# CREATING CARBON OFFSETS IN AGRICULTURE THROUGH NO-TILL CULTIVATION: A META-ANALYSIS OF COSTS AND CARBON BENEFITS

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**Abstract.** Carbon terrestrial sinks are often seen as a low-cost alternative to fuel switching and reduced fossil fuel use for lowering atmospheric $CO_2$. To determine whether this is true for agriculture, one meta-regression analysis (52 studies, 536 observations) examines the costs of switching from conventional tillage to no-till, while another (51 studies, 374 observations) compares carbon accumulation under the two practices. Costs per ton of carbon uptake are determined by combining the two results. The viability of agricultural carbon sinks is found to vary by region and crop, with no-till representing a low-cost option in some regions (costs of less than $10 per tC), but a high-cost option in others (costs of 100–$400 per tC). A particularly important finding is that no-till cultivation may store no carbon at all if measurements are taken at sufficient depth. In some circumstances no-till cultivation may yield a "triple dividend" of carbon storage, increased returns and reduced soil erosion, but in many others creating carbon offset credits in agricultural soils is not cost effective because reduced tillage practices store little or no carbon.

## 1. Background

Sequestration of carbon in agricultural ecosystems represents a potentially significant opportunity for offsetting anthropogenic carbon dioxide emissions that cause climate change. Lal et al. (1998) estimate that changes in global agricultural practices could sequester over 200 million metric tons of carbon (Mt C) per year; indeed, changes in agronomic practices in the United States are thought to have the potential to offset nearly 10% of its total carbon emissions (FAO, 2001). The Intergovernmental Panel on Climate Change (IPCC, 2000) quotes figures showing that conservation tillage alone could store more than a ton of carbon per hectare per year, while others provide figures that range from a low of 3 to a high of 500 kg C $ha^{-1}$ $yr^{-1}$ (Uri, 2001; Follett, 2001). Thus, agriculture seems to have the potential to make an important contribution to the mitigation of climate change;

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for example, Canada is counting on agricultural activities to meet some 5% of its Kyoto target (Climate Change Plan for Canada, 2002).

No-till cultivation is the only type of conservation tillage that appears to bring about carbon benefits (Uri, 2001; West and Marland, 2002), but it increases production costs (because more chemical inputs are required) and often reduces yields (Lerohl and van Kooten, 1995). Today 36% of U.S. farmers use some form of conservation tillage (Kurkalova et al., 2001) and 92% of corn, soybean, wheat and sorghum is cultivated by systems other than the traditional moldboard plow (Allmaras et al., 2000). As of 1998, zero- or no-till (NT) techniques were used on over 19 million ha in the U.S. alone (Uri, 2001). Although this falls short of the USDA's 1974 prediction that 45% of U.S. cropland would be under NT by the year 2000 (Phillips et al., 1980), more land could be switched to NT given adequate incentives.

Pautsch et al. (2001) estimated the effects of a variety of subsidy schemes on the adoption of conservation tillage, demonstrating that a subsidy could lead to the sequestration of more than 2 Mt C yearly for a period of many years in Iowa alone. However, in their model, this target could be achieved only at a cost of $550 per ton of carbon (tC), and then using only the most efficient or carefully discriminating policy. If C uptake is purchased using less efficient policies (e.g., paying the same price for all land used to sequester carbon), the minimum cost rises to over $700 per tC. These estimates are high compared with the 20–$30 per t $CO_2$ (70–$100 per tC) "market price" widely anticipated if the Kyoto Protocol is fully implemented (Sandor and Skees, 1999) and even lower market price with the U.S. not participating in Kyoto. However, the high costs reported by Pautsch et al. (2001) are not definitive, and a more thorough investigation is certainly warranted. The purpose of this study is to provide an in-depth review of the economic case for carbon sequestration through no-tillage cultivation techniques.[1]

Compared to forestry where researchers have estimated costs of sequestering carbon, direct estimates of the cost of carbon uptake in agricultural systems is lacking. Rather, various studies in agricultural economics report on the difference in net returns between conventional and no tillage agronomic systems under various conditions, while soil scientists have examined differences in soil carbon. As a result, we approach our task by conducting two meta-regression analyses, using the empirical regression results to calculate possible costs of carbon uptake in agriculture for different locations and crop types. In the first regression, we estimate the economic costs of NT vs. intensive or conventional tillage (CT), and then, in the second, examine how much carbon the practice is likely to sequester. Our statistical analyses of more than 100 studies and some 900 estimates suggest that, compared to CT, NT seems to sequester too little carbon at too high a cost to make this means of mitigating climate change an attractive alternative to emissions reduction. However, there are some exceptions where an effort to switch from conventional to no till agriculture does lead to a low-cost carbon benefit.

## 2. Statistical Approach: Meta-Regression Analysis

Meta-regression analysis (MRA) is a systematic process for analyzing data from a variety of studies on a given phenomenon to discover the factors that influence it. Regression analysis is used to identify links between study characteristics and predicted outcomes, so that broad trends within the data can be recognized and used as the basis for making projections about expected outcomes under a variety of circumstances. Although individual studies provide estimates of the relationship between variables at a given point under a limited set of circumstances, MRA seeks to move from the results of individual studies to a more general description of the relationships between the variables (Smith and Kaoru, 1990; Curtis and Wang, 1998). More specifically, MRA relies on statistical methods to determine significant trends or findings in the literature, decreasing the need for more subjective (and descriptive) reviews (Stanley, 2001). In addition, by analyzing the results from a large number of studies, MRA can identify a significant trend even where many individual studies might have failed to detect the trend (Mann, 1990). MRA can explain study-to-study variation by determining the extent to which methods, design and data affect reported results (Stanley, 2001).

However, looking at a diverse group of studies requires that attention be paid to study-specific effects. For example, various investigators have different ideas about the precise meaning of "net returns," with some including the opportunity cost of land and/or the cost of a farmer's own labor while others focus only on variable costs, treating land and own labor as fixed. Differences among studies can be addressed statistically by specifying a different error term for each set of data. This is done here using "random effects" analysis.

