Estimating the Economic Value of Temporary and Permanent Carbon Sequestration Activities on Agricultural Land

Mark Sperow
West Virginia University
P.O. Box 6108
Morgantown, WV 26508-6108
Mark.Sperow@mail.wvu.edu

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Abstract

This paper estimates the value of carbon from soil sequestration and emission reductions from setting aside highly erodible land. Increases in soil carbon are estimated using the Intergovernmental Panel on Climate Change soil organic carbon inventory method and NRI data. Emission reductions are estimated using fuel use data from USDA-ERS.

Introduction

Greenhouse gas (GHG) emissions may be reduced by carbon (C) sequestration, in terrestrial systems for example, or through direct emission reductions from decreased fossil fuel use. The GHG mitigation effect of an emissions reduction and C sequestration may be different because of the time the C remains out of the atmosphere. While C sequestered in the soil may be released back to the atmosphere when the soil is disturbed, an emission reduction represents permanent removal of C from the atmosphere (Lewandrowski, et al., 2004). GHG mitigation is enhanced through both soil C sequestration and emission reductions when land is removed from crop production.

Research suggests that C sequestration in agricultural soils could play a meaningful, though not predominant, role in helping mitigate greenhouse gas increases (Bruce et al., 1999; Flach et al., 1997; Lal et al, 1998; Paustian et al., 1997a, 1997b; Sperow et al., 2003). Many facets of agricultural land management and land use change have been examined for their potential to increase soil C stocks (Bruce et al., 1999; Lal et al., 1998; Lal et al. 1999; Paustian et al., 1997a; Paustian et al., 1997b). Soil C sequestration may be increased through adoption of activities such as setting aside highly erodible land (HEL) (plant to grass and/or legumes), reduce tillage intensity, include winter cover crops, and decrease summer fallow. Lal et al. (1998, 1999) estimated that potential soil C sequestration from improved management on U.S. cropland was 75 to 208 Tg C (Teragram = 10^{12} g = million metric tonnes) per year for several decades. Bruce et al. (1999) estimated that U.S. agricultural soils have the potential of sequestering 75 Tg C per year over the next 20 years. Analyses that account for climate and soil management estimate that the biophysical potential C sink from widespread adoption of activities that increase soil C at 35 – 83 Tg C yr^{-1} (Sperow et al., 2003). This soil C sink represents about 15% of the estimated reduction required to satisfy the Kyoto Treaty (7% below the 1990 emission levels), or nearly twice the CO_2 emissions from agricultural production in the form of fossil energy use, manufacture and distribution of fertilizer and pesticide, and soil erosion.

Switching from annual crops to perennial vegetation increases residue production, plant roots, and reduces soil disturbance, thus enhancing soil C sequestration (Paustian et al., 1997b). Setting aside highly erodible land and planting perennial vegetation has the same effect on soil C as the Conservation Reserve Program (CRP). The CRP is a voluntary cropland retirement program in the U.S. designed to change land use from annual to perennial vegetation, in particularly erodible land (HEL). Areas enrolled in CRP are removed from crop production for ten years and planted to native or introduced grass species or trees. Follett et al. (2001a; 2001b) estimated annual soil C sequestration (0-20 cm depth) of 9.5 Tg C yr^{-1} from 10.6 Mha of CRP land based on paired sampling of 14 sites in the Great Plains and western Corn Belt. Gebhart et al. (1994) estimated a similar total of 11 Tg C yr^{-1} for a deeper (0-300 cm) depth increment, based on sampling at five sites in the southern and central Great Plains. Paustian et al. (2001) estimated soil

C sequestration of 6 Tg C yr^{-1} on 10 Mha of CRP land using a regional application of the Century model (Metherell et al., 1993; Parton et al., 1994). Sperow et al., (2003) estimated soil C sequestration of 4.5 Tg C yr^{-1} on 13.2 Mha of CRP lands using a modified version of the IPCC calculation method.

