "The Crp Increases Soil Organic Carbon." *Journal of Soil and Water Conservation* 49:488-492.

Gilley, J.E.; J.W. Doran; D.L. Karlen; T.C. Kaspar, 1997. "Runoff, Erosion, and Soil Quality Characteristics of a Former Conservation Reserve Program Site." *Journal of Soil and Water Conservation* 52(3): 189-193

Heaton, E.A., S.P. Long, T.B. Voigt, M.B. Jones, and J. Clifton-Brown 2004. "Miscanthus for Renewable Energy Generation: European Union Experience and Projections for Illinois." *Mitigation and Adaptation Strategies for Global Change* 9(4):433 - 451.

Heaton, E.A., T.B. Voigt, and S.P. Long 2006. "Miscanthus X Gigantus: The Results of Trials Alongside Switchgrass (Panicum virgatum) in Illinois." Plant Science Departmnent, University of Illinois at Urbana-Champaign.

Houghton, R.A., and J.L. Hackler 2000. "Changes in Terrestrial Carbon Storage in the United States. 1:The Roles of Agricultural and Forestry." *Global Ecology and Biogeography* 9(2):125-144.

INRA, 2002. "Mitigation of the Greenhouse Effect. Increasing Carbon Stocks in French Agricultural Soils." edited by D. Arrouays, J. Balesdent, J.C. Germon, P.A. Jayet, J.F. Soussana, and P. Stengel: French Institute for Agricultural Research (INRA).

Ismail, I., R.L. Blevins, and W.W. Frye 1994. "Long-Term No-Tillage Effects on Soil Properties and Continuous Corn Yields." *Soil Science Society of America Journal* 58:193-198.

Just, Richard E., and Gordon C. Rausser. 1981. "Commodity Price Forecasting with Large-Scale Econometric Models and the Futures Market." *American Journal of Agricultural Economics* 63:197-208.

Kahle, P., S. Beuch, B. Boelcke, P. Leinweber, and H.R. Schulten. 2001. "Cropping of Miscanthus in Central Europe: Biomass Production and Influence on Nutrients and Soil Organic Matter." *European Journal of Agronomy* 15:171-184.

Khanna, M., B. Dhungana, and J. Clifton-Brown 2006. Costs of Producing Switchgrass and Miscanthus for Electricity Generation in Illinois: Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign.

Krug, E.C., and S.E. Hollinger, 2003. "Identification of Factors That Aid Carbon Sequestration in Illinois Agricultural Systems." Review Report. Illinois State Water Survey (March), The Illinois Department of Natural Resources, Champaign.

Lal, R., J.M. Kimble, R.F. Follett, and C.V. Cole. 1998. *The Potential of U.S. Cropland to*

Sequester Carbon and Mitigate the Greenhouse Effect. Chelsea, MI: Ann Arbor Sci. Publ.

Lewandowski, I., J.M.O. Scurlock, E. Lindvall, and M. Christou 2003. "The Development and Current Status of Potential Rhizomztous Grasses as Energy Crops in the U.S and Europe." *Biomass and Bioenergy* 25(4):335-361.

Lewandrowski, J., M. Peters, C. Jones, R. House, M. Sperow, M. Eve, and K. Paustian.2004. "Economics of Sequestering Carbon in the U.S. Agricultural Sector." Economic Research Service TB-1909, U.S. Department of Agriculture, Washington, DC.

Liu, Shuguang, Jinxun Liu, and Tom R. Loveland. 2004. "Spatial-Temporal Carbon Sequestration under Land Use and Land Cover Change." in *Proceeding of 12th Int. Conf. on Geoinformatics - Geospatial Information Research,* University of Gävle, Sweden

Manley, J., G.C. van Kooten, K. Moeltner, and D.W. Johnson 2005. "Creating Carbon Offsets in Agriculture through No-Till Cultivation: A Meta Analysis of Costs and Carbon Benefits." *Climate Change* 68(1):41-65.

Mann, L.K. 1985. "A Regional Comparison of Carbon in Cultivated and Uncultivated Alfisols and Mollisols in the Central United States." *Geoderma* 36:241-253.

