Estimating Potential Economic Net Carbon Flux from U.S. Agriculture Using a High Resolution Integrated Socioeconomic-Biogeophysical Model.

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Abstract

Accurate estimation of the carbon abatement potential of a national carbon market upon U.S agricultural lands is needed by climate analysts, policy makers and carbon market organizers. A high resolution integrated socioeconomic-biogeophysical model is created by overlaying soils data and satellite land use data using GIS. The economic component of the model has been disaggregated to the county level, where, in each county, cropping activities have been expanded to include conventional tillage, reduced tillage and no-tillage operations.

The model is used to test changes in net carbon flux induced by conservation tillage incentives on existing U.S. cropland in the eight major crops. The maximum *technical* potential reduction in net carbon flux is estimated to be 34 million metric tons carbon (MMT C) below baseline. The *economic* potential reduction in net carbon flux at incentives below $500 per ton carbon is estimated to be 20 MMT C below baseline, and 14.6 MMT C at an offered incentive of $125 per metric ton carbon. These estimates are considerably less than previous estimations of carbon abatment in U.S. agricultural lands.

High resolution data indicate that the northern corn belt, Red River Valley and Mississippi Delta have the greatest economic potential for carbon abatement. Application of incentives based on gross soil sequestration potential leads to leakage in regions where land is reallocated from low input production to higher input carbon sequestering practices.

Introduction

Carbon sequestration in U.S. agricultural lands is moving from theoretical speculation and into actual implementation. The Chicago Climate Exchange is now paying farmers in some regions for their use of no-tillage practices that act to increase the level of carbon in soils. Currently, incentives are low and the market is small, but if the U.S. re-enters the Kyoto Protocol or legislates a similar cap-and-trade system for carbon emissions, incentives will likely increase rapidly. Many Congressional bills currently under consideration target the agricultural sector as a source of carbon offsets under proposed cap-and-trade programs (Branosky, 2007). Accurate estimation of the carbon abatement potential of a national carbon market upon U.S agricultural lands is needed by climate analysts, policy makers and carbon market organizers. A high degree of geographic resolution – in both economic and soil data – is essential for accurate estimation and in moving the market into national implementation.

Potential quantities of carbon that can be sequestered if all possible mitigating land use changes were enacted is referred to as *technical* potential sequestration. Nationally, potential technical quantities of carbon sequestration (from afforestation, cropland to pasture conversion and conservation tillage) have been estimated at as high as 207 million metric tons per year (Lal,1998). Other studies, using integrated economic-biogeophysical models have placed the *economically* feasible quantities far lower in the range of 7 to 70 million metric tons per year. This translates into U.S. carbon emission offsets as low as 0.5% or as great as 12%. The large range in estimations is due to differences in model design and scope, such as differences in payment structure and sequestration practices.

Knowledge of achievable abatement quantities and their corresponding costs will influence future policy choices, such as whether government agencies see it as worthwhile to subsidize market operation costs. Due to the heterogeneity of soil properties, climate, and management practices, a high degree of geographic resolution, in both economic and soil data, is essential in accurate estimation, and in moving the market into national implementation. Previous national studies have weighted economic and soils data within fairly large geographical regions. The accuracy of both technical and economic quantities can be improved by a major refinement in agricultural carbon modeling – the use and integration of the most disaggregated data available *with national coverage*.

Objective

The objective of our research is to estimate *net carbon flux* of US agricultural lands from changes in management practices induced through carbon incentives by making use of data with the highest degree of resolution available. We will use the model to test a national carbon program based on designs of regional carbon sequestration programs emerging today. We will employ geographically discriminating incentives to 'all adopters' on gross sequestration ability. The high resolution data will refine potential sequestration estimates, and account for regional changes in emissions and net carbon flux. Furthermore, the model will simulate annually for 20 years, allowing estimation of market evolution during the important short to medium term. This analysis will greatly improve both national and regional estimates, with consistent national coverage, of economic potential carbon abatement from incentive-induced changes in US agricultural management practices.

Previous studies have identified conservation tillage as the most promising of the sequestration alternatives. The current analysis will limit the scope to the impacts of conversion of cropland to conservation tillage through an incentive mechanism. Conventional tillage, reduced tillage and no-tillage of the eight major crops in the lower 48 states will be analyzed. Three primary results of this analysis will inform the policy process: 1) the amount of carbon, nationally, that can abated through incentives on conservation tillage, 2) regional areas of greatest abatement potential, and 3) a methodology for conversion of carbon price to regional incentive per acre.

Literature Review

Several studies have estimated the technical potential of soil carbon sequestration, which refers to the amount of carbon abated if proposed land management practices are adopted on all relevant lands. Lal et al. (1998) estimated 75-208 million metric tons carbon (MMT C) of potential soil sequestration from optimal adoption of conservation tillage, water management, improved pasture management, and land restoration. Follett (2001) estimated that if reduced tillage were widely adopted, fallow periods were reduced, cover crops were used on more acres, and production inputs were used more efficiently, then 30 to 105 MMT C per year could potentially be sequestered in U.S. soils. Sperow et al. (2003) estimates that up to 83 MMT C per year can potentially be sequestered through widespread adoption of best management practices.

Sperow et.al. find that adoption of no-till is the largest potential contributor of up to 47 MMT C per year. Potential soil carbon sequestration was estimated to be highest in the northern corn belt and Mississippi delta regions.

Technical potential quantities of carbon sequestration may not be reachable due to economic constraints. Adoption of proposed land management practices to meet ‘technical potential’ may mean producers would forgo more income than the new practices earn. Also, if incentives were offered, initial changes in land use may increase commodity prices and make further land-use changes too expensive. As in most markets, carbon sequestration will likely face increasing marginal costs, in which initial quantities of sequestered carbon may be realizable at low payment levels, yet further gains in sequestered carbon could only be made at higher incentive levels. For these reasons, several studies have analyzed the economic potential of soil carbon sequestration through the use of economic models. These models include the dynamic interactions of competition within crops for land use, along with the underlying demands from other sectors such as livestock, food and energy. While several economic studies have looked at carbon sequestration locally (Antle et al., 2001, Pautsch et al., 2001, Plantinga et al., 1999), only two have looked at the subject nationally (McCarl and Schneider, 2001, Lewandrowski et al., 2004).

McCarl and Schneider (2001) measure the economic potential of several mitigation strategies simultaneously including soil sequestration, afforestation and biofuel offsets in their ASMGHG model. They estimate that agricultural lands can sequester a maximum of 70 MMT of carbon though the use of changes in management at carbon prices below $500 per metric ton of carbon (MT C). McCarl and Schneider include conservation tillage, manure management and conversion of cropland to pasture within their defined category of land management. They do not consider transaction costs or discounting for impermanence, and only pay incentives to 'new adopters' (and also emissions taxes on management that result in higher emissions) -- therefore they consider their cost estimates as lower bounds. The study also accounts for changes in emissions from input use in estimating net abatement quantities. The ASMGHG model disaggregates the nation into 63 regions and 22 commodities and is solved for market equilibrium in 10 year iterations. Soil carbon data is aggregated to the regional level and the EPIC biophysical model is used to estimate sequestration quantities associated with crop and tillage types within the regions.