Converting 25.7 Mha (million hectares) of HEL from crop production to set-aside increases soil C 10.5 Tg C yr^{-1} (million metric tons of carbon per year) over the baseline U.S. agricultural soil C sequestration rate of 17.1 Tg C yr^{-1} (Sperow, 2003). The predominant crops in 1997 produced on HEL included 9 Mha of small grains, 4.5 Mha of corn, 3.6 Mha of soybean and 3.7 Mha of summer fallow.

In addition to the soil C gains derived from setting aside HEL, fossil fuel use for activities such as planting, harvesting, and grain drying is eliminated. The C embodied in the fossil energy that is no longer used needs to be included in the carbon sequestration accounting to capture all of the benefits of a set-aside program. While this emission reduction may have a different value than the C sequestered in soils, because of the "permanence" issue, both are assumed to have the same GHG mitigation effect for this analysis, and therefore may be combined to derive a C value.

While the biophysical potential of agricultural soils to sequester soil carbon has been characterized relatively well, the economic impact of changes in agricultural production to enhance carbon sequestration has not been fully analyzed. A limited number of regional and national analyses have estimated carbon prices by assessing the incentive required to encourage landowners to adopt carbon sequestering activities (Antle et al., 2001; McDowell et al., 1999; Peters et al., 2001). Peters et al. (2001) reviewed twelve studies that estimate carbon prices with and without international trading. Carbon prices without international trading range from $48 to $407 per ton with an average value of $199 per ton (Peters et al., 2001).

Previous studies exogenously apply various carbon prices and analyze the change in production activities and producer income to determine how much soil C could be sequestered under different scenarios. For the most part, these simulation models depend upon assumptions about the ease of transition from one management system to another and how quickly agricultural producers change in response to exogenous shocks. The objective of this analysis is to estimate the change in U.S. crop production and to derive a carbon value from setting aside HEL that is in crop production. This analysis does not consider whether landowners would be willing to enroll in a set-aside program, but rather only estimates compensation for enrollment in a land set-aside program that would provide similar income to historic production activities. Profit maximizing landowners may be indifferent between earning an annual rental rate from set-aside and the same income from producing crops. These estimates of the market value of soil and emission reduction C will aid policymakers and industries that may be required to reduce emissions.

The change in soil C sequestration, effect on U.S. crop production, C from emission reductions, and value of C from setting aside HEL are assessed for the major U.S. crops (corn, soybean, wheat, sorghum, and cotton) that account for nearly 80% of the C losses from cropland soils. Barley is not considered because rental rates for land planted to barley are not available. The study provides the spatial distribution of HEL in crop production and the change in soil C, crop production, and fossil fuel use that results from conversion to a soil C enhancing activity. The analysis also assesses whether targeting specific regions of the country for set-aside enhances soil C sequestration and minimizes the impact on producer income. The results of this analysis will be useful for identifying alternative income streams for landowners and to inform policymakers of the environmental and economic consequences of some greenhouse gas mitigating activities.

Methods

The carbon content of fuels used during crop production were derived for gasoline, diesel, natural gas, and LP gas, which varied by crop and state (USDA-ERS, 2003b). When data were not available for a state included in the analysis, national average fuel use data were used. These data allowed calculations of the average, minimum and maximum carbon content for each fuel for all crops included in the analysis.

Soil C accumulation rates on set-aside land are estimated using a modified version of the Intergovernmental Panel on Climate Change (IPCC) soil organic C inventory method together with the National Resources Inventory (NRI) and other data. Baseline and potential soil C stock changes are calculated using the IPCC inventory factors in conjunction with land use, management and soil information derived from 1997 National Resources Inventory (NRI) data (Nusser and Goebel, 1997) and ancillary data sets. The NRI consists of about 1.3 million actual and imputed sample locations across the U.S. in which land use, land management, and other resource information has been collected every five years since 1982. For this analysis the IPCC method is used to estimate soil organic C stocks and flows that result from land use and land management changes in the conterminous U.S. for the period 1982 to 1997 and projections to 2017. The standard inventory period used in the IPCC method is twenty years. Organic soils (i.e. peat and muck soils) used for agricultural production are not included in this analysis, although their contribution to net CO_2 emissions from agricultural activities is significant (Ogle et al., 2003).