Matthews, R.B., and P. Grogan. 2001. "Potential C Sequestration Rates under Short-Rotation Coppiced Willow and Miscanthus Biomass Crops: A Modeling Study." *Aspects of Applied Biology* 65:303-312.

McCarl, B., and U. Schneider 2001. "The Cost of Greenhouse Gas Mitigation in U.S. Agriculture and Forestry." *Science* 294(5551):2481–2482.

McCarl, B.A., D.M. Adams, R.J. Alig, and J.T. Chmelik 2000. "Competitiveness of Biomass Fueled Electrical Power Plants." *Annals of Operations Research* 94(1):37–55.

McLaughlin, S.B., R. Samson, D.I. Bransby, and A. Weislogel 1996. Evaluating Physical, Chemical, and Energetic Properties of Perennial Grasses as Biofuels. Nashville, TN: Proceedings of the Seventh National Bioenergy Conference, pp. 1–8.

McLauchlan, K.K.; S.E. Hobbie; W.M. Post, 2006. "Conversion from Agriculture to Grassland Builds Soil Organic Matter on Decadal Timescales." *Ecological Applications*, 16(1): 143-153

McLaughlin, S.B., and L.A. Kszos 2005. "Development of Switchgrass (*Panicum virgatum*) as a Bioenergy Feedstock in the United States." *Biomass and BioEnergy* 28:515-535.

McLaughlin, S.B., D. Ugarte, C.T. Garten, L.R. Lynd, M.A. Sanderson, V.R. Tolbert, and D.D. Wolf 2002. "High-Value Renewable Energy from Prairie Grasses." *Environmental Science and Technology* 36:2122-2129.

Parks, P.J., and I.W. Hardie 1995. "Least-Cost Forest Carbon Reserves: Cost Effective Subsidies to Convert Marginal Agricultural Land to Forests." *Land Economics* 71(1):122-136.

Paustian, K., C.V. Cole, D. Sauerbeck, and N. Sampson 1998. "CO_2 Mitigation by Agriculture: An Overview." *Climate Change* 40:135-162.

Paustian, K., H.P. Collins, and E.A. Paul 1997 " Management Controls on Soil Carbon." In E. A. Paul, K. Pasutian, E. T. Elliot, and C. V. Cole, ed. *Soil Organic Matter in Temperate Agroecosystems.* Boca Raton, FL.: CRC Press.

Pautsch, G.R., L.A. Kurkalova, B. Babcock, and C.L. Kling 2001. "The Efficiency of Sequestering Carbon in Agricultural Soil." *Contemporary Economic Policy* 19(2):123-134.

Plantinga, A.J., T. Mauldin, and D.J. Miller 1999. "An Econometric Analysis of the Costs of Sequestering Carbon in Forests." *American Journal of Agricultural Economics* 81(4):812 824.

Penman, J., M. Gytarsky, T. Hiraishi, T. Krug, D. Kruger, R. Pipatti, L. Buendia, K. Miwa, T. Ngara, K. Tanabe, and F. Wagner. 2003. "Good Practice Guidance for Land Use, Land Use Change and Forestry." Published by the Institute for Global Environmental Strategies (ICGES) for the InterGovernmental Panel on Climate Change (IPCC).

Prueger, J.H., J.L. Hatfield, T.B. Parkin, W. P.Kustas, and T.C. Kaspar 2004. "Carbon Dioxide Dynamics During a Growing Season in Midwestern Cropping Systems." *Environmental Management* 33(1):330-343.

Puget, P.; R. Lal; C Izaurralde; M. Post; L. Owens, 2005. "Stocks and Distribution of Total and Corn-Derived Soil Organic Carbon in Aggregate and Primary Particle Fractions for Different Land Use and Soil Management Practices." *Soil Science* 170(4): 256-279

Richards, K.R. 1997. "The Time Value of Carbon in Bottom-up Studies." *Critical Reviews in Environmental Science and Technology* 27:S279-S292.

Robertson, G.P.; E.A. Paul; R.R. Harwood, 2000. "Greenhouse Gases in Intensive Agriculture: Contribution of Individual Gases to the Radiative Forcing of the Atmosphere." *Science* 289(5486): 1922-1925.

Schnitkey, G. 2003. "Estimated Cost of Crop Production in Illinois." Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign.

