Relative Efficiency of Sequestering Carbon in Agricultural Soils Through Second Best Instruments

Gregory R. Pautsch
Associate Scientist
Center for Agricultural and Rural Development
Iowa State University
Ames, IA 50011
Phone: (515)-294-6234
Fax: (515)-294-6336
Email: grpautsc@iastate.edu

Bruce A. Babcock
Director
Center for Agricultural and Rural Development
Professor
Department of Economics
Iowa State University
Ames, IA 50011
Phone: (515)-294-5764
Fax: (515)-294-6336
Email: babcock@iastate.edu

JEL classication code:
Q38 Nonrenewable Resources and Conservation – Government Policy.

This Journal Paper No. J-18435 of the Iowa Agriculture and Home Economics Experiment Station, Ames, Iowa; Project No. 3363, supported by Hatch Act and State of Iowa funds.

1. Introduction

The Kyoto Protocol to the United Nations Framework Convention on Climatic Change, [UNFCCC, 1998], proposes to limit future aggregate anthropogenic carbon dioxide equivalent greenhouse gas emissions (Article 3.1). The Kyoto Protocol also establishes the concept of credits for carbon sinks. These credits can be used to meet a country's emission limitation and reduction commitment. Currently, carbon sinks are limited to recent efforts in afforestation, reforestation, and deforestation and do not include agricultural soils (Article 3.3). However, Article 3.4 leaves the future inclusion of agricultural soils a distinct possibility by stating "…Parties to this Protocol shall…decide upon modalities, rules, and guidelines as to how, and which, additional human-induced activities related to greenhouse gas emissions by sources and removals by sinks in the agricultural soils and the land use change and forestry categories shall be added to or subtracted from the assigned amounts…"

Tillage practices are important human-induced activities that deal with carbon sequestration and greenhouse gas emissions from agricultural soils [Lal et al, 1998]. Conservation tillage reduces soil and water erosion when compared to conventional plow-based tillage systems. Conservation tillage uses crop residue to serve as mulch to protect and increase the soil organic carbon (SOC) levels. Conventional tillage systems disturb the soil and leave it unprotected from wind and rainfall, resulting in a decrease in SOC levels. Increasing the adoption of conservation tillage practices will increase carbon sequestration rates in agricultural soils and decrease the greenhouse gas emissions from the agricultural sector.

The purpose of this research is to discuss the relative efficiency of various government-based and market-based instruments available to policymakers that reduce the amount of carbon emissions from agricultural soils through the increased adoption of conservation tillage. First, various government-based subsidy schemes that encourage the adoption of conservation tillage are examined. Next, various market-based policy instruments of granting producers a carbon credit [Sandor and Skees, 1999] are examined. The total expected cost of reducing agricultural carbon emissions to a certain level is estimated for both the government-based and market-based policies. The relative efficiency of different programs is then determined.

2. Modeling the Supply of Environmental Goods

Estimating the likely changes in environmental quality from policies that affect agricultural decisions involves modeling farmer responses to the adopted policy and the subsequent change in environmental quality. The mapping of policy changes to changes in environmental quality is clearly an ex ante exercise. Policy makers do not know with certainty how farmers will react to the policy nor do they know precisely how environmental quality will change. The approach taken here recognizes the ex ante nature of this mapping and estimates the expected supply of environmental quality given a policy induced price change.

Environmental quality supply depends on the farmer’s choice of production practice and the environmental impact of that practice. Expected supply is then the weighted average of the environmental quality supply from each practice, where the weights are the probability of adopting the associated production practices. Hence, the expected change in environmental quality from a newly instituted policy is dependent upon the increased probability that the more environmental-friendly practice is adopted and the expected change in environmental quality given that the more environmental-friendly practice is adopted. Since both adoption probabilities and the change in environmental quality vary across farmers and production sites, the site-specific expected change in environmental quality must be aggregated across all sites to obtain the aggregate change in expected supply.

2.1 Farmers Adoption Decisions

Producers will adopt either a conventional or conservation tillage system when growing their crops. Let $E\pi^{cv}$ and $E\pi^{cs}$ denote the expected returns from conventional and conservation tillage practices. Producers are assumed to be risk neutral and adopt the tillage system that maximizes expected returns. A conservation tillage system is adopted when the expected returns from conservation tillage exceed the expected returns from conventional tillage, i.e., $E\pi^{cs} > E\pi^{cv}$. The expected returns from conventional and conservation tillage, however, are not observable. The choice between conventional and conservation tillage is observable as well as production and geographical characteristics such as soil, weather, land, and cropping patterns.

The expected returns from each tillage system is assumed to be linearly related to the vector of observable production and geographical characteristics (x),

$$E\pi^{t} = \beta^{t} x + \varepsilon^{t} \qquad t = \{cv, cs\} \tag{1}$$

Let $Y = 1$ denote the adoption of conservation tillage and $Y = 0$ denote the use of conventional tillage. The probability of a producer adopting conservation tillage with characteristics x is,

$$\begin{aligned}\Pr[Y=1\mid x] &= \Pr\left[E\pi^{cs} > E\pi^{cv}\mid x\right] = \Pr\left[\left(\beta^{cs}-\beta^{cv}\right)x+\varepsilon^{cs}-\varepsilon^{cv}>0\mid x\right]\\ &= \Pr[\beta x+\varepsilon>0\mid x] = \Pr[\varepsilon>-\beta x\mid x]\end{aligned} \tag{2}$$

The error term ε is assumed to be logistically distributed. So then,

$$\Pr[Y=1\mid x] = G(\beta x) = \frac{e^{\beta x}}{1+e^{\beta x}} \tag{3}$$

Suppose a “green” payment, *k*, is offered to further induce adoption of conservation tillage practices. The adoption of conservation tillage will occur if the expected returns from conservation tillage plus the green payment exceed the expected returns from conventional tillage, i.e., $E\pi^{cs}+k > E\pi^{cv}$. With green payments, the probability of a producer adopting conservation tillage practices with characteristics x becomes,

$$\Pr[Y=1\mid x] = \Pr\left[E\pi^{cs}+k > E\pi^{cv}\mid x = G(\beta x+k) = \frac{e^{\beta x+k}}{1+e^{\beta x+k}}\right] \tag{4}$$

2.2 Environmental Supply Curves

The choice of a tillage system affects the environment in many different ways, such as the degree of soil erosion, the amount of soil carbon released into the atmosphere, and the runoff and leaching of pesticides as well as fertilizer nutrients. The magnitude of carbon emissions from different tillage practices depends upon various production and geographical characteristics such as soil, weather, land, and cropping history. Suppose there are *I* different production sites indexed by the subscript *i*, $i=1,\ldots,I$. Denote the carbon emissions from the i^{th} production site when using conventional and conservation tillage as $Y0(x_i)$ and $Y1(x_i)$.