Default values for baseline soil C stocks are provided along with a series of coefficients that determine carbon stock changes as a function of climate, soil type, disturbance history, tillage intensity, productivity, and residue management (IPCC, 1997b). Documentation of the inventory methods for land use and management change are in the IPCC Workbook Module 5 (Land-Use Change and Forestry; IPCC, 1997b) and Reference Manual, Chapter 5 (Land-Use Change and Forestry; IPCC, 1997c).

Six climate regions are delineated for the conterminous US cold temperate, dry (CTD), cold temperate, moist (CTM), warm temperate, dry (WTD), warm temperate, moist (WTM), sub-tropical dry (STD), and sub-tropical moist (STM) based on the IPCC broad climatic region criteria (Eve et al., 2001). Average daily temperature and precipitation are computed using the PRISM (Parameter-elevation Regressions on Independent Slopes) climate mapping system (Daly et al., 1994; Daly et al., 1998) and then used to assign land units to one of the six IPCC climate regions.

Each NRI point is categorized by climate and soil type. State, county and MLRA (Major Land Resource Area (NRCS, 1981)) membership accompanying each point serve to locate the point within a climate region. The dominant taxonomic soil order for each point is derived by referencing the soil map unit identifier, which is linked to each NRI point (Eve et al., 2001; NRCS, 1994).

The baseline analysis considers the change in soil C from crop system and management changes between 1982 and 1997. Agricultural areas producing corn, cotton, sorghum, wheat, or fallow in 1997 on HEL are then removed from production. Pasture, range, hay, vegetable crops, and other crop activities are included in the baseline estimates, but are not included in the analysis of set-aside. Crop rotations that include hay, whether rotated with small grains or row crops, are removed from the analysis because these rotations already provide high rates of carbon sequestration. Irrigated land, continuous rice and rice in rotation, which are generally produced on flooded soils under anaerobic conditions, are not included in the analyses.

Soil C stocks changes between 1982 and 1997 (the period of record for NRI) are computed to provide an estimate of C changes that have already occurred, as a baseline from which potential soil C increases can be compared. Baseline soil C change using the twenty-year IPCC inventory default factors (IPCC, 1997b), adjusted for our shorter 15-year inventory period (i.e., multiplied by 0.75) are estimated first. We estimated the change in soil C for each of the 1.3 million observed and imputed NRI points (Nusser and Goebel, 1997), to derive estimates of soil C stock change within each MLRA and for all US cropland. The average change in soil C stock for each climate-soil-land use/management category is computed with the following equations

$$\delta C = [\sum_{NRI=1}^{N} \sum_{t=1}^{T} (SC_{1997} - SC_{1982})] * 0.75 \quad (1)$$

$$SC_{1997} = (Ha_{1997} \times SC_R \times BF \times TF_{1997} \times IF_{1997}) \quad (2)$$

$$SC_{1982} = (Ha_{1982} \times SC_R \times BF \times TF_{1982} \times IF_{1982}) \quad (3)$$

where δC = the change in C stocks for that land use scenario over the 15 year period (expressed as Tg),

N = the NRI points,

T = conventional tillage, reduced tillage, and no-till (in the baseline, each NRI point contained a proportion of each tillage system based upon CTIC derived data),

