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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/tC), but a high-cost option in others (costs of \$100-\$400/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.

Keywords: costs of soil carbon credits; conventional and zero tillage systems; carbon accumulation in soil

Creating Carbon Offsets in Agriculture through No-Till Cultivation:

A Meta-Analysis of Costs and Carbon Benefits

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 ten percent 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; 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 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). While this falls short of the USDA's 1974 prediction that 45% of U.S. cropland would be under no-till 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 tonne 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 versus 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 sequesters 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. While 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 (Curtis and Wang, 1998; Smith and Kaoru, 1990). 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:

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

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

As indicated in (1), some variables may produce similar sub-group 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 (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” versus “other crops” (D_W). Since the sub-sample 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 $\overline{Z}_2$.

This leaves remaining elements of $\overline{Z}_2$ (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 $\overline{Z}_2$ may include information on rainfall, which should yield similar sub-sample 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 meta-regression. 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 meta-model. 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 intra-source correlation.

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

$$y_{\mathrm{i}} = x_{\mathrm{i}}\beta + \varepsilon_{\mathrm{i}} \quad \text{with} \quad \varepsilon_{\mathrm{i}} = \mu_{\mathrm{i}} + e_{\mathrm{it}}, \tag{2}$$

where y_i is a vector of s_i observations on the returns of tillage stemming from study i, β 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 ε_i is an $s_i \times 1$ vector of error terms that collects both non-shared elements of $\overline{Z}_2$ (as explained above), and all elements of $\overline{Z}_{1,t}$, t=CT,NT flowing from study i. As indicated in (2) and based on the discussion above, the two error components are treated separately in our analysis and denoted as μ_i and e_{it}, respectively. Following standard random effects assumptions (Hsiao, 1986; Greene, 2000, pp.567-78), we specify the elements of e_{it} to be independently distributed with common mean of zero and variance of σ^2_e. We further stipulate the distribution of μ_i as:

$$E[u_i] = 0, \qquad E[u_i\, u_j'] = \sigma_\mu^2\, I_{si} \qquad i = j$$
$$= 0 \qquad i \neq j \tag{3}$$

where E denotes the expectations operator, and I_{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 σ^2_u. As indicated in (3), these deviations are uncorrelated across studies.

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

$$y = X\beta + \varepsilon = X\beta + \mu + e \qquad with$$
$$\mu = \begin{bmatrix} \mu_1 \\ \mu_2 \\ \vdots \\ \mu_n \end{bmatrix} \qquad E[\mu\mu'] = \sigma^2_\mu \cdot I_N \qquad E[ee'] = \sigma^2_e \cdot I_N \tag{4}$$

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.570-72).

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 4×10^9 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 no-till 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 potential 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 erosion prevention have already been undertaken via targeted agricultural programs, such as the U.S. Conservation Reserve Program and similar programs in other countries.

To estimate the effects of tillage on a farm’s net returns, we gathered 536 observations from 52 published sources (Table 1). Estimates were converted to U.S. dollars per metric ton and calibrated to 1982-84 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 addition to net returns for each type of tillage, data were collected on production year, crop and location. Data are summarized in Table 2.

Aside from the regional indicators and the wheat dummy mentioned above, our meta-regression 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 meta-regression 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. 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 3. 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 μ_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 results is provided in Table 4 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 (IPCC, 2000; Kern and Johnson, 1993; Uri, 2001). While NT is an effective soil-conservation (soil carbon enhancing) strategy in many areas, in semi-arid regions where crop-fallow rotations are common, a switch to continuous cropping will conserve soil and increase soil carbon content (Antle and McCarl, 2002; Smith and Young, 1999). Tillage fallow is practiced in semi-arid 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) 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, while 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 meters.

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 (Salinas-Garcia et al., 1997; Dick, 1983; Doran, 1980; 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 (Yang and Kay, 2001; Yang and Wander, 1999; Dick, 1983).

The mechanism by which conventional tillage 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 no-till 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 5.