Only carbon supply curves will be derived, but other environmental supply curves can be developed in a similar fashion. The expected amount of carbon emitted into the atmosphere at the i^{th} production site is equal to the amount of carbon released into the atmosphere when using conservation tillage multiplied by the probability of using conservation tillage plus the amount of carbon released into the atmosphere when using conventional tillage multiplied by the probability of using conventional tillage. With green payments, the expected amount of carbon emitted into the atmosphere on a per acre basis at the i^{th} production site is denoted as, $LOSS_i(k \mid x_i)$, and equal to,

$$LOSS_i(k \mid x_i) = Y0(x_i) + G(\mathrm{b}x_i + k)(Y1(x_i) - Y0(x_i)) \qquad (5)$$

The total expected amount of carbon sequestered from the i^{th} production site, $Q_i(k \mid x_i)$, is defined as the difference between the amount of carbon released into the atmosphere if conventional tillage is used with certainty minus the expected amount of carbon emitted into the atmosphere under the green payment,

$$Q_i(k \mid x_i) = [Y0(x_i) - LOSS_i(0 \mid x_i)]NA_i + [LOSS_i(0 \mid x_i) - LOSS_i(k \mid x_i)]NA_i \qquad (6)$$

The intercept of the expected carbon supply curve is the level of carbon sequestered without any green payment, while the slope is the expected increase in sequestered carbon (or reduction in carbon emissions) as a result of increasing the green payment.

2.3 Policy Analysis

Various government-based subsidy programs that encourage the adoption of conservation tillage could placed be under the auspices of the Environmental Quality Incentives Program (EQIP). EQIP offers financial, educational, and technical assistance where significant natural resource problems, such as soil erosion, exist. A by-product of reducing soil erosion is increased carbon sequestration in agricultural soils resulting from lower levels of carbon emissions. Under an EQIP subsidy program, a green payment in the form of a per acre subsidy is offered to producers in order to encourage the adoption of conservation tillage. Once a green payment is presented, producers can either accept or refuse the offer. Producers adopting conservation tillage practices receive their per acre subsidy and producers using conventional tillage practices receive nothing.

An EQIP subsidy scheme could take many different forms. A single EQIP subsidy program is when all producers are offered the same per acre subsidy. A minimum cost EQIP subsidy program is defined as the subsidy scheme that minimizes the expected cost of sequestering an expected level of carbon. Other possible EQIP programs could base the subsidy payment according the producer’s location and/or crop grown. This paper examines the relative efficiency of a single subsidy EQIP program by comparing it the minimum expected cost EQIP subsidy program.

Market-based solutions are also investigated in the form of a carbon credit program. In a carbon credit program, producers receive a carbon credit from the government that is redeemable in an organized carbon market outside of the agricultural sector. Given the market price of carbon, producers can either sell their carbon credit and use conservation tillage practices or keep their carbon credit and use conventional tillage practices. Carbon credit programs are differentiated by the amount of carbon credit given to each producer. It will be shown that by varying the distribution of carbon credits given to producers, a market-based carbon credit program can be equivalent to any type of government-based EQIP subsidy program.

2.3.1 EQIP Subsidy Programs

An EQIP subsidy program is a collection of subsidies, denoted by $k = (k_{imn})$, where k_{imn} is the per acre subsidy offered to the producer at the i^{th} site of the m^{th} state growing the n^{th} crop. The expected number of acres using conservation tillage practices under an EQIP subsidy program k is denoted as $NA(k)$ and equal to,

$$NA(k) = \sum_{m=1}^{M} \sum_{i=1}^{r_m} \sum_{n=1}^{N} \left[G(\mathrm{b}x_{imn} + k_{imn}) NA_{imn} \right] \tag{7}$$

where;

x_{imn} = production characteristics of the i^{th} site in the m^{th} state growing the n^{th} crop,

M = number of states in the study area,

r_m = number of production sites in the m^{th} state,

N = number of crops.

The total expected level of carbon sequestration, $Q(k)$, under an EQIP program is equal to the sum of the expected amount of carbon sequestered by each producer,

$$Q(k) = \sum_{m=1}^{M} \sum_{i=1}^{r_m} \sum_{n=1}^{N} Q_{imn}(x_{imn}, k_{imn}) \tag{8}$$

where;

Q_{imn} = expected supply of the j^{th} enviromental measure from the i^{th} site in the m^{th} state growing the n^{th} crop.

The total expected cost of an EQIP subsidy program, $TC(Q(k))$, is equal to,

$$TC(Q(k)) = \sum_{m=1}^{M} \sum_{i=1}^{r_m} \sum_{n=1}^{N} k_{imn} \left[G(\mathrm{b}x_{imn} + k_{imn}) NA_{imn} \right] \tag{9}$$

Many different EQIP subsidy schemes will produce the same expected overall level of carbon sequestration but at different expected costs. The subsidy scheme that minimizes the total expected cost of acquiring a given level of expected carbon, $\overline{Q}$, is found by,

$$\underset{k_{imn}}{Min}\ L=\sum_{m=1}^{M}\sum_{i=1}^{r_m}\sum_{n=1}^{N}\left[k_{imn}G(\beta x_{imn}+k_{imn})NA_{imn}\right]+\lambda\left[\overline{Q}-\sum_{m=1}^{M}\sum_{i=1}^{r_m}\sum_{n=1}^{N}Q_{imn}(x_{imn},k_{imn})\right] \qquad (10)$$

The first order condition states that at the minimum, the expected marginal cost of acquiring carbon is equal across all producers,

$$\lambda^{*}=\frac{\partial TC_{imn}}{\partial Q_{imn}}=\frac{\partial TC_{imn}/\partial k_{imn}}{\partial Q_{imn}/\partial k_{imn}}=\frac{NA_{imn}G(\beta x_{imn}+k_{imn}^{*})+NA_{imn}k_{imn}^{*}\,\partial G(\cdot)/\partial k_{imn}^{*}}{NA_{imn}\left[Y0(x_{imn})-Y1(x_{imn})\right]\partial G(\cdot)/\partial k_{imn}^{*}} \qquad (11)$$

$$=\left(\frac{k_{imn}^{*}+1+e^{\beta x_{imn}+k_{imn}^{*}}}{Y0(x_{imn})-Y1(x_{imn})}\right)\ \text{for}\ \ i=1,\ldots,r_m\ ;\ m=1,\ldots,M\ ;\ n=1,\ldots,N$$

The variable $\lambda^{*}=\left[\partial L/\partial\overline{Q}\right]$ represents the optimal expected marginal cost of acquiring carbon, TC_{imn} is the total expected cost of acquiring carbon from the i^{th} site in the m^{th} state growing the crop, and k_{imn}^{*} represents its optimal subsidy. If the expected marginal cost of acquiring carbon from a source exceeds the expected marginal cost from another source, then total expected cost of carbon sequestration can be lowered by altering the subsidy scheme. Decreasing the subsidy of the more expensive provider and increasing the subsidy of the less expensive provider, such that the total level of carbon sequestration is unchanged, will lower the total expected cost of carbon sequestration. Total expected costs are lowered until the marginal cost of acquiring expected carbon are equalized across all sources.