This methodology is best explained by starting with a description of the results typically provided by an underlying source study. Assume a given study $i$ performs a regression analysis on plots under NT and CT regimes. It then reports the separate average net returns for each set of plots based on the following fitted model:

$$\begin{aligned} \hat{\bar{y}}_{\mathrm{NT}} &= \bar{Z}'_{1,\mathrm{NT}}\beta_1 + \bar{Z}'_2\beta_2 \\ \hat{\bar{y}}_{\mathrm{CT}} &= \alpha_{\mathrm{CT}}D_{\mathrm{CT}} + \bar{Z}'_{1,\mathrm{CT}}\beta_1 + \bar{Z}'_2\beta_2 \end{aligned} \tag{1}$$

where the $\hat{\bar{y}}$'s represent predicted average net returns for subsamples of plots under NT and CT, respectively, $D_{\mathrm{CT}}$ is a dummy term equal to 1 if a plot is under CT, and equal to 0 otherwise, $\alpha$ is the change in regression intercept for returns associated with CT, the $\beta$-terms denote vectors of estimated coefficients, and the $Z$-matrices include the sample means of regressors for the two subgroups.

As indicated in Equation (1), some variables may produce similar subgroup means for NT and CT plots. They are captured in $\bar{Z}_2$. Examples might be climate variables or economic indicators that are independent of tillage regime. In contrast, some explanatory variables may produce different subgroup means for NT vs. CT plots. They are collected in vector $\bar{Z}_{1,t}$, $t$ = CT, NT, in Equation (1).

Examples may be tillage regime related outlays for machinery and labor, or other farm characteristics strictly associated with either regime.

Meta-analysis uses these results in an overlapping "umbrella" regression. It employs all reported $\hat{\bar{y}}$'s from qualified underlying studies. However, it can only build on regressors that are common to *all* underlying sources. For the net-return model in this study, these are geographic regions ($R_1$ = South, $R_2$ = Other North America, $R_3$ = Outside North America), and an indicator variable for "wheat" vs. "other crops" ($D_W$). Since the subsample averages of these regressors usually do not vary by much in original studies (e.g., 50% of both CT and NT plots are located in the South for a given study), they are captured in $\bar{Z}_2$.

This leaves remaining elements of $\bar{Z}_2$ (i.e., tillage-invariant sample means of regressors for a given underlying study) that are *not represented in all underlying sources*. For example, for a given study $\bar{Z}_2$ may include information on rainfall, which should yield similar subsample means for CT and NT plots if each plot type exhibits the same geographical distribution. However, this regressor may not be employed in another source study (which nonetheless provides useful estimates of $\hat{\bar{y}}$'s and information on regions and wheat). Therefore, it cannot be included in the metaregression. At best, it could be modeled as another indicator equal to "1" if rainfall was part of the original set of regressors and "0" otherwise. Alternatively, its effect on predicted net returns will be subsumed in the error term of the metamodel. Recognizing that this error component is shared by all observations flowing from a specific source study improves the efficiency of estimates, as it guards against biased standard errors and unreliable $t$-statistics. The technique of random effects is one way of controlling for this intrasource correlation.

Thus, we can specify the contribution of a given source study $i$ to the meta-regression compactly as

$$y_i = x_i\beta + \varepsilon_i \quad \text{with} \quad \varepsilon_i = \mu_i + e_{\text{it}}, \tag{2}$$

where $y_i$ is a vector of $s_i$ observations on the returns of tillage stemming from study $i$, $\beta$ is a vector of coefficients to be estimated through meta-analysis, $\boldsymbol{x}_i$ is an $s_i \times k$ matrix of regressors shared by all source studies, and $\varepsilon_i$ is an $s_i \times 1$ vector of error terms that collects both nonshared elements of $\bar{Z}_2$ (as explained above), and all elements of $\bar{Z}_{1,t}$, $t$ = CT, NT flowing from study $i$. As indicated in Equation (2) and based on the discussion above, the two error components are treated separately in our analysis and denoted as $\mu_i$ and $e_{\text{it}}$, respectively. Following standard random effects assumptions (Hsiao, 1986; Greene, 2000, pp. 567–578), we specify the elements of $e_{\text{it}}$ to be independently distributed with common mean of zero and variance of $\sigma_e^2$. We further stipulate the distribution of $\mu_i$ as:

$$\begin{aligned} E[u_i] = 0, \quad E[u_i\, u'_j] &= \sigma_\mu^2 I_{si} \quad i = j \\ &= 0 \qquad\quad i \neq j \end{aligned} \tag{3}$$

where $E$ denotes the expectations operator, and $I_{\text{si}}$ an $s_i \times s_i$ identity matrix. Thus, each contributing study "draws" a study-specific constant term from a normal

distribution with mean zero and variance $\sigma_u^2$. As indicated in Equation (3), these deviations are uncorrelated across studies.

In addition, we assume that $\mu_i$, $e_i$ and $x_i$ are uncorrelated within and across studies. The full model over all $n$ studies takes the form:

$$y = X\beta + \varepsilon = X\beta + \mu + e$$

with

$$\mu = \begin{bmatrix} \mu_1 \\ \mu_2 \\ \vdots \\ \mu_n \end{bmatrix} \quad E\left[\mu\mu'\right] = \sigma_\mu^2 \cdot I_N \quad E\left[ee'\right] = \sigma_e^2 \cdot I_N \tag{4}$$

where $y$ is a vector of size $N = \sum_{i=1}^{n} s_i$ by 1, and $X$ is a $N \times k$ matrix of regressors shared by all sources. Equation (4) can be estimated using Generalized Least Squares (GLS) or Maximum Likelihood (MLE) Methods (Greene, 2000, pp. 570–572).

## 3. Estimating Costs of Reduced Tillage

Conservation tillage was not initially recommended for implementation to sequester carbon but to limit soil erosion. As many as $4 \times 10^9$ tons of topsoil are lost each year in the United States alone (King, 1985), adversely affecting agricultural productivity and causing silt accumulation in rivers. Under NT and other conservation techniques, soil loss is reduced by 75–90% (Dillaha et al., 1988; Krause and Black, 1995), which in many cases is a sufficient incentive to promote adoption of soil conservation practices. Other governmental programs have also been implemented to address the issue of erosion, so *new* programs focusing on carbon are unlikely to generate benefits related to erosion sufficient to outweigh carbon benefits. Erosion costs (and benefits of avoided erosion) are not included in this model but represent an additional porential benefit of conservation tillage.

Rational farmers adopt conservation tillage to the point where the cost of so doing equals the perceived benefits of reducing soil erosion. There are already some subsidies in place for adopting reduced tillage and NT. When carbon uptake benefits are added, with farmers paid for changing tillage practices, there is a "double dividend"—carbon benefits plus additional soil conservation benefits that are not captured privately (see Antle and McCarl, 2002 for summary and discussion). Soil erosion costs are ignored in our analysis as we assume that the major gains of cost-effective prevention have already been undertaken via targeted agricultural programs, such as the U.S. Conservation Reserve Program and similar programs in other countries.