Lewandrowski et al. (2004) estimated 7 – 35 MMT of potential economic sequestration in agricultural lands below $125 per MT. Using the USMP model, which is a spatial and market equilibrium model similar to ASMGHG. USMP model disaggregates the nation into 45 regions and 10 major crops. For estimating changes in soil carbon, Lewandrowski et al. used the Intergovernmental Panel on Climate Change (IPCC) methodology developed as a first order approach to estimating soil carbon changes. The initial soil carbon levels were derived from weighting 1997 National Resources Inventory (NRI) data points to ten farm production regions. IPCC parameters for changing from conventional tillage to no-tillage and from conventional tillage to reduced tillage were applied to the initial carbon levels to arrive at the net change in soil carbon. Lewandrowski et al. model a complex assortment incentive program design through four scenarios. The scenarios investigate farmer response to rental payments versus full asset value (permanence assumption), payment of only incentives versus the additional of taxes on emitting management practices, and paying farmers some of the 'cost share' of conversion to alternative practices versus requiring farmers to bear the full burden of conversion. Scenario two is most similar to the modeling framework reported in this paper, with full asset payment (assume carbon sequestration is permanent). In scenario two, 27.6 MMT of carbon are estimated to be abated at $125 per ton carbon.

Methodology

The analytical tool used to conduct this analysis is an integrated socioeconomic-biogeophysical model. The integrated model will use economic and soil data at the highest degree of resolution feasible in order to improve regional estimation. The economic heart of the model is a modified version of POLYSYS, which is a partial equilibrium displacement model which iterates annually and simulates until the year 2025. This version of POLYSYS has been disaggregated to the county level, where, in each county, cropping activities have been expanded to include conventional tillage, reduced tillage and no-tillage operations. Baseline acres for each tillage type are derived from trends in Conservation Technology Information Center survey data (CTIC, 2002). Tillage yields are based upon National Agricultural Statistic Service county averages and extrapolated to tillage yield by meta-analysis of regional tillage experiments (NASS, 2007). The model will make use of over 3,000 regional crop budgets which are based upon regional differences in crop operations. Both direct and indirect use of energy and emissions of carbon are tied to each input of the operation budgets, therefore the model can simulate net flux of carbon.

Carbon net flux is a result of both changes in soil carbon *and* changes in carbon emissions from inputs. Since some carbon-sequestering management operations emit less emissions, there could be considerably greater potential amounts of net carbon reductions than if only accounting for soil carbon. The linear programming model allows for changes in soil carbon to be integrated into the incentive system itself. Additionally, the linear program design will allow for the accounting of domestic leakage in the agricultural carbon market. Leakage is defined as the unintended *increase* in atmospheric carbon as a result of policies to *decrease* atmospheric carbon.

Biogeophysical data on soil type and the ability of each crop type to sequester carbon upon each unique soil will be integrated into the model through the overlay of regional carbon management response curves (West et al., 2003), STATSGO soils regions (USDA, 1994) and Landsat land use cover data (Vogelmann, 2001). The carbon management response curves give the percentage change in carbon per year of a particular management practice. STATSGO data gives initial soil carbon at the MUID (soil map unit ID) level. And Landsat data tie crop acres to soil type at the 30x30 meter resolution, which will allow us to know what soils each field is grown upon. The accuracy of carbon accumulation is greatly improved by this methodology. The biogeophysical module will allow for estimation of the annual amounts of carbon that a particular crop in a particular county under a particular tillage-type can accumulate. The annual carbon changes will be mapped at the 30x30 meter resolution. A schematic of data layer integration is given in figure 1.

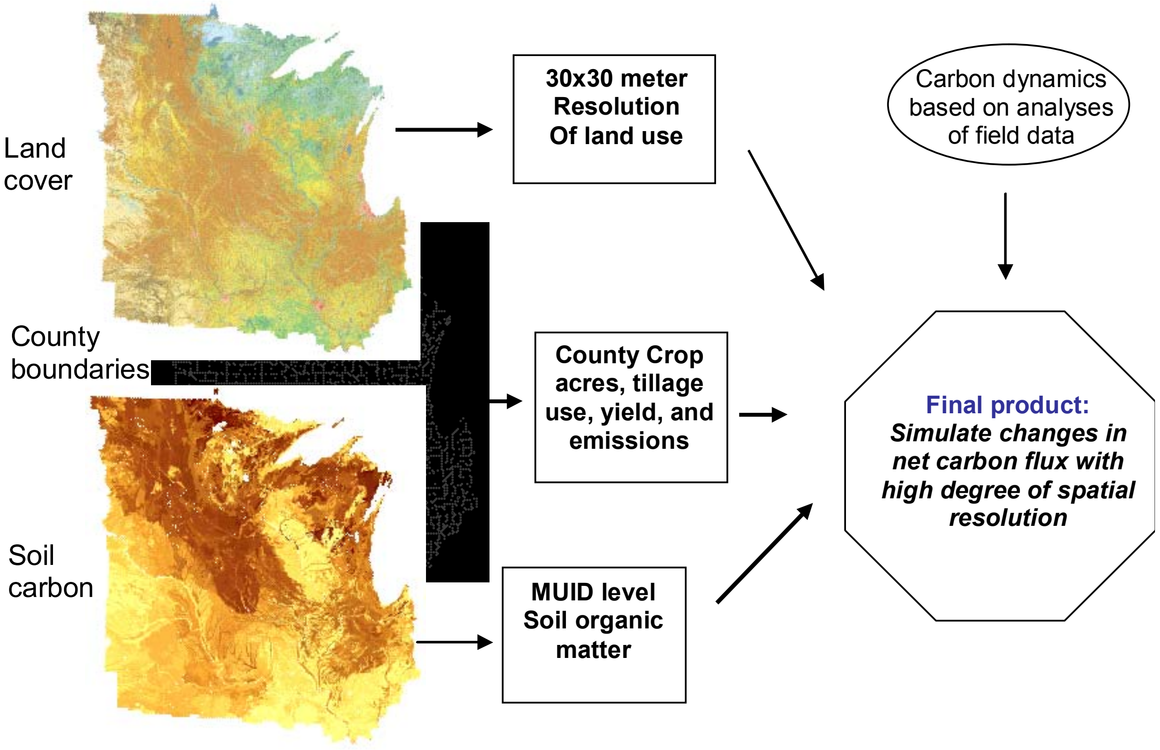

Figure 1. Depiction of methods for integrating county level crop and tillage data with higher resolution land use and soils data.