The first order condition is re-written as follows,

$$\lambda^{*}=\left[\frac{k_{imn}^{*}}{Y0(x_{imn})-Y1(x_{imn})}\right]\left[1+\frac{1}{\omega_{imn}}\right]\ \text{for}\ \ i=1,\ldots,r_m\ ;\ m=1,\ldots,M\ ;\ n=1,\ldots,N \qquad (12)$$

where;

$$\omega_{imn} = \left[\frac{\partial G(\cdot)}{\partial k_{imn}}\right]\left[\frac{k_{imn}}{G(\cdot)}\right] = \text{ elasticity of adoption.}$$

The optimal subsidy offered to producers is dependent upon their willingness to adopt conservation tillage practices and their ability to sequester carbon through conservation tillage practices. The elasticity of adoption (ω_{imn}) represents a producer's willingness to adopt conservation practices. The greater the elasticity of adoption, the greater the increase in the probability of adopting conservation tillage for a marginal increase in the subsidy. Per acre difference in the amount of carbon emissions between conventional and conservation tillage $(Y0(x_{imn}) - Y1(x_{imn}))$ represents the producer's ability to sequester carbon. Under the cost minimizing EQIP subsidy program, producers with a greater willingness to adopt conservation tillage and ability to sequester carbon will receive the greater per acre subsidies.

The second order condition for a minimum is not met globally, since the adoption function may be either concave or convex. A grid search was conducted to find the λ^* that minimized the total expected costs of sequestering an expected level of carbon.

Offering a different subsidy to each producer, will, however, create very high administrative costs and may also be politically infeasible. To avoid potential these barriers, suppose the EQIP subsidy program encouraging the adoption of conservation tillage consists of only a single per acre subsidy offered to all producers, so that $k_{imn} = \bar{k}$ for all (i, m, n). Such a program is more politically feasible and has lower administrative costs, but the overall expected transfers to producers would be higher for a given expected level of carbon sequestration.

Figure 1 presents the relative inefficiency of the single EQIP subsidy program when compared to the minimum cost EQIP subsidy program for the two-producer case. The iso-carbon curves, Q_0 and Q_1, represent the combination of subsidies offered to producers (k_1, k_2) that leave the overall expected level of carbon sequestration unchanged. The iso-cost curves, TC, represent the combination of subsidies offered to producers that leave the overall expected cost of carbon sequestration unchanged. The slopes of the iso-carbon and iso-cost curves are shown to be convex and concave, respectively, but this may not necessarily be the case. As stated previously, the adoption function may either be concave or convex.

The 45° ray $\vec{S}$ represents the solution set for the single EQIP subsidy program $k_1 = k_2$. At point B, the single EQIP subsidy program is expected to sequester Q_0 amount of carbon at an expected cost of TC_1. At this point, the iso-cost curve is steeper than the iso-carbon curve. This implies that for a marginal decrease in the subsidy to producer 2, the increase in the subsidy to producer 1 needed to keep the expected level of carbon sequestration unchanged is smaller than the increase needed to keep expected costs unchanged. Hence, expected costs can be lowered without changing the expected level of carbon sequestration. Expected costs are decreased until the slope of the iso-cost curve equals the slope of the iso-carbon curve, so that the marginal cost of acquiring carbon is equal across producers.

Points A and C represent the minimum cost EQIP subsidy schemes that are expected to sequester Q_0 and Q_1 amounts of carbon, respectively. The relative inefficiency of the single EQIP subsidy scheme can be expressed as the increase in total expected costs, TC_1 - TC_0, for the given level of carbon sequestration Q_0 as well as in terms of the decreased level of carbon sequestration Q_1 - Q_0 for a given level of expected cost TC_1.

2.3.2 Carbon Credit Program

A carbon credit program is denoted by the distribution of carbon credits to producers, $z = (z_{imn})$, where z_{imn} is the per acre carbon credit given to the producer at the i^{th} site of the m^{th} state growing the n^{th} crop. The agricultural sector is assumed to be a price-taker in an external carbon market and producers are able to sell their carbon credit at an exogenous carbon price p. Hence, the per acre incentive to adopt conservation tillage under the carbon credit program is equal to pz_{imn}.

Every possible EQIP government subsidy program has an equivalent market-based solution. For example, the carbon credit program that mimics the minimum cost EQIP subsidy program is denoted as $z^* = (z^*_{imn})$ where $z^*_{imn} = k^*_{imn} / p$ and k^*_{imn} is the minimum cost EQIP subsidy offered to the producer at the i^{th} site of the m^{th} state growing the n^{th} crop. Similarly, the carbon credit program that mimics the single EQIP subsidy program, $\bar{k} = k_{imn}$ for all (i, m, n), is denoted as $\bar{z} = z_{imn}$ for all (i, m, n), where $\bar{z} = \bar{k} / p$ is the carbon credit given to all producers.

3. Empirical Analysis

The study region consists of the Lake States of Michigan, Wisconsin, and Minnesota; the Corn Belt States of Ohio, Indiana, Illinois, Iowa, and Missouri; and the Plains States of North Dakota, South Dakota, Nebraska, and Kansas. The crops in the analysis are corn, soybeans, wheat, sorghum, and hay and fourteen major rotations were identified [Babcock et al, 1997]. The primary data source is the USDA National Resource Conservation Service's National Resource Inventory (NRI) conducted at

160,000 points in the twelve-state study area. For each NRI point, information is collected on the natural resource characteristics of the land, the farming practices used by the producer, and weather characteristics.

The empirical analysis relies heavily on two models previously developed and used in the Center for Agricultural and Rural Development's (CARD) publication Resource and Agricultural Policy System's (RAPS) 1997 Agricultural and Environmental Outlook [Babcock et al, 1997]. First, is the Acreage Response Modeling System (ARMS) which projects crop choices and crop rotation given the climatic conditions and market conditions at each of the 160,000 points in the study area. Second, the Site-Specific Pollution Production modeling system which estimates the environmental effects of different management practices. The estimation of these systems used information from the NRI survey conducted by the National Resource Conservation Service (NRCS) of the United States Department of Agriculture (USDA), the USDA's Census of Agriculture, Cropping Practices Survey, and Crops County data [Babcock et al, 1997].