Virtually 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 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 extend, 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 meta-regression. Accordingly, a random effects specification with $\ln(C_{\mathrm{is,NT}} - C_{\mathrm{is,CT}})$ as dependent variable was chosen for this model. The regression results are provided in Table 6. 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 $\overline{Z}_2$ in equation (1) and thus renders the components of intra-study error μ_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. No-till 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 no-till 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) 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 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 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 50cm under NT (p. 765).

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 cm 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 7 where carbon sequestration is determined for depths of 25 cm 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/tC depending on region, crop grown, time land is in no till (not shown in Table 7), and depth of measurement. Clearly, situational factors impact 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 versus CT. High per-hectare 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 conventional tillage, 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 no-till 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 no-till may be exaggerated, and Six et al. (2002) found that N_2O emissions counteract the CO_2 savings that no-till 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, while 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 no-till 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 t C upwards, generally much higher than the at most \$35–\$110 per tC expected as a result of Kyoto’s flexibility mechanisms.

Endnotes

[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 years to the present no-till has been practiced on some fields for as long as 30 years.

[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, page 425.

[5] As indicated in Table 3, the null hypothesis of no intra-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 \$ t C^{-1} (Table 7).

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Table 1. Data Sources for Net Returns Information

Cost estimate sources				Mean returns/ hectare	
Source	Location	Study year	# observations	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	1993	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	1993	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	1990	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
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 number of articles: 52	Means	1990.25	10.5	$223.73	$209.65
Total number of observations: 536	Minima	1976	2	($55.13)	($113.08)
	Maxima	2001	48	$862.77	$851.80

Table 2. Variables, Means and Medians for Returns to Tillage Data (n=536)

Variable	Mean	Median
Returns to tillage (US$ / hectare)	$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.

Table 3. 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 US & 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 US & 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
σ_u	193.91
σ_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 hectare per year). 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

Table 4. Estimated returns of tillage and opportunity cost of NT[a]

Crop	Region	CT returns ($/ha)	NT returns ($/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.

Table 5. Summary of studies of soil carbon comparisons

Source	Main Location	Year data Collected	# obs	Mean stored Mg C/ 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
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 # of articles: 51	Means	1991.6	7.71	24.14	27.50	35.66
Total # of observations: 374	Median	1992	6	17.7	20.52	20
	Minima	1975	1	7.14	7.63	7.5
	Maxima	1999	30	101.35	105.22	200

[a] As quoted in Frye & Blevins (1997)

[b] Numbers in Campbell et al. (1995, 1996, 1999)

Table 6. 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 US & Canada (=1; 0 otherwise)	-0.032
	(-0.59)
Years under no-till 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
σ_u	0.10
σ_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)

Table 7. 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	∞[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 years of NT.

[b] Since the difference in the amount of soil carbon stored under NT versus 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.