Core Socio-Economic Model

The socioeconomic modeling component of the analysis will be based on University of Tennessee's Policy Analysis System model (POLYSYS; De La Torre Ugarte and Ray 2000, Ray et al. 1998a). POLYSYS is a theoretically rigorous model which is capable of estimating annual changes in land use and crop prices associated with changes in yield and management practices in the United States (De La Torre Ugarte et al. 1998, Ray et al. 1998b). The POLYSYS modeling framework can be conceptualized as a variant of an equilibrium displacement model (EDM). The general appeal of EDMs is in part due to the inherent ability to complete modeling exercises in a wide variety of market structures (Piggot et al. 1995, Wohlgenant 1993, Brown 1995, Kinnucan 1996).

POLYSYS anchors its analyses to U.S. Department of Agriculture (USDA) published baseline of projections for the agriculture sector. USDA 10 year baseline projection period has been expanded endogenously through 2025 for this analysis. Changes in agricultural land use, based on cropland allocation decisions made by individual farmers, are primarily driven by the expected productivity of the land, the cost of crop production, the expected economic return on the crop, and domestic and world market conditions. By providing POLYSYS with data for production inputs, changes in yields and incentive levels that would accompany carbon management options, we can estimate potential changes in land-use.

Crops currently considered in POLYSYS include corn, grain sorghum, oats, barley, wheat, soybeans, cotton, rice, and hay. For this analysis, the decision making linear programming model (LP) is moved from the Agricultural Statistic Area to the county level, and the activities in each regional LP model are expanded to include conventional tillage, reduced tillage and no-tillage of each crop. By combining historical data from the National Agricultural Statistics Service on crop acreage and the Conservation Tillage Information Center (CTIC) on tillage use, 'base' county level acres of each crop and tillage regime are estimated. The base county acres are then adjusted to sum to USDA national baseline projections. In the LP models, each crop and tillage type combination is a unique *activity*, with a corresponding net present value for evaluating relative profitability. Nine crops and three tillage operations sum to a possibility of 27 unique activities in each county. In every simulation, POLYSYS iterates through 3111 counties, solving for the optimal linear programming solution in each county.

High Resolution Data

To increase spatial accuracy of the county level crop and tillage data, we superimpose National Land Cover Data (NLCD) on State Soil Geographic (STATSGO) data. NLCD is derived from early 1990's Landsat Thematic Mapper satellite data and has a spatial resolution of 30 meters. The NLCD is available for the conterminous U.S. and represents 21 land cover/use classes. Subclasses under the planted/cultivated classification include pasture, row crops, small grains, fallow, and urban/recreational grasses. For this analysis, subclasses row crops, small grains and pasture will be assigned specific crop types as indicated by the NASS data for the respective county. One spatial polygon may be assigned more than one crop type, in which case there will be a percentage value representing the percent area associated with each crop type. State Soil Geographic (STATSGO) database regions (MUID's) will overlay the above. MUID regions will have an associated base carbon level. Using this method the base soil carbon level and land use will be known for all cropland within each county. We estimate a national weighted average base carbon level on agricultural lands of 13 MT per acre.

By combining and overlaying NASS, CTIC, NLCD and STATSGO data we arrive at polygons (made up of 30x30 meter land use at its smallest units) with unique combinations of land use – tillage type – carbon level. More spatially explicit estimates of base carbon level are figured by distributing county crop acres to the land use polygons. For example, in Figure 2, we have a simplified situation where there are row crops and small grains within one county boundary. The overlay of NLCD and STATGO indicates that all small grain acres are grown on Soil B with only 5 tons per acre base carbon. The data also indicate that row crops are grown on both Soil A and B, with the majority in Soil B. The county acres of row crops would then be distributed to these base soil regions by the ratio of area in each determined by the overlay. This methodology allows more precise determination of 'base carbon' for each crop type within the county, that will then be used to calculate estimation of sequestration ability.

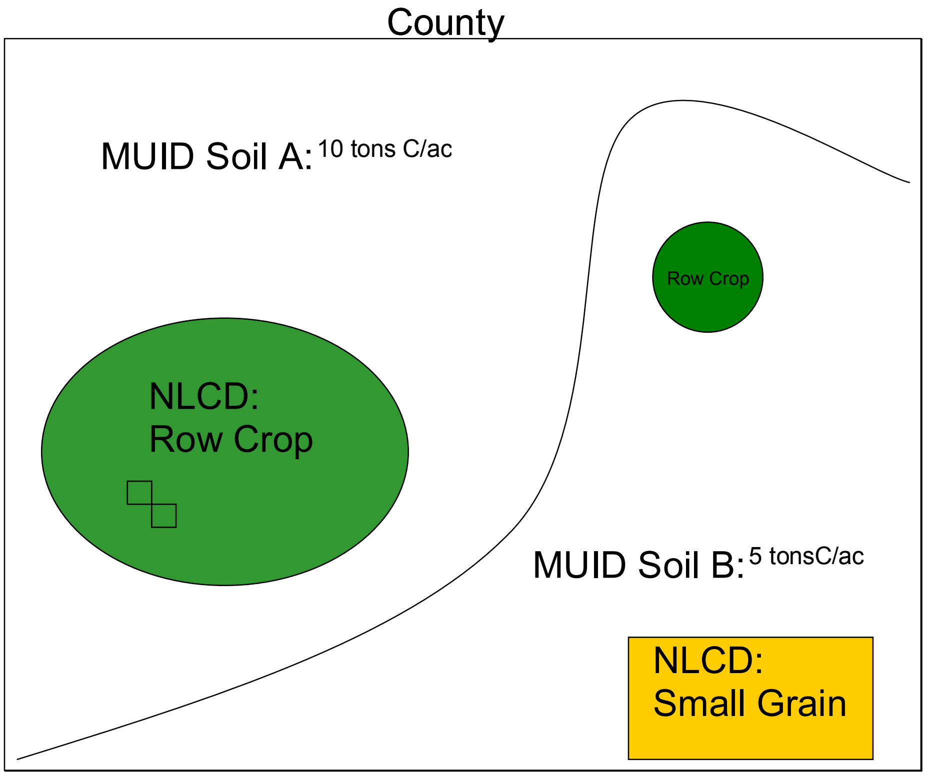

Figure 2. Locating County Crop Acres in Soil Type: Two soil MUID regions are overlaid on one county, Soil A and Soil B. NLCD landuse is also overlaid. Green row crop lands and brown small grain lands are identified and the soil underlying them are known.