Ha_{1997}	=	the number of hectares in that land use (crop rotation, CRP, etc.) in 1997,
SC_{1997}	=	soil carbon stock in 1997,
SC_{1982}	=	soil carbon stock in 1982,
SC_R	=	the IPCC default estimate of soil C under native vegetation - reference level (varies by climatic zone and soil type),
0.75	=	factor to adjust 20 year inventory to the 15 years of data used,
BF	=	the IPCC base factor (in this analysis of soil C potentials, the base factor is the same for 1982 and 1997),
TF_{1997}	=	the IPCC tillage factor based upon the tillage system in 1997,
IF_{1997}	=	the IPCC input factor based upon residue inputs from cropping activities in 1997,
Ha_{1982}	=	the number of hectares in that land use (crop rotation, CRP, etc.) in 1982,
TF_{1982}	=	the IPCC tillage factor based upon the tillage system in 1982,
IF_{1982}	=	the IPCC input factor based upon residue inputs from cropping activities in 1982.

The total change in soil C stocks for the climatic region is the sum of soil C stock changes for each land use category within the region. Baseline changes in soil C stocks were then converted to annual average rates of change (Tg C yr^{-1}) for the fifteen-year inventory period. When land is set-aside for twenty years, soil C accumulations are estimated with the same equations, but the starting period is 1997 and the ending period is 2017. It is not necessary to adjust the calculation to fifteen years.

The opportunity cost of land, the land rental rate, is derived from the USDA-ERS Costs and Returns by the USDA-ERS designated Farm Resource Regions (USDA-ERS, 2003). Farm Resource Regions are used in the analysis to account for the variability in land prices, which are dependent upon local or regional markets, land quality, and climatic characteristics. The economic value of sequestered carbon is estimated using the 1995-2003 average annual rental rates for land (table 3). In general, rental rates are based upon the value of the crop that can be produced on the land, so should reflect all costs and returns adequately. Land rental rates are adjusted to 2003 dollars using the Producer Price Index (PPI) to allow direct comparison between land units and years and to calculate an average land rental rate. The carbon price estimate uses the combined effect of the C from an emission reduction, and soil C sequestered.

The impact on total production of removing land from crop production is estimated using county crop yield data derived from USDA-NASS and the NRI to identify the crop grown on each of the 1.3 million NRI sample locations (actual and imputed points combined) by year (1979-1997, the years available from 1997 NRI data). County average yield data from 1995-1997 are used to account for weather variability and technological changes that have enhanced crop yields. When county level yield data are not available, average yield from adjacent counties are used as a proxy for actual county yield.

Results and Discussion

The U.S. counties and area of crop production on HEL are shown in figure 1. Crop production on HEL occurs intensively in the Great Plains region and in the Corn Belt, but is also present in most regions of the country. The five crops considered in this analysis and fallow activities account for a total of 107 Mha with baseline soil C sequestration of -9.5 Tg C yr^{-1}. As shown in table 1, corn production accounts for the largest area (34 Mha) and highest soil C emissions (-4.3 Tg C yr^{-1}) followed by wheat (28.4 Mha) with soil C emissions of -2.1 Tg C yr^{-1}. Under the baseline scenario, except for a small number of counties, agricultural production on HEL results in soil C losses, as shown in figure 2. In 1997, 20.6 Mha of HEL were used for crop production that resulted in soil C losses of -2.6 Tg C yr^{-1}, or nearly 30% of all emissions from agricultural land planted to the crops analyzed. Corn and wheat represent the largest area of HEL with average soil C losses of -1.0 Tg C yr^{-1} and - 0.60 Tg C yr^{-1} respectively during the baseline period of 1982-1997.

Setting aside HEL eliminates soil C emissions from all regions. Estimated soil C sequestration from setting aside 20.6 Mha for twenty years is over 8.2 Tg C yr^{-1} and nearly 9.3 Tg C yr^{-1} when emission reductions are included (table 2). The net increase over the baseline conditions is 11.9 Tg C yr^{-1}. Reduction in wheat production contributes the most to increases in soil C (3.9 Tg C yr^{-1}) followed by corn (2.9 Tg C yr^{-1}).