Given the crop choices and crop rotations predicted by ARMS, the next steps are to estimate the probability of adopting conservation tillage practices at each of the NRI points in the study area and to estimate the difference in carbons emissions from conventional and conservation tillage. Conventional tillage is defined as a tillage system that maintains less than 30% residue cover. While, conservation tillage is assumed to be no-till and is defined as a tillage system that maintains at least 70% residue cover [CTIC, 1993]. The remainder of this section will present the empirical conservation tillage adoption model and the estimated relationship between tillage practices and carbon emissions from agricultural soils.

3.1 Conservation Tillage Adoption Model

Table 1 presents the variables used to estimate the probability that conservation tillage is practiced at each of the NRI points in the study area. All data were for the 1992-growing season. Tables 2-4 present for the Corn Belt, Lake States, and Northern Plains, the estimated influence of each of these variables on the probability of adopting conservation tillage as well as the standard error and associated t-statistic. The overall fit of the predicted logit model to conservation tillage adoption is very strong in the Lake States and Northern Plains States and is satisfactory in the Corn Belt region. The percentage of correct predictions by the logit model is 86.4% for the Lake States, 84.7% for the Northern Plains States, and 71.5% for the Corn Belt States.

3.1.1 Calibration Factor

Table 5 presents the percentage of acres in conservation tillage for each of the five crops in each of the twelve states during 1992 and 1997. The percentage of acreage where conservation tillage practices are used has changed significantly from these two time periods. The conservation tillage adoption model is estimated using 1992 data, so a calibrating factor, α, is introduced to accurately reflect the current tillage environment from the 1992 base year. The model estimates are adjusted by selecting an α such that the proportion of land using conservation tillage practices in the current year equals the expected proportion of land predicted by the adoption model. The conservation tillage adoption rate of a producer with characteristics x, calibration factor α, and green payment k becomes,

$$\Pr[Y=1 \mid x] = G(\beta x + \alpha + k) = \frac{e^{\beta x + \alpha + k}}{1 + e^{\beta x + \alpha + k}} \qquad (13)$$

3.1.2 Identifying Restriction

In the estimation of the conservation tillage adoption model, the error term is assumed to be logistically distributed with a fixed variance of $\pi^2/3$. This variance determines how much of a payment is needed to increase the probability of adoption to a certain level. In 1997, 39.8% of the total study area acreage was in conservation tillage. This implies an “overall study area average” βx value of -0.4138, so that the overall adoption rate is $G(\beta x) = e^{\beta x}/\left(1 + e^{\beta x}\right) = 0.398$. The payment, k, needed to ensure a 95% percent adoption rate is then $3.36 per acre, i.e., $e^{-0.4138+k}/\left(1 + e^{-0.4138+k}\right) = 0.95$. This payment is the same whether the choice is between tillage systems, investment choices, or business decisions.

For the logit model to be meaningful in each separate application, an additional “identifying” restriction is needed to reflect the resistance of adopting conservation tillage. The payments necessary to entice 95% of current non-adopters of environmentally beneficial management practices such as integrated pest management, legume crediting, manure testing, and soil moisture testing have been estimated in the range of $65 to $75 per acre [Cooper and Keim, 1996]. The current adoption rates for these practices are, however, much lower than for conservation tillage. Hence, it is assumed that a smaller payment is needed to reach a 95% adoption rate of conservation tillage.

In the analysis, it is assumed that a 95% adoption rate occurs with a $20 per acre subsidy. The subsidies offered to producers that increase the likelihood of conservation tillage adoption are then multiplied by 5.96. This factor is found by dividing the assumed $20 payment by the payment found with the unidentified logit model ($3.36).

3.2 Tillage Practices and Carbon Emissions

The Site-Specific Pollution Production (SIPP) modeling system [Mitchell et al, 1997] uses information from the Erosion Productivity Impact Calculator version 5300 [Sharpley and Williams, 1988], the Pesticide Root Zone Model 2.0 [Mullins et al, 1993], and both the NASS and NRI databases [USDA/SCS, 1994]. SIPP estimates the changes in several environmental measures due to different management practices. These environmental measures are changes in SOC levels, water erosion, wind erosion, nitrogen runoff, nitrogen leaching, atrazine runoff, atrazine leaching, and atrazine volatilization. A more detailed discussion of the process used to estimate the influence of crop choice, crop rotation, tillage practice, and geographic information on carbon emissions and carbon sequestration is presented in Mitchell et al. (1997).

4. Results

Table 6 presents the state estimates of the 1997 levels of carbon sequestration and each state's conservation tillage adoption rates as well as their potential for additional carbon sequestration. In the study area, approximately 11.45 million metric tons (mmt) of carbon were sequestered from the current use of conservation tillage. The states sequestering the greatest amounts of carbon from tillage practices are Iowa, Nebraska, and Illinois. The states sequestering the least amount of carbon from tillage practices are Wisconsin, Michigan, and Ohio.

The overall rate of conservation tillage adoption for the study area is approximately 39.8%. The states with the least resistance to conservation tillage and thus have the greatest conservation tillage adoption rates are Nebraska, Iowa, and Missouri. The states with the greatest resistance to conservation tillage and thus have the lowest conservation tillage adoption rates are Minnesota, Wisconsin, Kansas, and North Dakota.

Table 6 also presents for each state the soil potential for sequestering carbon through tillage practices. This soil potential measure reflects the spatial heterogeneity of SOC levels in the study area. Iowa soil has by far the greatest potential for carbon sequestration from tillage practices (0.24 mt/acre), followed by Nebraska, Illinois and Minnesota (0.14 to 0.15 mt/acre). Missouri, Indiana, Wisconsin, North Dakota, and South Dakota soil can sequester 0.11 to 0.12 metric tons of carbon per acre. The soil with the lowest capability to sequester carbon is located in Kansas, Ohio, and Michigan.

If all the producers in the study area that grow corn, soybeans, wheat, sorghum, or hay adopted conservation tillage practices, an additional 14 million metric tons of carbon would be sequestered. The total amount of carbon sequestered would increase 125% to approximately 25.87 mmt. States with the greatest overall potential to sequester additional carbon are Iowa, Illinois, and Minnesota. While, states with the smallest overall potential to sequester additional carbon are Michigan, Wisconsin, Ohio, Missouri, and Indiana.

4.1 Estimated Carbon Supply Curve

Figure 2 presents the carbon supply curve for the single EQIP subsidy program. The carbon supply curve rises gradually and becomes nearly vertical as the maximum level of carbon sequestration is approached. An incentive payment of $8.40 per acre will sequester 18.44 mmt of carbon, while a payment of $20.50 per acre will sequester 23.90 mmt of carbon. The carbon supply prices depend greatly on the overall resistance to conservation tillage adoption as reflected in the identifying restriction. For example, the carbon supply curve will rotate up from S_0^C to S_1^C, if the identifying restriction were increased, so that 95% conservation tillage adoption throughout the study area is assumed to occur with a $30 rather $20 per acre subsidy.