Integrating Soil Carbon Dynamics

West and Post analyzed results from 67 long-term tillage studies on different soils nationally, consisting of 276 paired treatments. (West and Post, 2002). Carbon Management Response (CMR) curves were estimated for every major crop and rotation within the US, where the rate of sequestration varies annually until the new steady state is reached. From a carbon accounting perspective, CMR curves are useful in their ability to be serially connected to represent changes in soil carbon following multiple changes in land use.

Within this research, linear approximations of CMR curves will be applied to nine crop types (i.e., corn, soybean, wheat, sorghum, oats, barley, cotton, rice, and hay). The percentage change in soil carbon estimated by the CMR curves will be applied to a base map of soil carbon for the U.S. The soils base map is derived by taking the weighted average of the percent soil carbon and soil bulk density values for each region in STATSGO which yields estimates of volume of soil carbon for every STATSGO region (USDA 1994).

Estimating Budgets and Emissions

For the current analysis we have expanded the University of Tennessee's Agricultural budgeting system to cover over 3,500 conventional and alternative management scenarios representing baseline agricultural practices associated with specific regions of the U.S. Farm operations, inputs and costs have been updated and include regional budgets for conventional-till, reduced till and no-till for the major crops in the 305 Agricultural Statistic Districts (ASD). All counties within the ASD's are assumed to have the same operation budgets, but different yields. Operation budgets include labor time, machinery use, and all input quantities. Budget methodology is consistent with American Society of Agricultural Engineers (ASAE) standards for fuel quantities and labor time, and the American Agricultural Economics Association (AAEA) standards for all costs.

To estimate net carbon flux, and not simply soil carbon change, carbon emissions from the operations must be accounted for in the analysis. Both direct and indirect emissions are estimated and tied to each unique crop budget in POLYSYS. Direct carbon include emissions from the use of fuel on farms, carbon equivalent emissions for field decomposition of ammonia and lime. Indirect carbon, or embodied carbon, include emissions from from the processing, manufacturing and transportation of seeds, fertilizers, and chemicals applied to the field.

Projection of Tillage Trends for Baseline Estimation

Baseline simulation projects historic tillage trends forward in time. Analysis of tillage trends indicate that a significant structural shift occurred in 1996, after which the acres of reduced tillage remained steady, and the rate of adoption of no-tillage decreased. In this analysis, trends from 1996 through 2004 will be projected at a 50% lesser rate, at the state level, to the year 2025.

In the baseline case, 32 percent of U.S. cropland is in reduced tillage and 33% percent is in no-tillage by 2025 (up from 25% in 2006). Total uptake of carbon by U.S. soils increases from the current level of 18.7 MMT per year to 21.9 MMT per year by 2025. The change in soil uptake of 3.24 MMT C per year is offset by an increase in carbon emissions over the baseline period. The major cause of emission increases is the addition of 5 million acres of land into production by 2017, as projected by USDA baseline trends. In spite of conversion of lands to lesser emitting conservation-tillage regimes, total emissions from agriculture increase from 143.7 MMT per year to 149.2 MMT per year, and total net flux increases to 127.2 MMT per year by 2025 (table 1). All incentive induced changes in atmospheric carbon reported in the results section are divergences from this calculated baseline.

Table 1. Baseline Changes in Atmospheric Carbon through Projection Period as a Result of Agricultural Soils and Emissions (MMT C per year).

	2006	2025	Change
U.S. Agricultural Soils*	-18.70	-21.94	-3.24
Emissions			
Direct	105.61	109.16	3.55
Indirect	38.08	40.00	1.93
Total	143.68	149.16	5.48
Total Net Flux	124.99	127.22	2.24

* Assuming all land in conservation tillage is still accumulating carbon

Note: Negative values correspond to reduction in C emissions to the atmosphere.
Positive values correspond to increase in C emissions to the atmosphere.

Simulation

In the current analysis, our intention is to investigate carbon program implementation that is most similar in form to the emerging carbon trading markets – which is to pay 'all adopters' of tillage practices an incentive, and not only 'new adopters'. Furthermore, to arrive at an upper bound estimate of abatement potential, we assume permanent sequestration and give farmers the full asset value of carbon price (there is no discounting or transaction costs assumed).

The regional incentive level will be based upon ‘gross-sequestration’ potential, or the ability of the soil to uptake carbon from the atmosphere. The other option would be to apply the incentive to ‘net flux’ potential, which is the net amount of carbon reduction that occurs when both changes in soil uptake and emissions of C are totaled. Payments based on gross sequestration rather than net flux can cause leakage to occur through lands switching from conservation to conventional tillage. Although we employ a gross-sequestration based incentive, the majority of leakage is avoided due to payments going to ‘all adopters’. Lands already in no-tillage will not likely switch to conventional tillage. Leakage will still occur, through conversion of land to higher emitting crops, but by paying all adopters a major source is avoided. Once again, this implementation of the model is to estimate the upper bound potential of carbon abatement of a carbon program most similar to those emerging.

To do this, incentive levels are exogenously introduced to the modeling framework to trace the marginal supply curve. A particular carbon incentive level will add to the net present value of each unique crop, tillage and county combination depending upon each activity’s estimated ability to sequester carbon. Once again, each activity’s ability to sequester carbon is dependent upon a) the type of crop, b) the type of tillage, and c) the quality of soils it is grown upon. The conversion of national ‘per ton’ incentive to county and crop specific ‘per acre’ incentive can be written as:

$$\mathrm{Iacre}_{i,j} = C_{i,j} * \Delta_j * \mathrm{Iton}_{nat}$$

Where,

$\mathrm{Iacre}_{i,j}$ = carbon incentive ‘per acre’ in county i, for crop j ($ per acre).
$C_{i,j}$ = base carbon level in county i, for crop j (tonnes per acre).
Δ_j = change in carbon level per year of crop j, under tillage t.
Iton_{nat} = national incentive level ‘per ton’ of carbon ($ per ton).

The new net present value landscape will change the optimal solution within the linear programming models, and the incentive has acted to change crop and tillage mix both regionally and nationally. The new crop and tillage mix will act to sequester more carbon than in the ‘baseline’ case. Additionally, emissions may increase, through the use of more energy intensive chemicals, or decrease, through the use of less tractor operations. Net flux of carbon will be calculated and compared to the baseline scenario to reveal the total reduction in atmospheric carbon at the particular incentive level.