Schnitkey, G., D. Lattz, and J. Siemens 2003. "Machinery Cost Estimates: Forage Field Operation." Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign. www.farmdoc.uiuc.edu/manage/pdfs/Mach_forages_2003.PDF.

Sinnott, R.W. 1984. "Virtues of the Haversine." *Sky and Telescope* 68(2):159.

Six, J., R.T. Conant, E.A. Paul, and K. Paustian 2002. "Stabilization Mechanisms of Soil Organic Matter: Implications for C-Saturation of Soils." *Plant and Soil* 241(2):155-176.

Stavins, R.N. 1999. "The Costs of Carbon Sequestration: A Revealed Preference Approach." *The American Economic Review* 89(4):994-1009.

Tan, Z.X., S.G. Liu; C.A. Johnston; J.X. Liu; L.L. Tieszen, 2006. "Analysis of Ecosystem Controls on Soil Carbon Stock-Sink Relationships in the Northwest Great Plains." *Global Biochemical Cycles*, 20(4), Art. No. GB4012

Ugarte, D.G., M. Walsh, H. Shapouri, and S. Slinsky.2003. "The Economic Impacts of Bioenergy Crop Production on U.S. Agriculture." U.S. Department of Agriculture, Washington D.C (March).

Unger, P.W. 2001 "Total Carbon, Aggregation, Bulk Density, and Penetration Resistance of Cropland and Grassland Soils." In R. Lal(ed.)., Soil Science Society of America Special Publication, 57. *Soil Carbon Sequestration and the Greenhouse Effect*. Wisconsin: Soil Science Society of America. Madison, pp. 72-92.

Uri, Noel D, 1998. "Conservation Tillage and the Use of Energy and Other Inputs in US Agriculture." *Energy Economics* 20:389-410.

USDA, 2003. "Data and Statistics: National Agricultural Statistics Service." U.S. Department of Agriculture. U.S. Department of States, 2004. "U.S. Climate Policy." Washington, D.C.

VandenBygaart, A.J. and D.A. Angers, 2006. “Towards Accurate Measurements of Soil Organic Carbon Stock Change in Agroecosystems.” *Canadian Journal of Soil Science*, 86: 465-471.

Wander, M.M.; G. Bidart-Bouzat; and S. Aref, 1998. "Tillage Impacts on Depth Distribution of Total and Particulate Organic Matter in Three Illinois Soil." *Soil Science Society of America Journal*, 62:1740-1711.

West, T.O., G. Marland, A.W. King, W.M. Post, A.K. Jain, and K. Andrasko 2004. "Carbon Management Response Curves: Estimates of Temporal Soil Carbon Dynamics." *Environmental Management* 33(4):507-518.

Wu, J., R.M. Adams, C.L. Kling, and K. Tanaka 2004. "From Microlevel Decisions to Landscape Changes: An Assessment of Agricultural Conservation Policies." *American Journal of Agricultural Economics* 86(1):26-41.

Wu, JunJie, and Kathleen Segerson. 1995. "The Impact of Policies and Land Characteristics on Potential Groundwater Pollution in Wisconsin." *American Journal of Agricultural Economics* 77:1033-147.

Young, C.E., and P.C. Westcott 2000. "How Decoupled Is U.S. Agricultural Support for Major Crops?" *American Journal of Agricultural Economics* 82(3):762-767.

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[1] For example, the Renewable Portfolio Standard in Illinois sets a goal of producing 10% of Illinois' electricity using renewable energy sources by 2015 (http://www.commerce.state.il.us/dceo/News/pr08222006.htm).

[2] Perennial cropping eliminates soil carbon losses caused by annual physical disturbance associated with annual crops (planting, cultivation, fertilizer addition) and soil erosion by keeping soils covered with vegetation throughout the year and by developing prolific root systems that stabilize soil structure (Paustian et al. 1998; McLaughlin et al. 2002; Lewandrowski et al. 2004).

[3] Under the latter approach payments for additional carbon are based on that portion of the market value of permanent sequestration that occurs during the contract period.

[4] An alternative approach commonly used by studies is to assume a linear carbon accumulation function, where the sequestration potential is exhausted in 20 years (Pautsch et al., 2001; Penman et al. 2003; Lewandrowski et al. 2004).