The carbon supply curve relates carbon sequestered to the single per acre EQIP subsidy. To compare the efficiency of the single EQIP subsidy program and discuss its second-best nature, the total expected cost of acquiring sequestered carbon is examined and compared with the minimum cost EQIP subsidy program.

4.2 Cost of Acquiring Sequestered Carbon

Figure 3 compares the total expected costs of acquiring carbon from the single subsidy EQIP program and the minimum cost EQIP subsidy program. Under each program, the expected total cost curve is convex and becomes vertical near the capacity of 25.87 mmt of carbon. The expected cost under the single subsidy EQIP program is $172 million and $3.4 billion when sequestering 13.18 mmt and 23.90 mmt of expected carbon respectively. However, the expected cost under the minimum cost EQIP subsidy program is $53 million and $2.6 billion when sequestering 13.18 mmt and 23.90 mmt of expected carbon respectively. The relative efficiency of the single price instrument is shown in Figure 4. At a relatively low level of carbon supply, the cost of the single price instrument is 180% the cost of the minimum cost instrument. The inefficiency of the single subsidy EQIP program decreases fairly dramatically however as the amount of carbon supply increases because the amount of flexibility in the minimum cost program declines. This loss of flexibility arises because as carbon supply increases there are fewer and fewer low-cost providers of carbon and fewer and fewer producers who are selling their fixed supply of carbon to the market.

5. Conclusions

Currently, agricultural soils in the Midwest sequester approximately 11.45 mmt of carbon through the use of conservation tillage. States such as Iowa, Illinois, and Nebraska, have high SOC levels and high conservation tillage adoption rates and thus sequester the majority of the carbon. Other states such as Michigan, Wisconsin, and Ohio sequester the least amount of carbon, since they have either very low SOC levels or very low conservation tillage adoption rates. If all the crop producers in the Midwest adopted conservation tillage, then an additional 14.42 mmt of carbon (25.87 mmt of carbon overall) will be sequestered. Iowa, Illinois, Minnesota, and Kansas are states with the greatest potential to sequester additional carbon through the increased adoption of conservation tillage.

The purpose of this research was to examine various policy instruments that promote carbon sequestration in agricultural soils and mitigate greenhouse gas emissions through increased adoption of conservation tillage. It was shown that that by varying the distribution of carbon credits given to producers, a market-based carbon credit program can become equivalent to any type of government-based EQIP subsidy program. Hence, the payments needed to increase the agricultural sector’s adoption of conservation tillage can be switched from the public sector to the private sector.

The expected cost of carbon sequestration was estimated for the single subsidy and minimum cost EQIP programs. The same expected costs of carbon sequestration would occur under a carbon credit program as under the EQIP subsidy program given the appropriate distribution of carbon credits. A different subsidy or size of carbon credit for each producer, however, may be prohibitively costly due to high administrative and political costs. A single subsidy or size of carbon credit program will lower these costs, but will have higher operating costs. The relative inefficiency of the single subsidy EQIP program was measured in terms of the increase in expected costs when sequestering an expected level of carbon. The inefficiency of the single subsidy or carbon credit program relative to the minimum cost program is $119 million when sequestering 13.18 mmt of expected carbon and $800 million when sequestering 23.90 mmt of expected carbon. If the political and administrative costs are higher than these levels, then a single subsidy or carbon credit is more economically feasible.

Other intermediate program should also be investigated such as different subsidies or carbon credits based upon the producer’s location and/or crop grown. Another possible program could place producers into groupings such that the variance of the minimum cost subsidies or carbon credits in each grouping is minimized. These intermediate programs will have lower expected operational costs than the single subsidy or carbon credit programs as well as lower administrative and political costs than the minimum cost programs. Hence, overall expected costs of carbon sequestration may be lower with these other programs

Table 1. Variables used in estimating the conservation tillage adoption model.

Variables	Symbol
Intercept	INT
Slope of the land	SLOPE
Clay percentage of the soil	CL
Available water capacity of the soil	AWC
Organic matter percentage of the soil	OM
Soil Ph	PH
Permeability of the soil	PM
Mean of the maximum temperature during the corn growing season	TMAXM_C
Mean of precipitation during the corn growing season	PRECM_C
Standard deviation of precipitation during the corn growing season	PRCPST_C
Mean of the maximum temperature during the wheat growing season	TMAXM_W
Mean of snowfall during the wheat growing season	SNOWM_W
Standard deviation of snowfall during the wheat growing season	SNOWST_W
Mean of precipitation during the wheat growing season	PRECM_W
Standard deviation of precipitation during the wheat growing season	PRCPST_W
Dummy Variables	
Field is planted with corn in the current year	CORN
Field is planted with soybeans in the current year	SOYB
Field is planted with wheat in the current year	WHEAT
Field is planted with hay in the current year	HAY
Field is planted with sorghum in the current year	SORG
Field is planted with corn in the previous year	CORN_1
Field is planted with soybeans in the previous year	SOYB_1
Field is planted with wheat in the previous year	WHEAT_1
Field is planted with hay in the previous year	HAY_1
Field is planted with sorghum in the previous year	SORG_1
Land capability class-high	GOODLAND
Land capability class-low	BADLAND
Coarse textured soil	COARSE
Fine textured Soil	FINE
MLRA variables	MLRA---

Table 2. Parameter estimates, standard errors, and t-statistics for the Corn Belt States.

Parameter	Estimate	Error	t-statistic
INT	2.9512	1.6042	1.8396
CORN	1.5707	0.1961	8.0098
SOYB	1.3783	0.1995	6.9104
WHEAT	1.6080	0.2318	6.9381
HAY	0.7097	0.2555	2.7777
CORN_1	1.2827	0.1816	7.0624
SOYB_1	1.0017	0.1841	5.4400
WHEAT_1	1.0589	0.2250	4.7066
HAY_1	0.4000	0.2448	1.6343
GOODLAND	-0.0141	0.0818	-0.1718
BADLAND	-0.3527	0.2288	-1.5415
SLOPE	0.0056	0.0012	4.8044
CL	-0.0040	0.0065	-0.6160
AWC	-0.2626	1.4028	-0.1872
OM	0.0061	0.0131	0.4667
PH	-0.2497	0.0655	-3.8096
PM	0.0249	0.0257	0.9695
COARSE	0.1527	0.0798	1.9136
FINE	-0.0457	0.1575	-0.2898
TMAXM_C	-0.0557	0.0181	-3.0840
PRECM_C	26.2782	4.6056	5.7058
PRCPST_C	-12.2499	2.0970	-5.8417
TMAXM_W	0.0060	0.0104	0.5773
SNOWM_W	0.4951	0.2742	1.8057
SNOWST_W	-0.4110	0.1869	-2.1988
PRECM_W	-6.8504	4.7179	-1.4520
PRCPST_W	4.6612	2.8032	1.6628
MLRA1031	0.3154	0.1811	1.7417
MLRA1051	-0.0449	0.2390	-0.1878
MLRA1071	0.7396	0.1743	4.2431
MLRA1081	0.1300	0.1526	0.8518
MLRA1091	-0.3494	0.2024	-1.7266
MLRA1101	-0.4960	0.2026	-2.4487
MLRA1111	-0.6338	0.1638	-3.8705
MLRA1121	-1.3853	0.4364	-3.1743
MLRA1131	-1.1045	0.2337	-4.7262
MLRA1141	-0.6235	0.1949	-3.1989
MLRA1151	-0.6352	0.1808	-3.5137
MLRA1201	0.3074	0.3664	0.8388
MLRA1211	-1.1236	0.4614	-2.4353
MLRA1221	0.3713	0.4754	0.7809
MLRA1241	-1.7372	0.4892	-3.5515
MLRA1261	-1.9332	0.7930	-2.4378
MLRA1311	-1.6609	0.4280	-3.8806
MLRA1341	-0.3941	0.7372	-0.5346
MLRA1391	-1.1563	0.3175	-3.6422
MLRA981	-0.2618	0.3059	-0.8557
MLRA991	-0.1466	0.2339	-0.6267
MLRA95B1	0.2155	0.2329	0.9254