TABLE I
Data sources for net returns information

| Cost estimate sources Source | Location | Study year | Number of observations | Mean returns/ hectare | |
|---|---|---|---|---|---|
| | | | | Conv Til | No Till |
| Aleman | Nicaragua | 2001 | 6 | $648.08 | $762.46 |
| Asoegwu | Nigeria | 1987 | 4 | $862.77 | $640.99 |
| Bauer | Oregon | 1984 | 12 | $185.18 | $129.77 |
| Bone et al. | Ohio | 1976 | 20 | $185.94 | $181.62 |
| Buehring et al. | Mississippi | 1988 | 6 | $105.44 | $43.47 |
| Ditsch et al. | Kentucky | 1988 | 8 | $155.86 | $155.86 |
| Doster | Indiana | 1976 | 10 | $628.62 | $382.90 |
| Doster et al. | Indiana | 1983 | 10 | $24.58 | $39.42 |
| Doster et al. | Indiana | 1993 | 8 | ($11.12) | $30.33 |
| Duffy and Hanthorn | Midsouth | 1984 | 8 | $260.49 | $268.69 |
| Epplin and Al-Sakkaf | Oklahoma | 1995 | 2 | $138.25 | $65.04 |
| Epplin et al. | Oklahoma | 1991 | 2 | $45.42 | ($50.54) |
| Featherstone et al. | Indiana | 1991 | 8 | $27.37 | $50.46 |
| Hairston et al. | Mississippi | 1984 | 8 | $208.57 | $95.44 |
| Halvorsen et al. | Colorado | 1994 | 6 | $112.29 | $113.87 |
| Harman and Martin | Texas | 1988 | 14 | $162.18 | $195.53 |
| Harman et al. | Texas | 1985 | 12 | $86.85 | $133.75 |
| Hinman et al. | Washington | 1983 | 2 | $114.61 | $79.88 |
| Hudson | Tennessee | 1981 | 4 | $249.42 | $287.04 |
| Jolly et al. | Iowa | 1983 | 6 | $846.62 | $851.80 |
| Jones et al. | Texas | 1987 | 2 | $50.76 | $76.17 |
| Keeling et al. | Texas | 1988 | 8 | $622.93 | $732.18 |
| Klemme | Indiana | 1985 | 32 | $815.62 | $771.11 |
| Klemme | Iowa | 1983 | 4 | $650.47 | $605.52 |
| Krause and Black | Michigan | 1995 | 2 | $285.53 | $294.92 |
| Kurkalova et al. | Iowa | 2001 | 2 | $202.37 | $238.50 |
| Liu and Duffy | Iowa | 1996 | 12 | $5.04 | $61.43 |
| Martin et al. | Indiana | 1991 | 48 | $202.24 | $110.21 |
| Nakao et al. | Ohio | 1999 | 6 | $194.22 | $177.67 |
| Norwood and Currie | Kansas | 1998 | 32 | $76.00 | $51.87 |
| Norwood and Dhuyvetter | Kansas | 1993 | 4 | ($2.84) | ($3.88) |
| Ohannesian and Elterich | Delaware | 1979 | 20 | $92.08 | $112.76 |
| Olson and Weber | Minnesota | 1999 | 2 | $199.21 | $221.11 |
| Pearce et al. | Arkansas | 1997 | 12 | $305.66 | $233.79 |
| Phillips et al. | Illinois | 1997 | 12 | $49.77 | $139.01 |
| Sanford et al. | Mississippi | 1982 | 4 | $334.27 | $464.48 |

(*Continued on next page*)

TABLE I
(*Continued*)

| Cost estimate sources Source | Location | Study year | Number of observations | Mean returns/ hectare Conv Til | No Till |
|---|---|---|---|---|---|
| Segarra et al. | Texas | 1991 | 4 | $390.78 | $440.70 |
| Smith et al. | Alberta | 1996 | 4 | $35.05 | $19.39 |
| Smith et al. | Wisconsin | 1992 | 6 | $555.11 | $387.17 |
| Smolik and Dobbs | South Dakota | 1991 | 2 | $28.36 | ($5.68) |
| Thomas | Dominican Rep. | 1985 | 4 | $260.96 | $109.54 |
| Unknown | United States | 1984 | 4 | $240.01 | $326.53 |
| Weersink et al. | Ontario | 1992 | 12 | $69.21 | $100.85 |
| Wiese et al. | Texas | 1997 | 12 | ($55.13) | ($113.08) |
| Wiese et al. | Texas | 1998 | 2 | $428.35 | $487.03 |
| Wiese et al. | Texas | 1994 | 6 | ($15.91) | ($27.66) |
| Williams et al. | Kansas | 1990 | 10 | ($1.51) | ($1.58) |
| Yiridoe et al. | Ontario | 1993 | 6 | $178.21 | $196.98 |
| Young et al. | Washington | 2001 | 8 | ($0.35) | ($59.70) |
| Zantinge et al. | Ontario | 1986 | 2 | $338.76 | $277.01 |
| Zentner et al. | Saskatchewan | 1991 | 48 | $2.10 | ($23.51) |
| Zentner et al. | Saskatchewan | 1996 | 48 | $59.63 | $43.30 |
| Total articles: 52 | Means | 1990.25 | 10.5 | $223.73 | $209.65 |
| Total observations: | Minima | 1976 | 2 | ($55.13) | ($113.08) |
| 536 | Maxima | 2001 | 48 | $862.77 | $851.80 |

To estimate the effects of tillage on a farm's net returns, we gathered 536 observations from 52 published sources (Table I). Estimates were converted to U.S. dollars per metric ton and calibrated to 1982–1984 levels using the U.S. consumer price index.[2] We were primarily interested in the effects of tillage on returns, so we limited the scope of our data to those articles making direct comparisons between NT and conventional (moldboard) tillage, effectively isolating the effects of tillage. In additions to net returns for each type to tillage, data were collected on production year, crop and location. Data are summarized in Table II.

Aside from the regional indicators and the wheat dummy mentioned above, our metaregression model for net returns includes the following additional explanatory variables: a general intercept term, a dummy for CT, interaction terms of tillage with each of the regional indicators and with "wheat", and the number of years after 1973 that the study was performed.[3] The last variable illustrates the capability of metaregression analysis to examine a given research question from a broader perspective. By combining information from several source studies, MRA can exploit the resulting variability in study-specific characteristics and incorporate additional (observed) information to explain variability in the dependent variable.