Based on land rental rates and C sequestration estimated using the IPCC method, carbon prices range from $51 to $1912 per metric ton with a U.S. average of $286 (weighted by area and C sequestration). This is higher than carbon prices when emission reductions are not considered ($61 - $576 per metric ton and average of $320). While the lower value is similar to previous analyses, the upper range is substantially higher than values derived from previous research. One possible reason for this is that previous analyses have assessed management changes that have little effect on producer income, while this analysis completely removes the land from production. The sole source of farm income in the analysis is based upon the amount of soil C that can be stored over 20 years. Since the land rental rate was used to establish the C price, highly valued lands, which should be an indicator of productivity, with small increases in soil C, because sequestration is already high on highly productive land, result in high carbon prices.

The USDA-ERS designated Farm Resource Regions that are grouped by crop production specialization are used to gain an understanding of the spatial distribution of soil C and where costs are the highest. The highest average carbon price occurs in the Heartland ($223 per metric ton). This should be expected because the Heartland includes the Corn Belt region of the U.S. with productive soils that produce high valued crops, thus having higher land rental rates. The increase in soil C from setting aside HEL in the Heartland is over 2.5 Tg C yr^{-1}, which represents nearly 27% of the total soil C sequestration on set-aside lands. The Prairie Gateway, which encompasses the southern plains region, provides the least expensive soil carbon cost at $73 per metric ton. It also provides substantial soil C at 3.3 Tg C yr^{-1}, or over 36% of the soil C gains possible on set-aside land. The most HEL of any region is also removed from production, resulting in over 6.3 Mha less production in this Farm Resource Region.

The area removed from crop production and soil carbon gain that may be achieved under various price scenarios are included in table 3. When the price is not above $50 per metric ton, no land will be set-aside. This is not a surprising result since the lowest land rental rate in the U.S. is just over $70 ha^{-1} ($37 ac^{-1}) in the Prairie Gateway resource region. When the carbon price is $200 per metric ton, nearly 6.5 Mha are removed from crop production and contribute nearly 3.8 Tg C yr^{-1} (Figure 3) or 40% of carbon sequestration when all HEL is set-aside. At a price of $400 per metric ton, over 73% of the total possible soil C sequestration from set-aside may be attained.

To get a sense of the impact of the reduced production as it relates to total production, estimated production from each site is compared to average ending stocks in 2002 and 2003 (projected). When all HEL in the analysis is considered, the reduction in crop production is less than average ending stocks (table 4). Decreased sorghum production represents the greatest proportion of ending stocks (81%) while reduced cotton production would have the smallest effect (17%). While it may not be desirable to reduce ending stocks, these data indicate that setting aside HEL to increase soil carbon would not have large impacts on total crop production.

Conclusions

The soil carbon gains from setting aside highly erodible land are substantial. Overall, reduced fuel consumption increases C sequestration by over 1 TgC yr^{-1} and reduces the overall costs of C sequestration as a GHG mitigation activity by shifting out the supply curve. However, the data indicate that using the land rental rate as a proxy for the value of lost production income results in a high per unit cost for the sequestered soil carbon. The least costly Land Resource Region, Prairie Gateway, provides over 35% of the total soil C gains possible on HEL. Regions such as the Prairie Gateway that contribute significantly to the total soil C sequestered at lower costs should be the first targeted by any programs implemented to increase soil carbon.

The IPCC calculations provide estimates of soil C accumulations or emissions that result from management changes over twenty years. Therefore, a key assumption in this analysis is that HEL is set aside for at least twenty years. Converting the land from set-aside to crop production would negate much of the gain in soil C, depending upon how many years the land was set-aside. Soil C sequestration is noted with positive and C emissions with negative annual accumulation rates.

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Table 1. Total area of study crops produced in the U.S., annual rate of soil C sequestration from these crop activities, area of HEL by study crop and annual rate of soil C sequestration from cropping activities on HEL.