Table 3. Parameter estimates, standard errors, and t-statistics for the Lake States.

Parameter	**Estimate**	**Error**	**t-statistic**
INT	-14.6411	3.3969	-4.3101
CORN	1.0352	0.2681	3.8611
SOYB	1.0859	0.2940	3.6932
WHEAT	0.5174	0.5174	0.4018
HAY	0.8048	0.3445	2.3357
CORN_1	0.8792	0.2569	3.4227
SOYB_1	0.9463	0.2801	3.3790
WHEAT_1	0.9313	0.3915	2.3789
HAY_1	-0.0395	0.3195	-0.1236
BADLAND	-0.6069	0.4506	-1.3471
GOODLAND	-0.2904	0.1718	-1.6905
SLOPE	0.0043	0.0023	1.8531
CL	-0.0061	0.0119	-0.5154
AWC	7.0955	2.7723	2.5594
OM	-0.0580	0.0260	-2.2294
PH	-0.0923	0.1525	-0.6051
PM	0.0456	0.0383	1.1912
COARSE	0.0487	0.2165	0.2249
FINE	-0.5416	0.2461	-2.2011
TMAXM_C	0.0784	0.0383	2.0448
PRECM_C	50.6649	15.3214	3.3068
PRCPST_C	-9.4791	5.6442	-1.6795
SNOWM_W	2.8065	0.7068	3.9707
SNOWST_W	-1.7410	0.5372	-3.2408
PRECM_W	-15.4413	9.4357	-1.6365
PRCPST_W	12.3297	6.5991	1.8684
MLRA56	1.4711	0.6137	2.3972
MLRA57	1.9128	0.7747	2.4692
MLRA88	1.2093	1.1457	1.0555
MLRA90	0.0422	0.5574	0.0757
MLRA91	0.3683	0.5755	0.6400
MLRA96	1.8810	0.9535	1.9727
MLRA97	1.5120	0.5789	2.6120
MLRA98	2.5307	0.4896	5.1688
MLRA99	2.4763	0.5287	4.6834
MLRA103	0.1628	0.3893	0.4182
MLRA104	-0.5189	0.5619	-0.9235
MLRA105	0.6197	0.4985	1.2429
MLRA110	0.7856	0.9040	0.8690
MLRA111	2.2778	0.5416	4.2056
MLRA94A	0.5128	1.1483	0.4466
MLRA95A	1.0890	0.6939	1.5694
MLRA95B	1.5797	0.5356	2.9492
MLRA102A	0.4729	0.4827	0.9798

Table 4. Parameter estimates, standard errors, and t-statistics for the Northern Plains States.

Parameter	**Estimate**	**Error**	**t-statistic**
INT	-14.1734	2.0593	-6.8825
CORN	1.3173	0.1514	8.7029
SOYB	0.8987	0.2029	4.4282
WHEAT	0.4021	0.1077	3.7330
SORG	0.6030	0.1678	3.5935
HAY	-2.5358	0.5801	-4.3711
CORN_1	0.9716	0.1555	6.2461
SOYB_1	0.6106	0.1993	3.0639
WHEAT_1	0.7297	0.1064	6.8554
SORG_1	0.6047	0.1790	3.3789
HAY_1	1.2041	0.4795	2.5113
GOODLAND	0.1093	0.1045	1.0465
BADLAND	0.1461	0.2104	0.6941
SLOPE	-0.0025	0.0021	-1.2260
CL	0.0164	0.0082	2.0043
AWC	16.7711	2.6939	6.2256
OM	0.0516	0.0430	1.2018
PH	0.3541	0.1197	2.9571
PM	0.1278	0.0341	3.7468
COARSE	-0.1216	0.1354	-0.8978
FINE	0.2290	0.1756	1.3045
TMAXM_C	0.0601	0.0217	2.7689
PRECM_C	-33.8189	9.3786	-3.6060
PRCPST_C	4.1563	3.9678	1.0475
TMAXM_W	0.0537	0.0156	3.4482
SNOWM_W	-4.8374	1.4551	-3.3245
SNOWST_W	2.6641	0.5774	4.6138
PRECM_W	-5.6143	13.9250	-0.4032
PRCPST_W	-2.6382	5.2809	-0.4996
MLRA1021	-0.9129	0.3927	-2.3246
MLRA1021	-0.9854	0.2383	-4.1354
MLRA1061	-0.8352	0.2379	-3.5107
MLRA1071	-0.2982	0.3532	-0.8442
MLRA1121	-0.2457	0.3635	-0.6759
MLRA53B1	-1.4908	0.3719	-4.0087
MLRA53C1	-0.1766	0.3578	-0.4938
MLRA541	-2.7815	0.5462	-5.0923
MLRA55A1	-1.0761	0.3458	-3.1115
MLRA55B1	-1.2246	0.3088	-3.9663
MLRA55C1	-0.3868	0.2959	-1.3071
MLRA561	-2.0088	0.4271	-4.7034
MLRA58C1	-0.9188	1.0932	-0.8405
MLRA60A1	0.6615	0.8191	0.8076
MLRA611	3.7690	1.5238	2.4734
MLRA63A1	0.9498	0.4498	2.1115
MLRA63B1	-0.4355	0.4684	-0.9298
MLRA641	-0.7688	0.5133	-1.4979
MLRA651	0.0983	0.7116	0.1381

Table 5. Percentage of acres in conservation tillage by crop and state for 1992 and 1997.