Estimated Carbon Price

There is wide variation in estimates of potential carbon price if the U.S. were to begin regulating carbon emissions. Currently the U.S. is not part of the Kyoto Protocol and polluters of CO_2 are under no obligation to reduce emissions. All carbon trading at the Chicago Climate Exchange (CCX) is completely voluntary. CCX carbon price is around \$5 to \$10 per metric ton of carbon. In Europe, pre-Kyoto carbon prices have hovered in the range from \$20 to \$30 per metric ton (Kyoto regulations take effect from 2008 to 2012). Canada's Tory government estimated that it will take a carbon tax of \$195 per MT C to allow Canada to meet its Kyoto obligations (CTV.ca News, 2007). Sweden instigated a \$100 per MT C tax in 1991 and raised it to \$150 per MT C in 1997 (Brannlund,1999). In testimony before the U.S. House of Representatives Ways and Means Committee, Schneider stated that their research estimated a typical shadow price of \$200 per metric ton C to keep atmospheric carbon concentrations from more than doubling (Schneider and Mastrandrea, 2005). If the U.S. were to decide to reduce carbon emissions, we believe a carbon price of around \$125 per MT C is foreseeable. This analysis will estimate abatement responses from carbon incentive levels ranging from a very low level of \$12.5 per MT C up to a high estimate of \$500 per MT C, with \$125 being the analytical focal point.

Results

National Carbon Net Flux Supply Curve

Supply estimates at given incentive levels are much lower than in previous studies. If all cropland was switched to no-tillage, total carbon abatement *technical* potential reaches 56 million metric tons per year in 2025, which is 34 MMT above baseline. Incentives were increased up to \$500 per ton of carbon to reach the upper bounds of *economic* potential carbon abatement, which reaches 20 MMT above baseline by 2025. Soil carbon uptake accounts for 16.2 MMT C, and reductions in emissions contribute another 3.88 MMT to total atmospheric carbon reduction. The brown curve depicted in Figure 3 indicates the additional soil carbon above baseline that would be sequestered at given incentive levels. The green curve indicates the total reduction of atmospheric carbon from both soil sequestration and changes in agricultural emissions. Both curves increase at a fairly constant rate up until the \$125 per MT, after which further gains in abatement come at increasing marginal cost. At $125 per MT C incentive level, we estimate 14.6 MMT C can be abated by changes in tillage practice on U.S. agricultural lands. As incentives increase, the distance between the soil carbon and total abatement curves increase due to induced changes from higher emitting tillage practices to lesser emitting practices. Also, analysis of results indicate that leakage, caused by switching from low emission practices to higher emitting practices, is more of a problem at lower incentive levels.

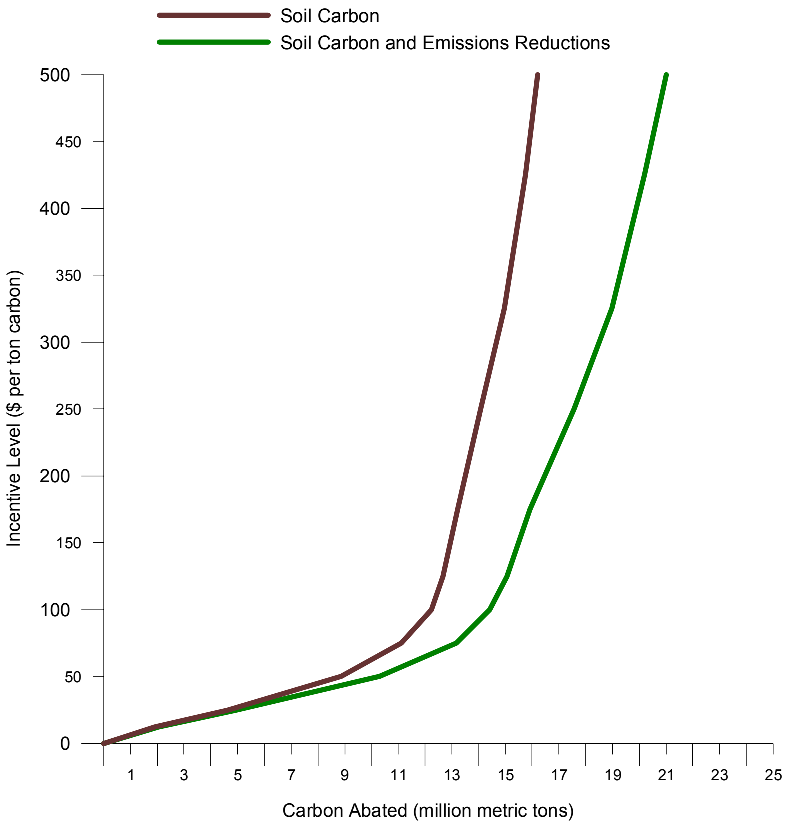

Figure 3. Carbon Abatement Supply Curve with Soil Carbon Changes and Total Carbon Changes Induced by Carbon Incentive by 2025.

An incentive of $50 per MT C is estimated to induce an increase of 8.86 MMT C in soil sequestration, a decrease of 1.17 MMT C in emissions, and a total net flux reduction of 10.03 MMT C (table 2). As incentives increase and land is put into conservation tillage, direct emissions from tractor operations decline. Indirect emissions slightly increase due to higher chemical usage in no-till operations. At the upper bound scenario of $500 per MT C incentive, conversion of cropland to conservation tillage results in a total reduction of 20 MMT C per year from the atmosphere below baseline projections.

Once again, in this analysis, not only new adopters, but all adopters are paid the incentive. Two separate assumptions of costs per MT are reported in table 2. The “All” category reports the marginal cost if all conservation tillage lands are assumed to still be accumulating additional carbon annually. The “New” category reports the marginal cost if it is assumed that only newly converted lands are still accumulating carbon. Total program costs at $125 per MT C are estimated at $4.33 billion, which is $118 per MT of net carbon flux reduction under the “All” assumption. The cost per MT C are slightly lower than the incentive levels due to the additional savings generated by net reductions in emissions, which were not accounted for in the setting of regional incentive levels. If we assume that, by 2025, it is most likely that lands already in conservation tillage in 2006 will have reached their carbon maximum and are no longer increasing in soil C, then estimated marginal costs are much higher. In this case, land in conservation tillage will be receiving payments regardless of whether they are still accumulating soil carbon or not. At $125 per MT C, new carbon abatement costs are estimated at $242 per MT C.

Table 2. Incentive Induced Changes in Atmospheric Carbon and Program Costs.

	Change Atmospheric Carbon (MMT) from Change in				**Abatement Cost**		
Incentive $ per ton	Soil Carbon	Direct Emissions	Indirect Emissions	Total Net Flux	Total Mil $	$ Per Tonne All*	New*
$0	0.00	0.00	0.00	0.00	$0	$0	$0
$12.5	-1.91	-0.15	0.01	-2.05	$298	$12	$56
$25	-4.62	-0.33	0.02	-4.93	$664	$25	$81
$50	-8.86	-1.24	0.07	-10.03	$1,540	$48	$116
$75	-11.12	-1.76	0.09	-12.79	$2,479	$71	$155
$125	-12.67	-2.09	0.12	-14.64	$4,327	$118	$242
$250	-14.08	-2.99	0.18	-16.89	$9,005	$232	$447
$500	-16.20	-4.16	0.28	-20.07	$19,069	$454	$818

* the incentive program simulated pays ALL adopters, not only the new adoptors

"All" costs assume that all conservation tillage acres are still gaining soil carbon.