TABLE II
Variables, means and medians for returns to tillage data ($n = 536$)

| Variable | Mean | Median |
|---|---|---|
| Returns to tillage (US$ / per ha) | $73.12 | $43.81 |
| Years after 1973 that the study was performed | 16.44 | 16 |
| Dummy = 1 if study involved wheat, sorghum, or barley | 0.27 | |
| Dummy = 1 if study occurred in the Southern U.S.[a] | 0.19 | |
| Dummy = 1 if study occurred in other regions[b] | 0.09 | |
| Dummy = 1 if study occurred outside North America | 0.03 | |
| Dummy = 1 if returns are for conventional tillage | 0.50 | |
| Interaction between tillage and wheat | 0.13 | |
| Interaction between tillage and the South | 0.10 | |
| Interaction between tillage and other regions | 0.04 | |
| Interaction between tillage and outside North America | 0.01 | |

[a] Studies include Arkansas, Mississippi, Oklahoma, Tennessee, and Texas.
[b]Studies include Colorado, Delaware, Oregon, Washington, and 14 observations from outside continental North America. Baseline region is the Corn Belt, including Indiana, Illinois, Iowa, Kansas, Kentucky, Michigan, Minnesota, Nebraska, and Ohio. For this part of the study, the Prairie region, Alberta, Manitoba, North Dakota, Saskatchewan, and South Dakota, was grouped with the Corn Belt, as tests showed returns did not significantly differ between the two regions.

To be specific, the year of analysis is generally invariant over all observations (plots) within a given source and is not included in any source-specific regression. Since year of study is reported in every source and varies over sources it is a valid candidate for inclusion in a MRA model.

The generalized least squares (GLS) regression results of crop returns on the explanatory variables are presented in Table III. Generally, our model fits the underlying data fairly well, as indicated by the significance of the majority of the coefficients, a highly significant Wald statistic, and a reasonably high $R^2$ value for overall variability. As expected for a data set with large differences in panel size (i.e., the number of contributed observations from a given study) and considerable variability in the elements included in $\mu_i$ and $e_i$ for each source study, estimated regression variances are relatively high and $R^2$ within is low.[4] However, the appropriateness of including a study-specific error term was strongly confirmed by a Lagrange Multiplier (LM) test for the constraint $\sigma_\mu = 0$.[5]

As expected, tillage practice is a significant predictor of farmers' net returns with the estimated coefficient indicating that, on average, producers using NT earned about $28 per ha less than their counterparts using CT. However, the effect of tillage on returns varies greatly with the region and crop in question. In the South, NT is much cheaper regardless of the crop grown. Thus, the initial indication that NT results in a fairly substantial per ha penalty turns out to be false for the southern United States.[6] A comparison of estimated net returns based on the regression

TABLE III
Random-effects GLS meta-regression results for returns to tillage[a]

| Explanatory variable | Estimated coefficient |
|---|---|
| Conventional tillage dummy | 28.130** (1.98) |
| Year returns obtained (after 1973) | −16.290*** (−5.43) |
| Wheat (= 1; 0 otherwise) | −72.670** (−2.42) |
| U.S. South (= 1; 0 otherwise)[b] | −123.585** (−2.36) |
| Other region within N. America (=1; 0 otherwise)[c] | −126.928 (−1.48) |
| Outside United states and Canada (=1; 0 otherwise) | 278.852** (2.20) |
| Tillage × Wheat dummy | 1.558 (0.07) |
| Tillage × South regional dummy | −27.453 (−1.06) |
| Tillage × Other region within N. America | −24.009 (−0.79) |
| Tillage × Outside United States and Canada dummy | 53.472 (0.81) |
| Intercept term | 483.956*** (8.72) |
| $R^2$ within | 0.090 |
| $R^2$ between | 0.263 |
| $R^2$ overall | 0.237 |
| $\sigma_u$ | 193.91 |
| $\sigma_e$ | 111.22 |
| Number of observations | 536 |
| Number of studies | 52 |
| Average observations per study | 10.3 |
| Wald $\chi^2(10)$ | 60.59*** |
| Lagrange multiplier test for random effects $\chi^2(1)$ | 2190.80*** |

[a]Dependent variable is returns to tillage (US$ per ha per yr). Regional baseline is the U.S. Corn Belt, which includes Illinois, Kentucky, Minnesota, Nebraska and Ohio. The $z$-values provided in parentheses: ***indicates statistical significance at the 1% level or better; **significance at 5% level or better; *significance at 10% level or better.
[b]South Carolina, Georgia and Texas.
[c]Alberta, Manitoba, North Dakota, Saskatchewan, and Eastern Canada.

results is provided in Table IV for six crop-region combinations.[7] Differences vary from a low of a few dollars per ha in the U.S. South to hundreds of dollars in regions outside North America. For the grain and corn belts of North America, the difference runs around $50 per ha. Thus, in some regions, the erosion benefits of NT may well exceed the costs of switching tillage practices.

## 4. Carbon Accumulation in Agricultural Soils: The Effect of Tillage Practices

It is generally acknowledged that, by changing from conventional (intensive) to no (zero) tillage, soil carbon will increase (Kern and Johnson, 1993; IPCC, 2000; Uri,

2001). While NT is an effective soil-conservation (soil carbon enhancing) strategy in many areas, in semiarid regions where crop-fallow rotations are common, a switch to continuous cropping will conserve soil and increase soil carbon content (Smith and Young, 1999; Antle and McCarl, 2002). Tillage fallow is practiced in semiarid regions primarily to conserve moisture and reduce risks, but this leads to less soil carbon. To overcome the risk component, subsidies could be required to get farmers to adopt continuous cropping, even if it is more profitable than the crop-fallow rotation. In any event, we do not include studies that examined these types of agronomic practices, focusing only on a comparison of CT and NT.

NT is an important part of a larger process by which sequestration may occur, but does it lead to greater carbon sequestration? The relationship between NT and carbon storage is a complex one. Researchers have examined the effects of crop type, rotation and fertilizers (Campbell et al., 2001), cover crops (Sainju, 1992), climate and soil texture (Torbert et al., 1998; Six et al., 1999) and time (Ding et al., 2002) on carbon storage potential. The impact on carbon flux of burning crop residue as opposed to leaving it on the ground has also been debated. Clapp et al. (2000) and Duiker and Lal (2000) favor leaving the straw, whereas Sanford et al. (1982) find that straw limits yields. Dalal (1989) even notes that burning residue contributes to carbon sequestration at depths as low as 0.9–1.2 m.

Studies that measure soil carbon to deeper levels tend to find less difference between NT and CT than do those that sample to shallower depths. Some researchers find that NT affects only the distribution of carbon in the soil rather than increasing the actual amount sequestered (Angers et al., 1995; Potter et al., 1998; Wanniarachchi et al., 1999). Many scientists have found no significant difference between the mass of carbon observed in NT soils and that found in intensively/conventionally tilled soils (Doran, 1980; Dick, 1983; Salinas-Garcia et al., 1997; Angers et al., 1997; Bergstrom et al., 2001). Most studies find a significant difference only in the top 5–15 cm, in some cases followed by an opposite trend in the next 15 cm (Dick, 1983; Yang and Wander, 1999; Yang and Kay, 2001).