	Corn		Sorghum		Soybean		Wheat		Hay		5 Crop Total	
State	1992	1997	1992	1997	1992	1997	1992	1997	1992	1997	1992	1997
Illinois	45.4	26.9	42.6	48.9	49.5	45.5	48.0	53.7	34.1	35.1	46.7	36.7
Indiana	30.7	33.8	15.2	36.2	41.0	60.3	48.5	51.4	27.1	32.0	35.5	45.8
Iowa	35.1	41.1	42.5	74.6	56.7	65.2	37.5	35.4	50.3	48.9	43.9	52.0
Kansas	46.2	54.5	31.5	37.9	24.4	27.3	23.3	23.8	14.7	15.7	25.7	29.4
Michigan	46.2	56.1	27.9	21.9	39.2	54.9	31.9	38.5	19.4	21.4	42.1	47.3
Minnesota	24.5	22.3	5.2	10.3	30.1	33.3	16.0	22.5	10.8	10.1	23.2	24.7
Missouri	50.8	55.7	30.1	33.0	41.3	51.9	46.1	53.0	50.4	45.4	45.7	50.5
Nebraska	59.4	68.1	44.6	54.3	46.4	63.3	30.1	25.5	23.7	22.1	45.5	54.1
North Dakota	23.7	27.3	19.4	11.5	12.3	15.5	29.7	35.4	19.6	17.0	26.8	30.6
Ohio	39.2	38.3	32.7	17.7	39.9	54.8	41.8	46.4	30.8	29.2	38.6	45.2
South Dakota	38.2	44.0	44.1	52.5	34.2	42.2	31.3	35.9	25.9	21.9	34.9	35.9
Wisconsin	32.5	35.9	6.2	13.9	27.6	44.5	10.6	14.8	10.3	12.9	23.3	29.1
Total	39.8	41.1	36.2	41.3	42.8	50.2	29.0	32.2	26.9	24.9	36.4	39.8

Table 6. Expected carbon sequestration and conservation tillage in 1997.

State	1997 Expected Level of Carbon Sequestration (mmt)	Additional Carbon Available (mmt)	1997 Conservation Tillage Adoption Rate	Soil Potential for Carbon Sequestration (mt/acre)
Illinois	1.3	2.1	36.7%	0.14
Indiana	0.7	0.8	45.8%	0.12
Iowa	3.0	2.7	52.0%	0.24
Kansas	0.8	1.6	29.4%	0.10
Michigan	0.3	0.3	47.3%	0.10
Minnesota	0.7	1.9	24.7%	0.14
Missouri	0.9	0.6	50.5%	0.12
Nebraska	1.6	1.1	54.1%	0.15
North Dakota	0.6	1.2	30.6%	0.11
Ohio	0.5	0.6	45.2%	0.10
South Dakota	0.7	1.0	35.9%	0.11
Wisconsin	0.3	0.5	29.1%	0.11
Total	11.4	14.2	39.8%	0.14

Figure 1. Relative Inefficiency of the Single Subsidy EQIP Program.