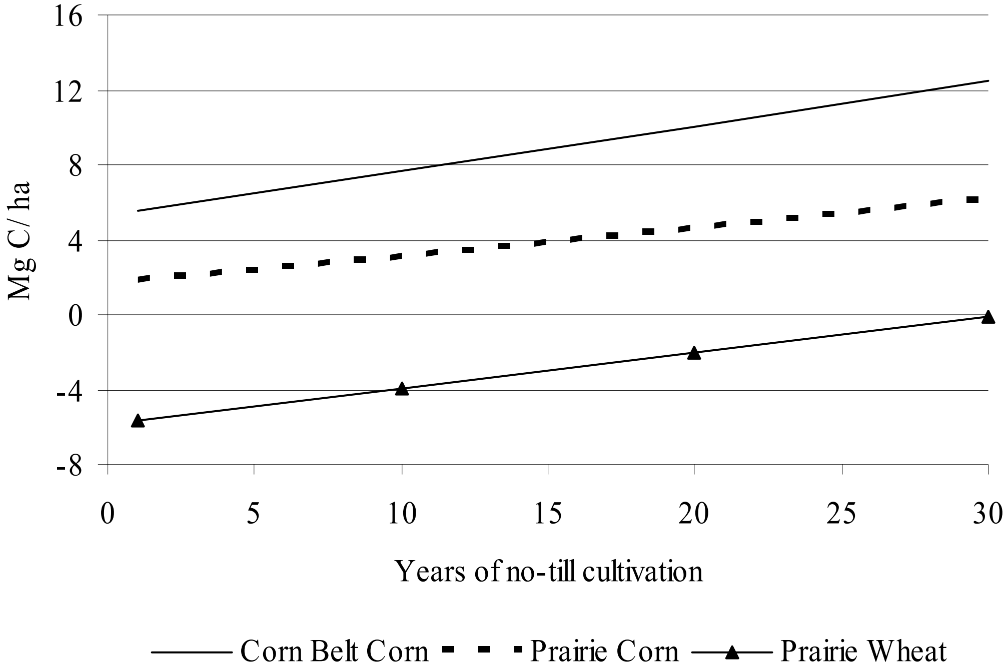


Figure 1. Carbon accumulation by NT over time based on 25 cm depth of measurement and planting in 1986.

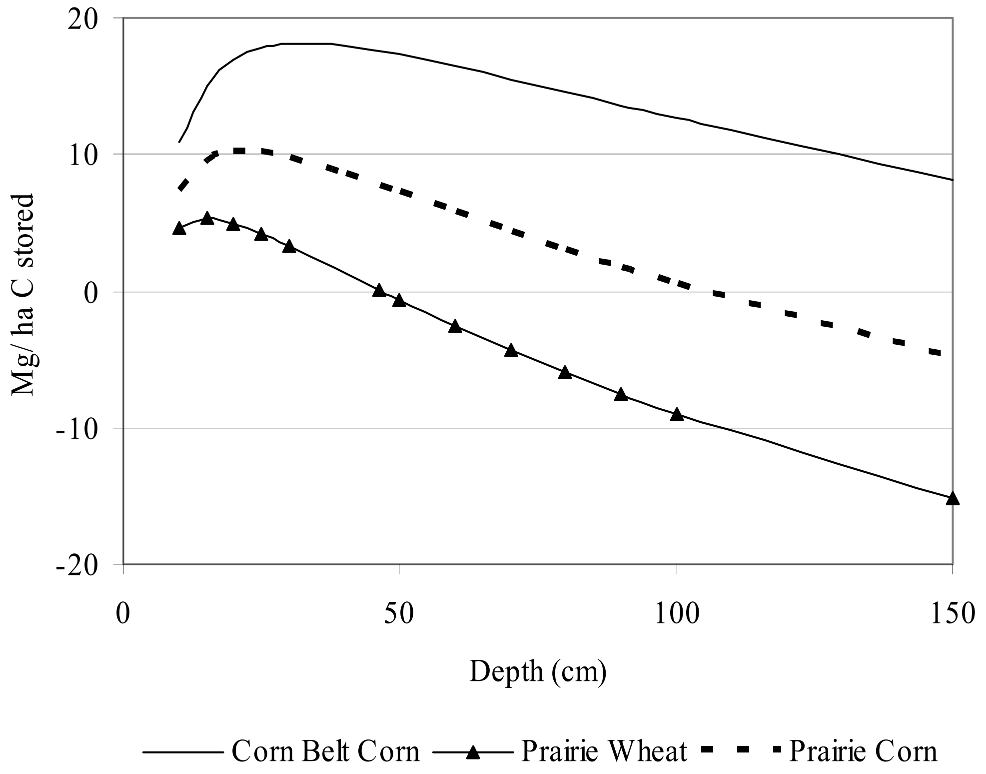
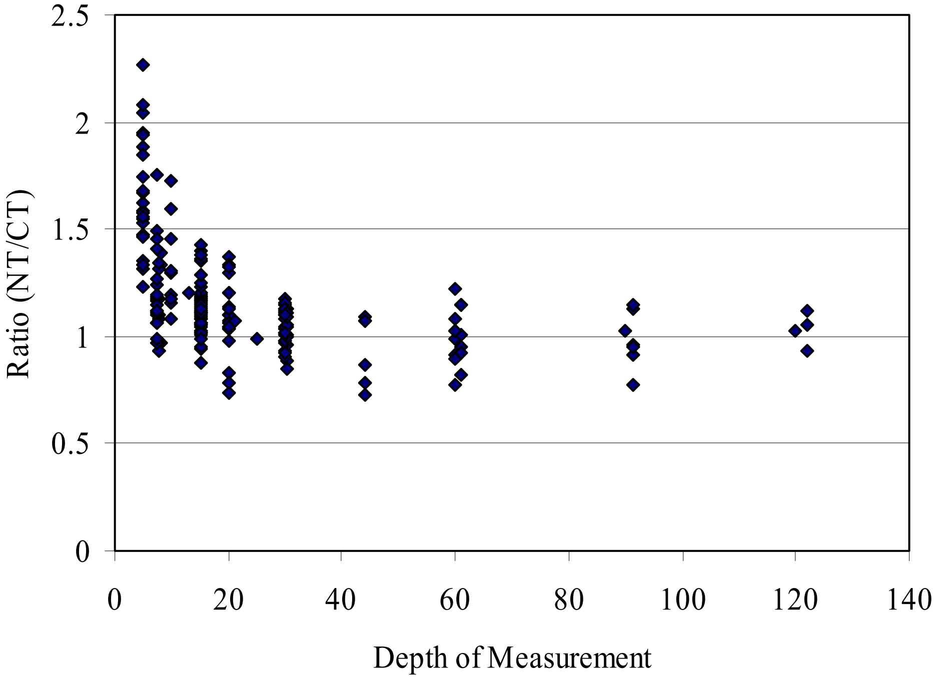