TABLE IV
Estimated returns of tillage and opportunity cost of NT[a]

| Crop | Region | CT returns ($ per ha) | NT returns ($ per ha) | Difference in returns (CT–NT) |
|---|---|---|---|---|
| Wheat | South | $136.76 | $132.79 | $3.97 |
| | Outside North America | $992.77 | $845.49 | $147.28 |
| | Corn Belt/Prairies | $404.23 | $351.65 | $52.58 |
| Corn/ Other | South | $262.69 | $261.49 | $1.20 |
| | Outside North America | $1,118.71 | $974.19 | $144.51 |
| | Corn Belt/Prairies | $530.17 | $480.35 | $49.82 |

[a]Expected returns using 1986 (sample mean) data converted to 2001 $US.

The mechanism by which CT might store more carbon than NT is unclear (Angers et al., 1997). CT increases $CO_2$ respiration as the soil is plowed (Lupwayi et al., 1999), but plowing appears to "push" organic matter deeper into the soil profile, thus facilitating the adsorption and stabilization of more organic material than is possible when the straw and residue remain concentrated on top of the ground (Paustian et al., 1997). In an analysis of carbon budgets in a deciduous forest ecosystem in Tennessee, Johnson and Todd (1998) find that woody biomass left above the soil is not converted to soil carbon but seems to be lost as $CO_2$. Perhaps plowing crop residues into the earth enables the soil to capture some of what would otherwise be lost as $CO_2$ through decay, thereby increasing soil carbon at plowing depth and below. This capture of soil carbon could be facilitated by direct contact with soil adsorption sites (such as Fe and Al hydrous oxides) that more effectively sequester carbon in soils.

We examine this issue using meta-regression analysis to evaluate how NT and CT compare in carbon storage potential. We collected 374 observations from 51 studies that compared the carbon stored under NT with that stored under conventional cropping. The explanatory variables shared by all sources and thus available for the MRA model are depth of sampling, location, year of study, crop grown, type of tillage, and number of years that NT was practiced (if it was). We limited our data to those cases reporting the actual mass of carbon in the soil. The reason is that Peterson et al. (1998) contend that evaluating soil carbon based on mass rather than concentration is preferable, while Yang and Wander (1999) indicate that "the use of concentration- or volume-based comparisons produces erroneous and misleading results" (p. 8). A summary of the data is provided in Table V.

All underlying source studies provide sets of pairs of observations on carbon storage under CT ($C_{is,CT}$) and NT ($C_{is,NT}$) for adjacent or nearby plots. This allows for a refinement of the MRA model used to assess net returns described in the previous section. Specifically, we take the difference $C_{is,NT}$—$C_{is,CT}$ for each study. This eliminates the undesirable effect of any joint omitted variables that may have biased carbon estimates under each regime in a given source study. We take this precautionary step as many of the variables likely to influence carbon storage, including climate, the use of cover crops, fertilizer applications and whether crop residue is burned, are not included in several of the underlying studies. At the same time, these unobserved effects are likely to be systematically correlated with included components, such as regions or crop indicators. If this is the case, reported carbon sequestration estimates will be biased. Our differenced specification for the dependent variable in the MRA model guards, at least to some extent, against this problem.

Most studies report results for several sets of plot pairs. Therefore, the discussion of model specification and error composition in the previous section extends in straightforward fashion to the specification of the carbon metaregression. Accordingly, a random effects specification with $\ln(C_{is,NT}—C_{is,CT})$ as dependent variable was chosen for this model. The regression results are provided

TABLE V
Summary of studies of soil carbon comparisons

| Source | Main Location | Year data collected | Number of observations | Mean stored (Mg C per ha) | | Max sample depth |
|---|---|---|---|---|---|---|
| | | | | Conv til | No till | |
| Alvarez et al. | Argentina | 1994 | 1 | 49 | 51 | 20 |
| Angers et al. | East Can. | 1994 | 7 | 31.74 | 31.23 | 60 |
| Balesdent et al. | France | 1990 | 6 | 25.55 | 26.11 | 30 |
| Barber et al. | Bolivia | 1993 | 2 | 12.04 | 14.70 | 15 |
| Bayer et al. | Brazil | 1994 | 2 | 47.4 | 52.9 | 30 |
| Beare et al. | Georgia | 1991 | 2 | 17.70 | 22.74 | 15 |
| Bergstrom et al. | Manitoba | 1998 | 17 | 21.90 | 20.52 | 48 |
| Black and Tanaka | North Dakota | 1989 | 30 | 68.69 | 67.92 | 91.2 |
| Blevins et al.[a] | Kentucky | 1975 | 12 | 27.43 | 31.53 | 30 |
| Blevins et al. | Kentucky | 1980 | 16 | 17.48 | 25.04 | 15 |
| Campbell et al.[b] | Saskatchewan | 1986–94 | 10 | 7.14 | 7.63 | 15 |
| Chan et al. | Australia | 1989 | 4 | 11.49 | 13.82 | 20 |
| Clapp et al. | Minnesota | 1993 | 8 | 29.36 | 30.05 | 30 |
| Dalal | Australia | 1981 | 6 | 34.47 | 35.55 | 120 |
| Ding et al. | South Carolina | 1999 | 3 | 9.34 | 12.53 | 15 |
| Doran | Nebraska | 1980 | 18 | 12.67 | 14.48 | 30 |
| Doran et al. | Nebraska | 1981–96 | 14 | 17.91 | 19.18 | 122 |
| Edwards et al. | Alabama | 1990 | 9 | 10.49 | 15.00 | 20 |
| Eghball et al. | Nebraska | 1989 | 1 | 52.11 | 57.27 | 30 |
| Franzluebbers et al. | Texas | 1991 | 3 | 21.16 | 27.18 | 20 |
| Freixo et al. | Brazil | 1998 | 8 | 36.09 | 38.4 | 30 |
| Groffman | Georgia | 1983 | 3 | 19.12 | 22.88 | 21 |
| Hansmeyer et al. | Minnesota | 1991–95 | 2 | 8.71 | 9.56 | 7.5 |
| Hendrix et al. | Georgia | 1989 | 2 | 12.14 | 15.38 | 20 |
| Hussain et al. | Illinois | 1997 | 2 | 35.63 | 43.47 | 15 |
| Ismail et al. | Kentucky | 1989 | 12 | 12.97 | 15.56 | 30 |
| Karlen et al. | Iowa | 1992 | 3 | 37.47 | 52.42 | 20 |
| Kessavalou et al. | Nebraska | 1995 | 1 | 10.00 | 11.66 | 15 |
| Kushwaha et al. | India | 1998 | 2 | 11.03 | 11.77 | 10 |
| Lamb et al. | Nebraska | 1981–82 | 6 | 10.29 | 11.32 | 30 |
| Larney et al. | Alberta | 1992 | 4 | 13.39 | 13.80 | 15 |
| Lilienfein et al. | Brazil | 1998 | 5 | 101.35 | 105.22 | 200 |
| Machado and Silva | Brazil | 1995 | 10 | 41.66 | 44 | 40 |
| Mahboubi et al. | Ohio | 1991 | 2 | 19.65 | 51.07 | 15 |
| Mrabet et al. | Morocco | 1998 | 3 | 16.98 | 20.03 | 20 |
| Nyborg et al. | Alberta | 1990 | 18 | 15.98 | 16.81 | 15 |