"New" costs assume that conservation tillage acres in practice from more than 20 years are no longer gaining carbon.

In the baseline case, by 2025 34% of total acreage in the eight major crops is in conventional tillage, 32% in reduced tillage and 33% in no-tillage. At an offered incentive of $125 per MT C, no-tillage practices are estimated to increase by 64 million acres to account for 54% of total acreage (table 3). At $500 per MT C, 107 million acres are estimated to switch to no-tillage to account for 68% of total acreage. Converted pasture to cropland does not receive the incentive, therefore total acreage does not increase in simulations.

Table 3. Acreage Changes Induced by Carbon Incentive (mil acres) by 2025.

Incentive $ per ton	Conventional tillage	% of Total	Reduced tillage	% of Total	No-tillage	% of Total
		34%		32%		33%
$12.5	-4	33%	-2	32%	6	35%
$25	-10	31%	-4	31%	14	38%
$50	-27	25%	-7	30%	34	45%
$75	-41	21%	-9	29%	51	50%
$125	-51	18%	-12	28%	64	54%
$250	-58	15%	-21	25%	80	59%
$500	-68	12%	-38	20%	107	68%

In most regions and crops, reduced-tillage has the highest yield, followed by conventional tillage and then no-tillage. As acres switch out of conventional and reduced tillage and into no-tillage, total production declines and prices rise. Table 4 reports the price changes of the four major commodities through the simulation period at $125 per MT carbon. Most price increases are no greater than three percent. New lands do not come into production for several reasons: First, we are using 2007 USDA baseline projections which already assume that over 10 million acres of idled cropland comes into production to meet increased ethanol demand. Therefore, most of the readily convertible idle cropland is already in baseline production. Second, since converted pastureland would not be accumulating soil carbon, it is assumed that converted pastureland does not receive incentives. And third, without incentives, the relatively small price rises listed in table 4 are not significant enough to bring other lands into production.

Table 4. Change in Prices Though Simulation Period at $125 per ton Carbon.

	2010	2015	2020	2025
Corn				
Baseline	3.55	3.35	3.37	3.19
Simulation	3.67	3.4	3.45	3.29
% Change	3.4%	1.5%	2.4%	3.1%
Soybeans				
Baseline	7	6.75	6.68	6.46
Simulation	6.91	6.77	6.77	6.56
% Change	-1.3%	0.3%	1.3%	1.5%
Wheat				
Baseline	4.35	4.55	4.42	4.31
Simulation	4.48	4.66	4.55	4.44
% Change	3.0%	2.4%	2.9%	3.0%
Cotton				
Baseline	0.57	0.56	0.616	0.621
Simulation	0.573	0.563	0.621	0.626
% Change	0.5%	0.5%	0.8%	0.8%

Regional Estimates

Figure 4 shows changes in soil carbon level per acre from baseline in 2025 at the $125 per MT C incentive level. The greatest gains in carbon per acre are estimated to be in the northern plains. Higher initial soil carbon in these regions allow for larger gains in soil carbon. Also, conversion of haylands in Minnesota, Wisconsin, Michigan, and New York to no-till allow greater accumulations of carbon per unit of area. Parts of Texas and the Mississippi Delta accumulate large amounts of *total* carbon due to large-scale conversion to no-till. This occurs, in spite of a somewhat lower ‘per unit area’ sequestration rate. Smaller and more dispersed gains in soil carbon occur in all agricultural regions of the U.S.

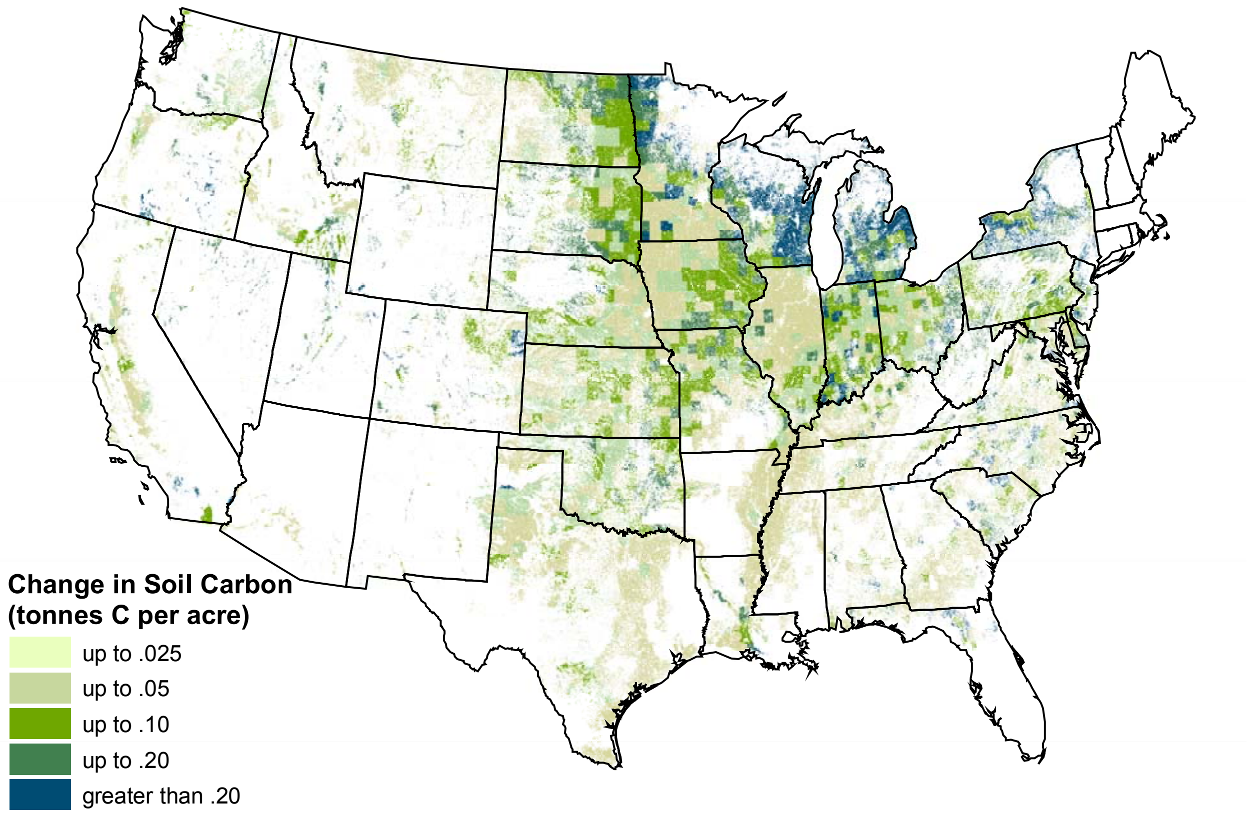

Figure 4. Change in Soil Carbon at $125 per metric ton: Average per acre in 2025.
* Although estimated at the sub county level, county level weighted averages are shown here due to current data limitations in mapping.