[5] In each period the maximum amount of biomass the power plant l can utilize is $q_l = \mu . z_l . f . \phi$ where μ is the fraction of cofiring capacity z_l is the capacity of the power plant, f is the amount of coal required to produce a unit of electricity and ϕ is the relative heat content of a unit of biomass compared to that of coal.

[6] See http://www.agecon.purdue.edu/pdf/Crop_Rotation_Lit_Review.pdf

[7] Based on personal communication with Gary Schnitkey, 2004. This is also supported by Uri (1998) who reports 16-21% higher average chemical costs for corn with conservation till compared to conventional till based on the 1987 Farm Costs and Return Survey of corn farms conducted by the NASS/USDA. His econometric analysis also shows that there exists a statistically significant positive relationship between chemical costs and adoption of conservation till for corn.

[8] This is based on a price of \$16.26/kg of the Cave-in-Rock variety from the Albert Lea Seed House, MN in 2005 (personal communication with Bob Koestler on Feb 20, 2006).

[9] Since our purpose was to obtain a proxy for transportation costs from a hypothetical field located in the county center to the power plants rather than exact distance, we did not use actual road distance. The *great circle* distance between two locations with (ϕ_1, λ_1) and (ϕ_2, λ_2) as their latitude and longitudes is $r\Delta\sigma$, where r is the great-circle radius of the earth's sphere which is 3963 statute miles and $\Delta\sigma$ is as defined below with $\Delta\lambda$ representing the difference in the longitudes of the two locations:

$$\Delta\sigma = 2\arctan\left\{\sqrt{\sin\left\{\frac{\phi_2-\phi_1}{2}\right\}^2 + \cos\phi_1\cos\phi_2\sin\left\{\frac{\Delta\lambda}{2}\right\}^2 / \cos\left\{\frac{\phi_2-\phi_1}{2}\right\}^2 - \cos\phi_1\cos\phi_2\sin\left\{\frac{\Delta\lambda}{2}\right\}^2}\right\}$$

[10] This requires 2 qt of Roundup^{TM}/acre at \$\$9.39/qt. and a machine to spray it at \$4.30/acre (in 2000 prices).

[11] These loan rates are obtained from FSA/USDA for 2003 (http://www.fsa.usda.gov/dafp/psd/LoanRate.htm)

[12] Studies differ in their approach to estimation of the expected price of a crop. Just and Rausser (1981) and Gardner (1976) argue in favor of futures price based on rational expectations assumption. Chavas and Holt (1990) assume adaptive expectations and use lagged market prices to obtain expected future prices. Chavas, Pope and Kao (1983) investigated the role of future prices, lagged market prices and support prices in their econometric analysis of acreage supply response of corn and soybeans in the US. They found that government's corn support program plays a major role in corn and soybean production decision and that future prices are not good proxies for expected prices in the presence of government program. Wu and Segerson (1995) use the higher of the current target price and a linear function of previous year's market price as a measure of expected price for program crops.

[13] http://nas.usda.gov/statistics_by_state/Illinois?Publications/Farm_Reports/2005/ifr0504.pdf

[14] www.eia.doe.gov/cneaf/electricity/st_profiles/illinois.pdf

[15] This figure might have been higher but this loss is believed to have been partly reversed due to increased productivity of crops and improved technologies in recent decades (Donigian et al. 1998; Houghton and Hackler 2000; Krug and Hollinger March 2003).

[16] http://ctic.purdue.edu/

[17] For example, north eastern counties including Cook, Dupage, Kendal, Lake, McHenry and Will have used 7.30, 2.73, 0.0, 7.15, 1.3 and 7.81 percent of their cropland for Miscanthus respectively in the absence of any carbon constraint. Carbon constraint of 10MMT induces conversion of 7.30, 10, 0.71, 10, 1.5 and 9.22 percent of cropland for Miscanthus in these counties respectively. Note that Cook, Dupage, Kendal, Lake, McHenry and Will counties have 18.5, 11.0, 155.0, 34.27, 210.4, and 254.37 thousands acres of cropland in 2002 (NASS, 2003) even though these counties are in Chicago city area. .