(*Continued on next page*)

TABLE V
(*Continued*)

| Source | Main Location | Year data collected | Number of observations | Mean stored (Mg C per ha) | | Max sample depth |
|---|---|---|---|---|---|---|
| | | | | Conv til | No till | |
| Peterson et al. | North Dakota | 1982–91 | 8 | 15.59 | 15.97 | 30 |
| Pierce | Michigan | 1997 | 8 | 28.78 | 33.89 | 20 |
| Potter et al. | Texas | 1996 | 7 | 13.92 | 14.29 | 20 |
| Rhoton et al. | US South | 1991 | 6 | 16.26 | 20.01 | 15.2 |
| Sainju et al. | Georgia | 1995–99 | 30 | 8.05 | 9.43 | 20 |
| Six et al. | Midwest | 1995 | 4 | 11.75 | 13.55 | 20 |
| Wanniarachchi et al. | Ontario | 1994 | 1 | 9.46 | 8.94 | 50 |
| Yang and Kay | Ontario | 1999 | 21 | 32.88 | 39.09 | 60 |
| Yang and Wander | Illinois | 1997 | 8 | 21.89 | 22.58 | 90 |
| Total articles: 51 | Means | 1991–96 | 7.71 | 24.14 | 27.50 | 35.66 |
| Total observations: | Median | 1992 | 6 | 17.7 | 20.52 | 20 |
| 374 | Minima | 1975 | 1 | 7.14 | 7.63 | 7.5 |
| | Maxima | 1999 | 30 | 101.35 | 105.22 | 200 |

[a] As quoted in Frye and Blevins (1997).
[b] Numbers in Campbell et al. (1995, 1996, 1999).

in Table VI. Compared to the meta-model for net returns, the carbon model generates higher goodness of fit statistics. This is expected, since the differencing of carbon uptake estimates over plot pairs also eliminates some elements of $\bar{Z}_2$ in Equation (1) and thus renders the components of intrastudy error $\mu_i$ much more homogeneous across sources. Nonetheless, a Lagrangian multiplier test still confirms the appropriateness of random effects at the 5% level of significance.

Several variables have a similar influence on the relationship between CT and NT. NT seems to be less effective at sequestering carbon on fields of wheat than on fields of other crops. NT in the Southern U.S. was more effective at storing carbon than NT in the Corn Belt area of the United States. On the Prairies and in other regions, NT was comparatively ineffective. As expected, the sign on the coefficient of the number of years under NT was positive, indicating that the longer NT is continued, the more carbon is stored (Figure 1), although this will level off as the soil becomes saturated (Antle and McCarl, 2002).

The negative coefficient on the depth of measurement supports the contention that the difference between NT and CT decreases as measurement depth increases. Extrapolated further, the model predicts that, in some cases, the difference will disappear completely, especially on the Prairies (Figure 2). Yang and Kay (2001)

TABLE VI
Random effects gLS Meta-regression results for tillage on carbon[a]

| Explanatory variable | Estimated coefficient |
|---|---|
| Wheat (=1; 0 otherwise) | −0.100*** (−3.99) |
| Corn/soybean rotation (=1; 0 otherwise) | −0.028 (−0.51) |
| South (=1; 0 otherwise)[b] | 0.012 (0,21) |
| Prairies (=1; 0 otherwise)[c] | −0.116** (−2.20) |
| Other NA region (=1; 0 otherwise)[d] | −0.002 (−0.02) |
| Outside United States and Canada (=1; 0 otherwise) | −0.032 (−0.59) |
| Years under NT cultivation | 0.009*** (3.82) |
| ln(depth) | −0.125*** (−12.02) |
| Years since base year (1973) | −0.005* (−1.74) |
| Constant | 0.560*** (10.01) |
| $R^2$ within | 0.32 |
| $R^2$ between | 0.54 |
| $R^2$ overall | 0.46 |
| $\sigma_u$ | 0.10 |
| $\sigma_e$ | 0.13 |
| Number of observations | 374 |
| Number of studies | 49 |
| Average observations/study | 7.6 |
| Wald $\chi^2(9)$ | 199.50*** |
| Lagrange multiplier test for random effects $\chi^2(1)$ | 21.00*** |

[a]Dependent variable is natural logarithm of the ratio of the mass of C under NT to that under CT. Regional baseline is the U.S. Corn Belt, which includes Illinois, Kentucky, Minnesota, Nebraska and Ohio. The *z*-values are provided in parentheses: ***indicates statistical significance at the 1% level or better, **significant at 5% level or better, *significant at 10% level or better.
[b]South Carolina, Georgia and Texas.
[c]Alberta, Manitoba, North Dakota and Saskatchewan.
[d]Eastern Canada (but only 29 observations).

note that although the statistical significance of treatment effects on soil carbon may disappear at greater depths, this could be attributed to the diminished variation of soil carbon at those depths (p. 153). Figure 3 indicates that, with the exception of a few outliers, the ratio between NT and CT is high initially but seems asymptotically to approach one. The graph of the difference between CT and NT, illustrating the simple mass amount of carbon stored by NT, shows that the variance of measurements remains high or even increases at depth, possibly reflecting different means of measurement. It is difficult to tell whether some carbon is in fact being stored, and further research should serve to clarify this issue.