Net Emissions changes per acre, depicted in figure 5, show that an incentive program can have mixed results. Farm operations and inputs cause emissions of carbon, and changes in crop and tillage types can lead to net changes emissions. In the majority of regions, such as the Red River Valley, Mississippi Delta and Ohio, increased conservation tillage is estimated to lead to net decreases in emissions. Yet in other regions, such as central Illinois and west Texas, increased no-tillage comes at a cost of increased emissions. No-tillage operations emit less directly, due to fewer tillage operations, but emit more indirectly due to increased chemical usage. In general, the net outcome is a drop in emissions when switching to no-till. But the mix of cropland is not static. Incentives to higher-sequestering crops act to pull land out of some crops and into others. For example, corn sequesters more carbon than wheat per year per acre, but the process of growing corn can be a much larger emitter of carbon than wheat. As a result, in some regions (red in figure 5) net emissions per acre actually increase.

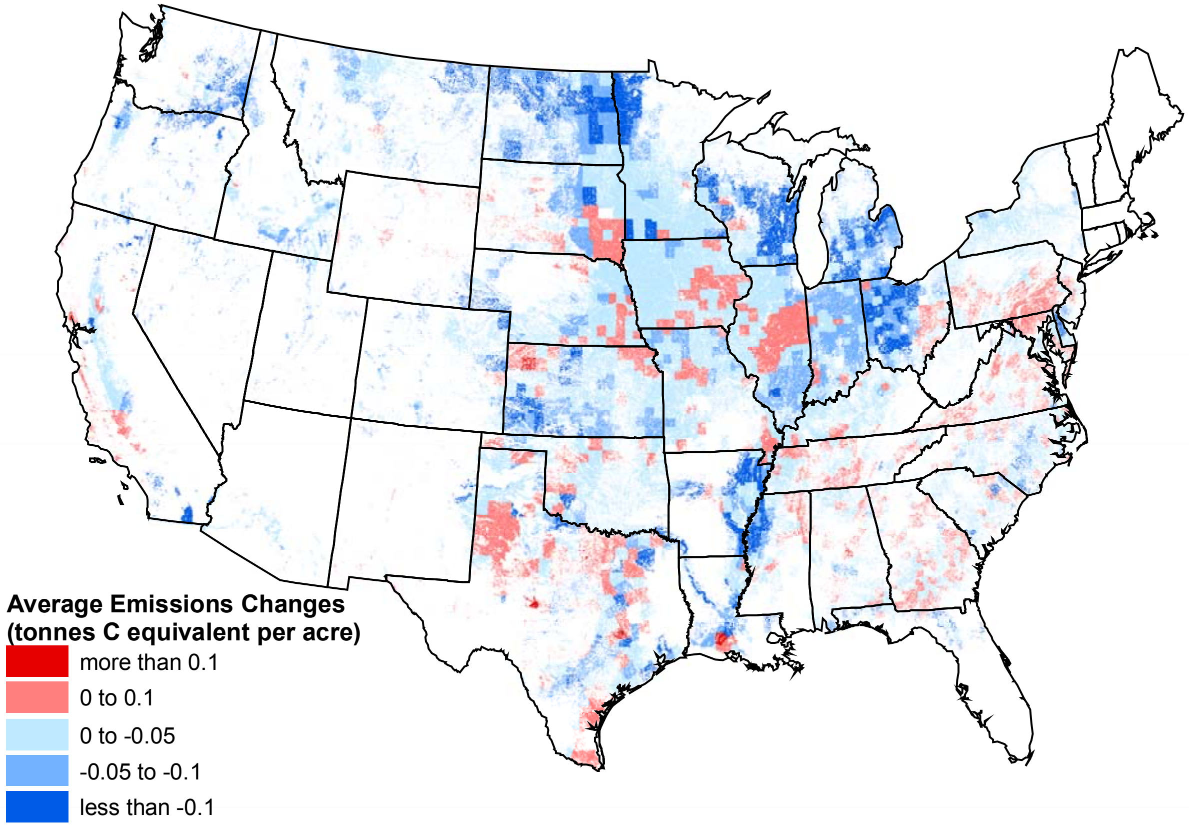

Figure 5. Changes in Emissions at $125 per metric ton: Average per acre in 2025.

Net carbon flux is defined as the net amount of carbon emitted by farming an area of land when both changes in soil carbon and input emissions are accounted for. Because total agricultural emissions far outweigh total soil sequestration, the beneficial effect of a carbon incentive will be to reduce the net flux of carbon. Regional net carbon flux as a result of an incentive of $125 per MT C is shown in figure 6. Here, we see that, in most regions, increases in soil carbon are enough to outweigh any increases in net emissions to result in a net reduction in carbon flux to the atmosphere. Yet in some regions, such as central Illinois, and parts of Texas and Georgia, the increase in emissions is greater than the countering increase in soil carbon, therefore the program acts to increase the net flux of carbon to the atmosphere. This is an unintended leakage caused by the incentive program targeting soil sequestration ability. Nationally, at $125 per MT C, there is 1.06 MMT of leakage.