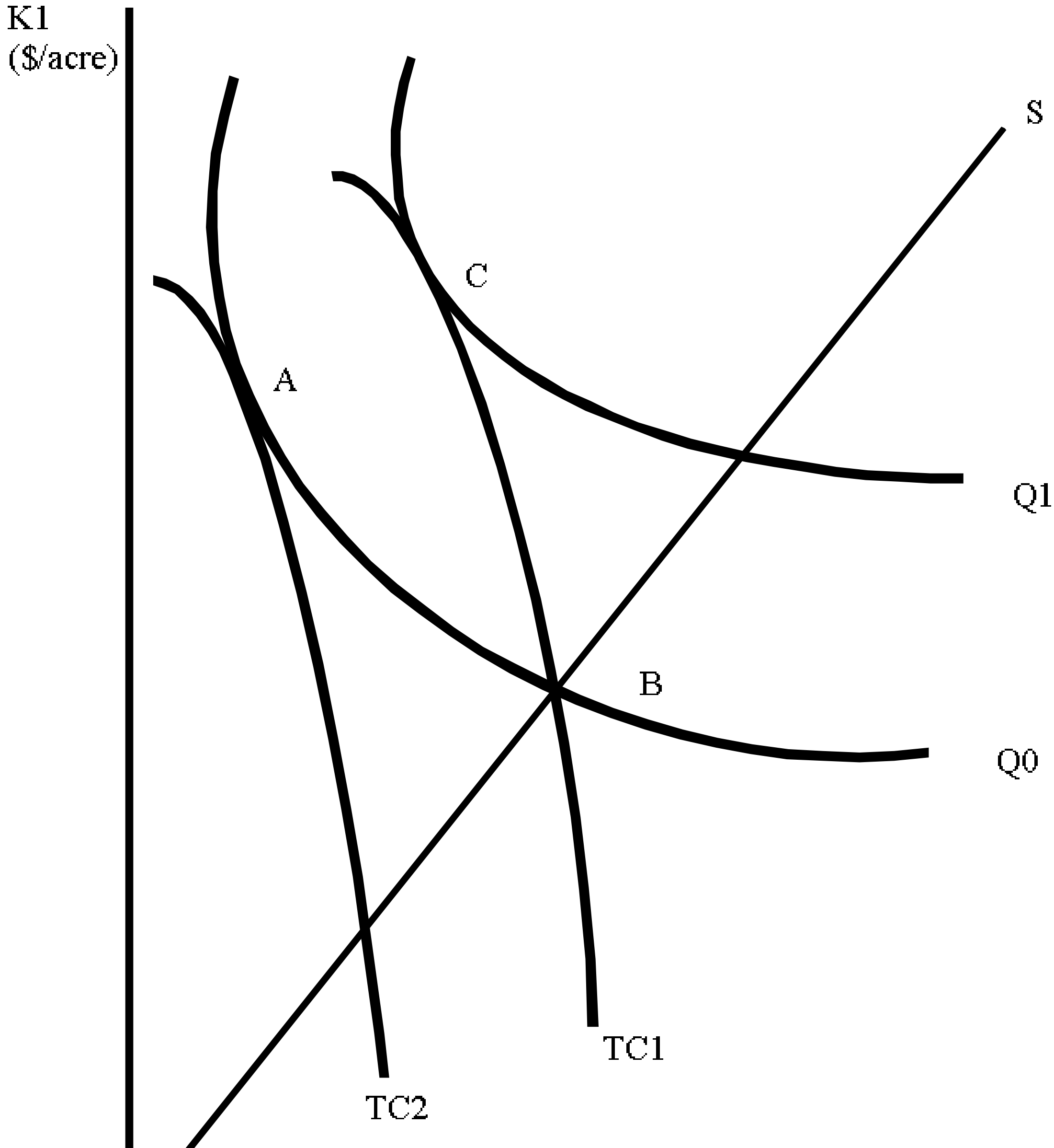


Figure 2. Carbon Supply under the Single Subsidy EQIP Program

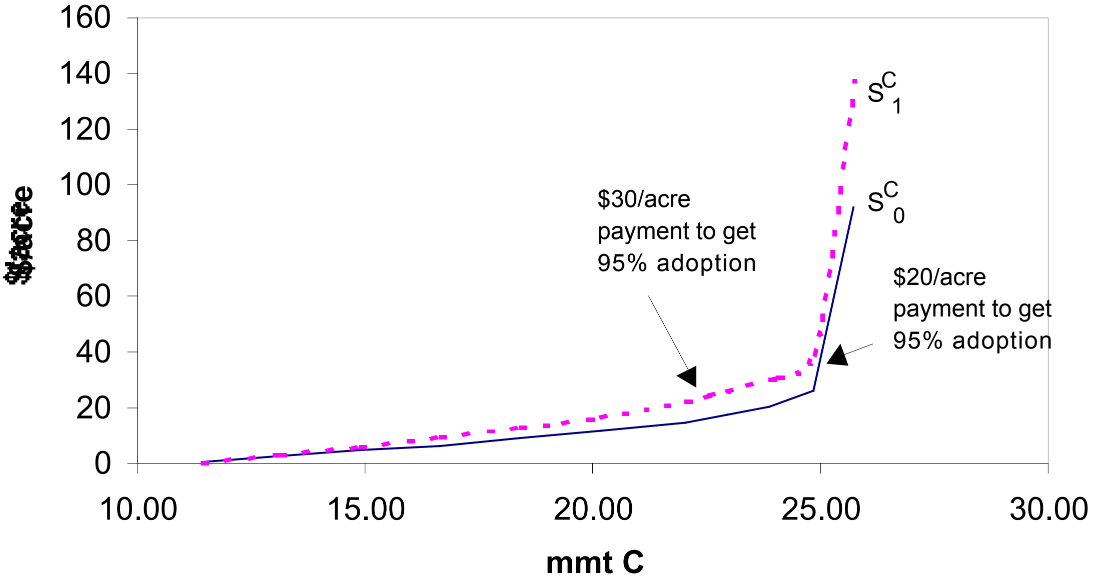
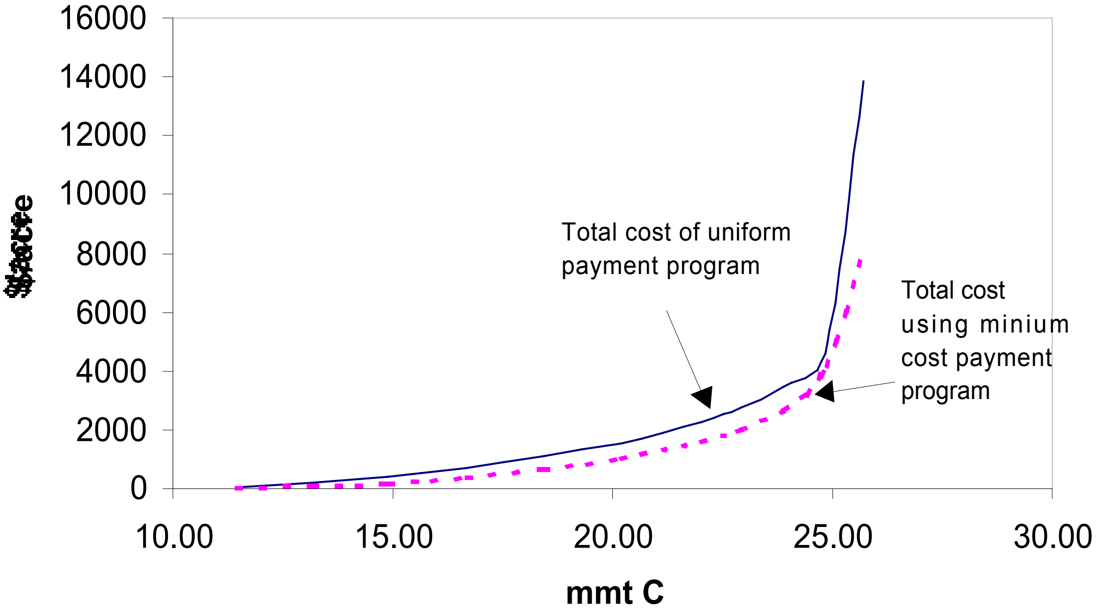


Figure 3. Total Cost of Obtaining Carbon Using First and Second Best Instruments



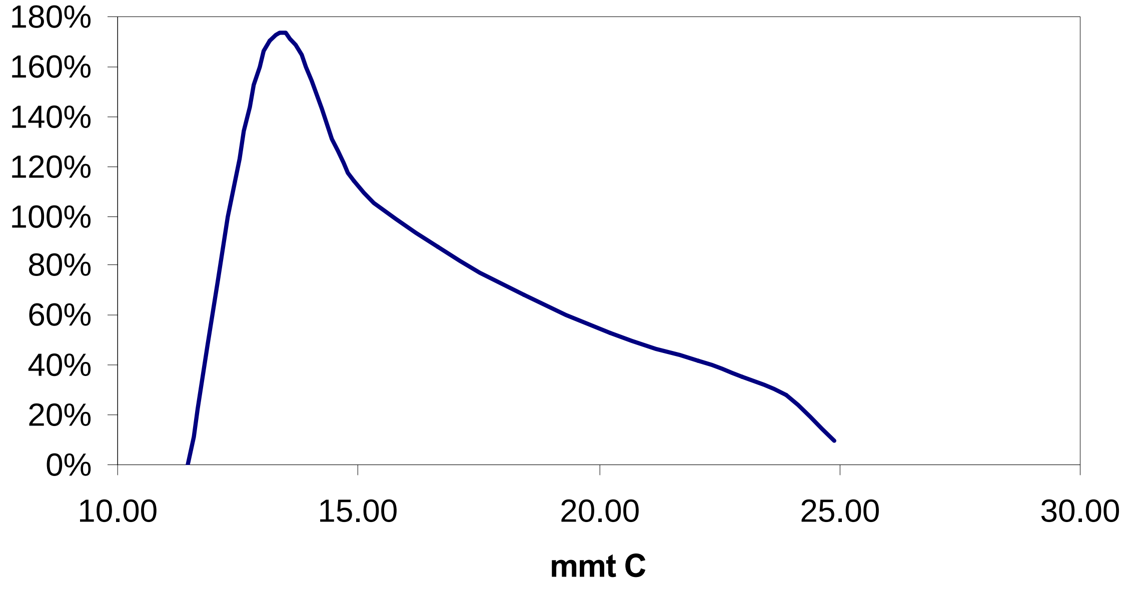


Figure 4. Percent Increase in Cost from Using Second Best Carbon Sequestration Instrument

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