There are some caveats. First, one reviewer pointed out that, although some studies comparing NT to CT in the Great Plains area find little direct sequestration

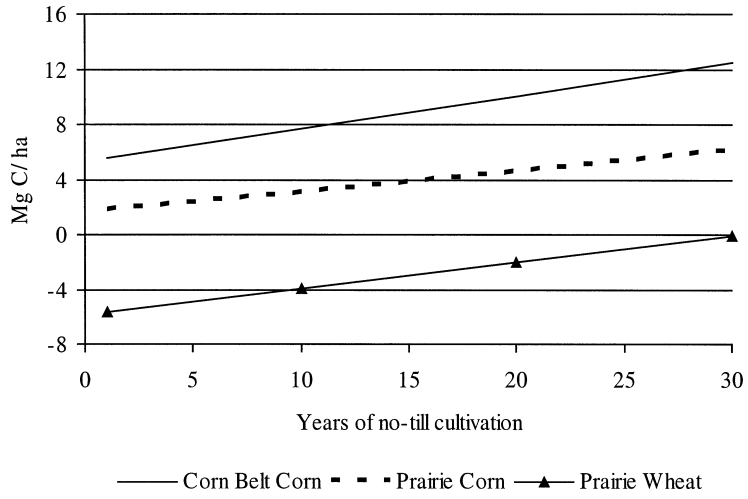


*Figure 1*. Carbon accumulation by NT over time based on 25 cm depth of measurement and planting in 1986.

of carbon in soil, NT can decrease the frequency of fallow, which would facilitate carbon accumulation (and we did not treat studies comparing continuous cropping with crop-fallow rotations). Likewise, most source studies probably ignore the carbon benefits of decreased erosion, which may be considerable.

Further, our regression may be extrapolating from the decrease observed at moderate depths and imputing a relationship that does not in fact hold. Most previous

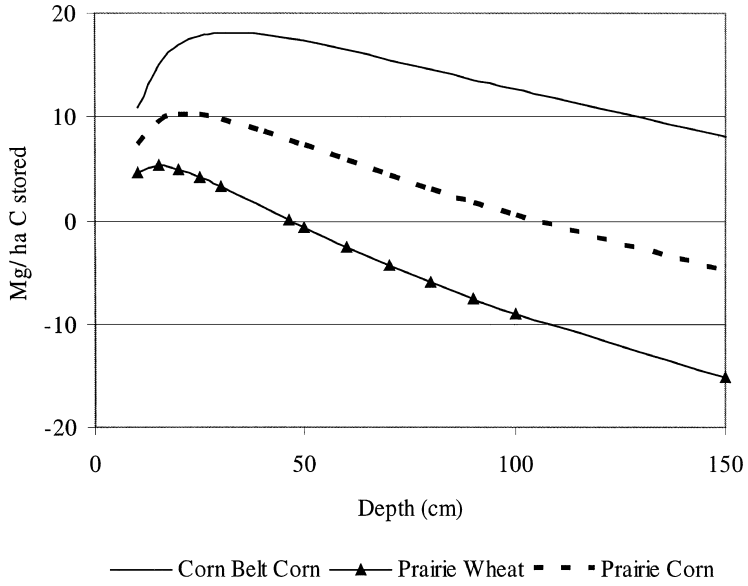


*Figure 2*. Amount of carbon stored by NT (relative to CT) over a range of depths of measurement assuming 30 yr of NT.

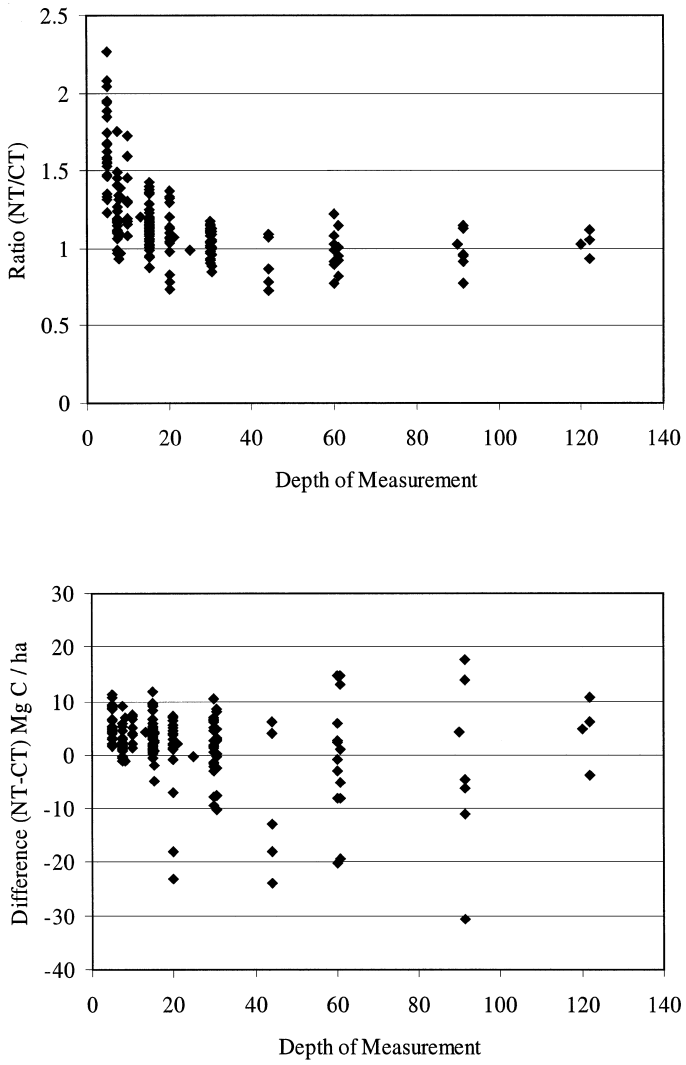


*Figure 3*. Comparison of mass of carbon stored under NT and under CT for all data points (soil depth in cm).

studies did not find significant differences between tillage treatments at depths below the plow layer. However, the hallmark of meta-regression analysis is its ability to detect significance where individual studies might not. Whether the effect we notice is a statistical artifact or a chemical reality should be further investigated using experimental or other means. In a similar summary evaluation of a large number of data points from published works, Six et al. (2002) also found evidence that deeper measurement shows less net sequestration, though they observed net carbon uptake to a depth of 50 cm under NT (p. 765).

TABLE VII
Net cost estimates per ton of carbon sequestered under NT[a]

| Region | Crop | Cost per tC at 25 cm | Cost per tC at 50 cm |
|---|---|---|---|
| South | Wheat | $10.06 | $12.61 |
| | Other crop | $1.94 | $1.96 |
| Prairies | Wheat | $376.08 | $\infty$[b] |
| | Other crop | $147.34 | $207.72 |
| Corn Belt | Wheat | $142.01 | $186.22 |
| | Other crop | $84.03 | $86.36 |

[a]Costs in 2001 $US for crops harvested in 1986, assuming 30 yr of NT.
[b]Since the difference in the amount of soil carbon stored under NT vs. CT is so small, the cost of employing NT as a means only to store carbon with no other benefits implies that cost per tC approaches infinity.