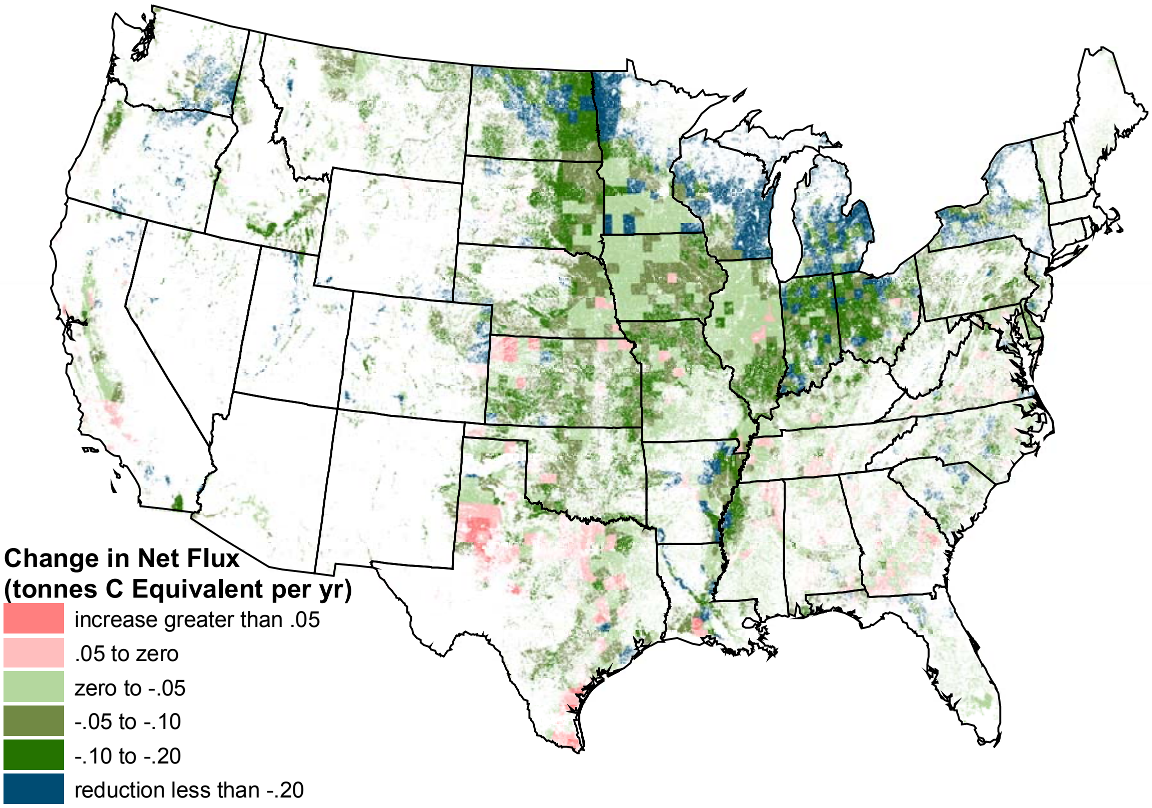

Figure 6. Change in Net Carbon Flux at $125 per metric ton: Averages per acre in 2025.
* although estimated at the sub county level, county level weighted averages are shown here due to current data limitations in mapping.

Conclusions and Discussion

The results of our analysis indicate a maximum technical potential of 34 MMT C above baseline. Economic potential reaches 20 MMT C per year above baseline at incentives lower than $500 per MT C. At this maximum level, a national program to sequester carbon in agricultural soils would reduce total projected U.S. carbon emissions by less than 1%. At $125 per MT C, we estimate that 15 MMT of carbon can be abated per year by 2025. Although soil carbon sequestration will not likely be a major solution to solving the carbon problem, some regional potential abatement quantities are estimated to be quite high. If the U.S. does legislate a cap and trade system to seriously reduce carbon emissions, it may act to further expand the already emerging soil carbon trading markets. In this analysis, we assume the basic payment structure of current trading markets ($ per tonne of soil sequestration potential paid to all adopters), but apply more regionally precise estimates of soil sequestration potential.

Results indicate that the Red River Valley, Mississippi Delta, and northern corn-belt have the highest potential to reduce net flux. In most regions, payment on gross sequestration yields an added benefit of reduced carbon emissions, as higher emitting conventional tillage is replaced with lower emitting no-tillage. Although the program is only paying for soil carbon increases, it also acts to reduce net carbon flux, for free, via net emissions reductions. Yet, in some regions, unintended increases of net carbon flux, or leakage, occur. The primary cause of leakage in some regions is due to incentives rewarding practices with higher emissions. Some practices that act to sequester large amount of carbon in soil also emit large amount of carbon through input use (no-till corn). Leakage occurs when acres are pulled out of lesser emitting crops and put into higher emitting crops, and the increase in soil carbon is not enough to offset the increase in emissions.

Nationally, the results of the analysis are considerably less than previous estimates (McCarl and Scheider, Lewenowski et.al.). There are several possible reasons for the lower estimate: a) differences in key parameters, such as 'base carbon' or 'rate of carbon growth' at the sub-county level may reduce incentives on lands with less carbon potential, b) other analyses include other management options besides conservation tillage, c) leakage in the current model implementation lowers total abatement potential, even with payment to 'all adopters', d) the baseline projection of tillage trends lessens the amount of net potential gain in carbon, and e) there may be differences in estimated regional budgets of the management options.

Once again, the purpose of the current analysis is to test national implementation of a carbon market that is simple in design, and similar to the newly emerging regional carbon markets. Due to many complications and program costs discussed in the literature of soil carbon sequestration (Paustian et.al., 2006, Pautsch, et.al.,2001), implementation of a national carbon program may have to be done in a simple manner of paying 'all adopters' on gross carbon sequestration ability. Paying all adopters on gross sequestration ability is simple, but has two major deficits. The first one being that some of the conservation tillage acres have been in practice for more than 20 years and may already have reached a steady-state carbon level. If so, the program is paying these farmers for carbon they are not sequestering. If the assumption is made that these older conservation acres are no longer sequestering additional carbon, this has the effect of increasing costs per ton by a factor of 1.0 to 4.5. These costs need to be weighed against the extra costs of the alternative policy design, such as only paying new adopters and penalizing conversion of conservation tillage to conventional tillage. The additional costs of paying early adopters of conservation tillage may be considered a cost of market implementation.

For the short to medium term, these extra costs may be worth the carbon gains and savings in program complexity.

The other deficit of the simple carbon program comes from payment on gross sequestration potential instead of net flux. Even though payment is made to all adopters, net emissions increases counteract soil carbon increases in some regions (1.06 MMT nationally at $125 per ton). This occurs when the newly adopted no-tillage practices emit more than the forgone conventional tillage practices (usually from switching crops). Our analysis indicates that leakage may be more of a problem at lower incentive levels. When incentives are low, it motivates existing conservation tillage acres to switch to another, higher sequestering (and higher emitting), conservation tillage crop (such as wheat to corn). This leakage problem is dampened at higher incentives because it motivates more acres to switch tillage-practice and not only crop-type. Because no-till emissions are almost always lower than conventional tillage emissions, changes in practices create less leakage. Yet it must be remembered that, nationally, net emissions are falling as a result of the incentives on ‘gross sequestration’. The reduction in net emissions comes as a ‘free’ carbon savings that are not being paid for with the offered incentives. Nationally at $125 per ton carbon, the benefits of the free carbon savings as a result of emissions reductions outweigh the leakage by 2.4 MMT.

This analysis is the first test of a model designed to yield geographically precise estimates of carbon sequestration, emissions and net flux. It is still a valid question to ask whether the increased complexity in geographic precision has really led to an actual gain in estimation accuracy. There is error involved in the estimation of county yields, base carbon level, sequestration rate, and budget costs. Estimation at a higher level of aggregation may act to even out these uncertainties, and therefore, give a more accurate estimate. To test whether increased model resolution improves actual estimations of carbon sequestration potential, the model will also be run at a lower degree of resolution. Both the high resolution and low resolution results will be compared to actual field level data. The hypothesis being that the high resolution estimations will be more accurate than low resolution estimations.

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