Figure 2. Amount of carbon stored by NT (relative to CT) over a range of depths of measurement assuming 30 years of NT.



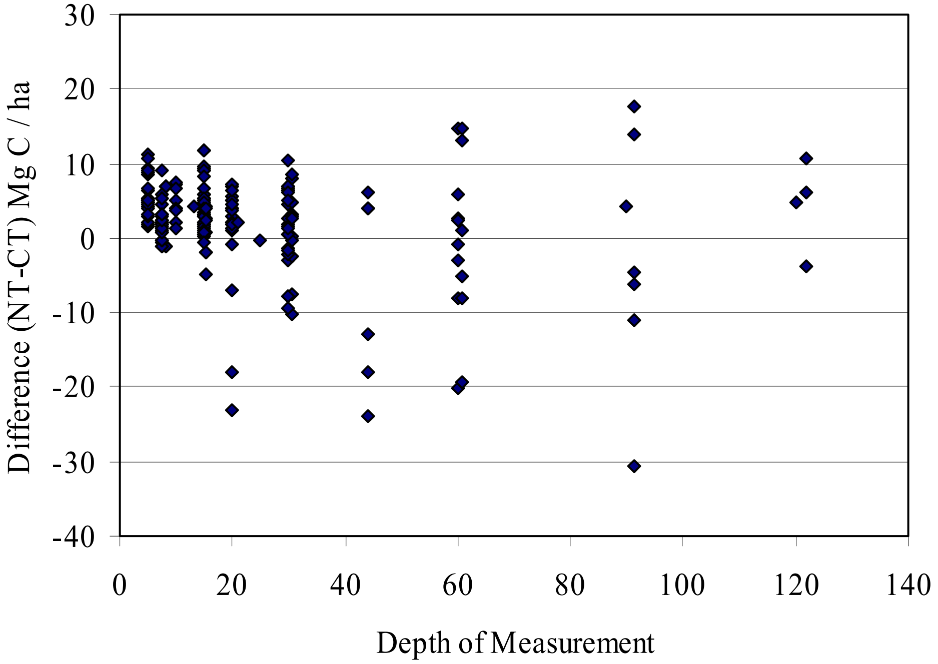


Figure 3. Comparison of Mass of Carbon Stored under NT and under CT for all data points (soil depth in cm)