Whatever may be proved or disproved in the future, the graphs also call attention to this study's finding that superficial storage may mean little for overall terrestrial storage. Despite the common observation that soil carbon concentration decreases with soil depth, the vast majority of soil carbon stocks lie in deeper soil horizons because of their generally greater mass. Shifting the concentration of carbon to within a few centimeters of the surface may not represent a significant systemic shift. Real alterations in the system require more substantial changes in human activity.

## 5. Costs of Creating Carbon Credits by Changing Tillage Practices

To derive a final result in terms of costs of carbon sequestered under NT, we computed expectations for the dependent variables from both models given different values for the regressors.[8] The results are provided in Table VII where carbon sequestration is determined for depths of 25 and 50 cm. Costs per ton of carbon sequestered increase significantly with depth, exceeding $200 per tC in the Prairies region of North America when wheat is grown, regardless of the depth of measurement. Indeed, costs vary widely from a low of $1.94 per tC to well over $300 per tC depending on region, crop grown, time land is in no till (not shown in Table VII), and depth of measurement. Clearly, situational factors affect the usefulness of NT as a method of sequestering carbon.

Two outcomes should be highlighted. First, in most places creating carbon offsets by changing tillage practices is simply not cost-effective, due in large part to the low mass of additional carbon stored with NT vs. CT. High per ha opportunity costs of using NT combined with low carbon uptake leads to high costs of creating carbon offsets. This conclusion supports that of Pautsch et al. (2001), who examined

the costs of carbon sequestration using subsidies to bring about changes in tillage practices. The second major conclusion is that, in some regions and with some types of crops, using NT to sequester carbon is quite inexpensive; a small amount of additional carbon can be stored at a modest cost. It is these situations that carbon sequestration programs need to target.

## 6. Discussion

Is there evidence that, compared to CT, adoption of no tillage leads to a "triple dividend"—higher net returns to farmers, reduced soil erosion and additional carbon uptake? In this study, we combined the results of meta-regression analyses of 52 studies (with 536 observations) of net returns and 51 studies (374 observations) of carbon uptake in soils to estimate the costs of carbon sequestration using conservation tillage, specifically no till. Although the switch from conventional or intensive tillage to no till appears to be quite inexpensive in some regions, our study raised important questions about its effectiveness as a low-cost means for creating carbon offset credits. One reason is that estimates of how much NT increases the mass of carbon in soils appear to be affected by the depth to which soil measurements were taken, as well as by the type of crop grown, region and length of time that no till was practiced. In particular, when soil measurements are to a sufficient depth, the difference in soil carbon between CT and NT is small in some locations.

Further, the costs of converting to a NT system are higher than anticipated, at least in some regions and for some crops. This is all exacerbated by the fact that adoption of no till and other soil conserving practices for the purpose of increasing soil carbon leads to a carbon pool that is ephemeral. When the ephemeral nature of this carbon pool is properly accounted for in the analysis, costs of creating soil carbon credits may be higher yet (see Antle and McCarl, 2002; Sedjo and Marland, 2003). Even where evidence suggests that there is a difference in soil carbon between practices, the costs of creating carbon offsets by subsidizing a switch in tillage practices may be too high and, with some exceptions, not generally competitive with emissions reduction.

Underlying factors such as high fixed investment costs, greater variability of income under NT compared to CT (higher on-farm risk), and cultural factors might militate against the adoption of no till. More recently, West and Marland (2002) noted that a more complete accounting of the use of fossil fuels in agriculture shows that the benefits of NT may be exaggerated, and Six et al. (2002) found that $N_2O$ emissions counteract the $CO_2$ savings that NT secured.

Society could rely on the third dividend of enhanced soil conservation (soil conservation and erosion prevention) to encourage farmers to adopt no till on a greater scale than currently, particularly since soil erosion results in off-site damages that could be substantial (Aw-Hassan and Stoecker, 1994). But many agricultural

programs already address this concern, and it is likely economically inefficient to use a carbon program to target soil conservation. It is inefficient because the fields resulting in the greatest off-site damages may not be the same as those that sequester and store the most carbon.

Overall, there remains some potential for generating carbon benefits at low cost by changing agronomic practices, but such benefits are limited. In order to be most cost-effective, economic instruments will need to be designed to target farmland where a switch from a conventional to a zero tillage system is most efficient in terms of its overall social costs and benefits. The results of our research suggest that the best opportunities for enhancing carbon stored in soils using NT practices are greatest in the U.S. South. However, if wheat is grown and/or production takes place on the northern Great Plains ("Prairies"), costs of carbon uptake will range from about $375 per tC upwards, generally much higher than the at most $35–$110 per tC expected as a result of Kyoto's flexibility mechanisms.

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## Notes

[1]We consider only NT in order to obtain the largest possible carbon benefits of switching agronomic practices, but also because research indicates that anything less than zero tillage will not prove effective in generating carbon credits (West and Marland, 2002; Six et al., 2002).

[2]This time period was chosen because of available data: see http://www.bls.gov/cpi/cpifaq.htm.

[3]The year 1973 was chosen somewhat arbitrarily, but also to allow 30 yr to the present: NT has been practiced on some fields for as long as 30 yr.

[4]For a good discussion on the derivation and interpretation of goodness-of-fit measures in panel data models, see the Stata Reference Manual, Release 6 (1999), Volume 4, Su-Z, p. 425.

[5]As indicated in Table III, the null hypothesis of no infra-panel error is clearly rejected.

[6]Regression analysis revealed that returns on the Prairies did not statistically differ from those in the Corn Belt on the basis of region alone, although the crop grown does affect returns.

[7]These are rough estimates only, providing a guideline rather than a precise assessment of the costs and returns involved. Because studies are so heterogeneous, many of the variables we wished to include were not available for a sufficient number of observations/studies. Therefore, the omitted variables are relegated to the error terms, limiting the fit of our regression equation. As long as included variables are not correlated with elements in either error component, estimates are unbiased.

[8]An auxiliary regression was performed to estimate the mass of carbon stored under CT, which was multiplied by the ratio of NT to CT (the dependent variable) and then subtracted to obtain the difference between CT and NT. This difference was divided by the number of years under NT to obtain tC $ha^{-1}$ $yr^{-1}$. The difference between estimated returns to NT and the estimated returns to CT was divided by the above result to get \$ $tC^{-1}$ (Table VII).

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