1997 Crop	*Total Area (Mha)*[a]	*Total Soil C ($Tg\ yr^{-1}$)*	*HEL Area (Mha)*	*Soil C from HEL in production ($Tg\ yr^{-1}$)*
Corn	34.0	-4.3	4.3	-1.00
Cotton	6.9	-0.7	1.2	-0.12
Sorghum	4.4	-0.5	0.7	-0.10
Soybean	27.3	-1.5	3.6	-0.55
Wheat	28.4	-2.1	7.4	-0.60
Fallow	3.6	-0.3	3.5	-0.24
Total	107.0	-9.5	20.2	-2.60

[a] Baseline and HEL areas and soil C sequestration rates do not include rotations with hay or irrigated land that is defined as HEL.

Table 2. Baseline soil C sequestration rate from production on HEL, soil C from setting aside HEL, reduced CO_2 emissions from not using fuels, and total C sequestration and emission reduction potential from setting aside HEL.

1997 Crop	*Baseline C from HEL* [a]	*Total C from HEL after Set-Aside*	*CO_2 Emission Reduction*	*C Sequestration and Emission Reduction*
	------------------------------ $TgC\ yr^{-1}$ ------------------------------			
Corn	-1.00	1.54	1.88	2.88
Cotton	-0.12	0.65	0.84	0.96
Sorghum	-0.10	0.29	0.35	0.45
Soybean	-0.55	1.28	1.43	1.98
Wheat	-0.60	2.98	3.25	3.85
Fallow	-0.24	1.51	1.51	1.75
Total	-2.60	8.25	9.26	11.86

[a] Soil C sequestration rates for baseline and set-aside do not include soil C rate for irrigated crops or rotations that include hay or the CO_2 emissions from fossil fuel use.

Table 3. Farm Resource Region 1995-2003 average land rental rate by crop ($ ha^{-1}) adjusted to 2003 dollars with the Producer Price Index (PPI).

	Crop ($ ha^{-1})				
Farm Resource Region	Corn	Cotton	Sorghum	Soybean	Wheat
Basin and Range	n/a[a]	n/a	n/a	n/a	123.87
Eastern Uplands	109.19	n/a	84.93	101.13	n/a
Fruitful Rim	n/a	318.91	n/a	n/a	n/a
Heartland	225.56	168.70	138.85	231.19	158.34
Mississippi Portal	n/a	126.44	n/a	151.67	114.09
Northern Crescent	150.63	n/a	79.47	170.75	164.49
Northern Great Plains	125.78	n/a	n/a	101.61	87.92
Prairie Gateway	179.00	55.52	57.13	130.15	70.38
Southern Seaboard	88.78	101.56	85.10	91.75	n/a

[a] Data are not available.

Table 4. Hectares that may be enrolled in a set-aside program when the price per metric ton of carbon is varied, the soil C that may be attained from those acres, and the percentage of total soil C sequestration from set-aside.

Price ($ per metric ton)	*Area with soil C (,000 ha)*	*Area with soil C + Emission Reduction (,000 ha)*
50	0	0
100	990	1,318
200	4,597	5,153
300	4,289	4,363
400	2,764	3,120
500	1,476	2,608
600	1,979	1,417
>1000	3,888	1,934

Table 5. Crop Production impacts of removing HEL from production activities.

1997 Crop	*Total Production Loss[a]*	*2002-2003 Ending Stocks*
Corn (Mil. Bu)	512.0	1339
Cotton (Mil. 480 Lb Bales)	1.1	6.5
Sorghum (Mil. Bu)	42.1	52
Soybean (Mil. Bu)	133.2	193
Wheat (Mil. Bu)	259.9	631

[a] Based on average county yields. *Source:* USDA-NASS. 2003. Crops County Data Files. http://www.nass.usda.gov/indexcounty.htm

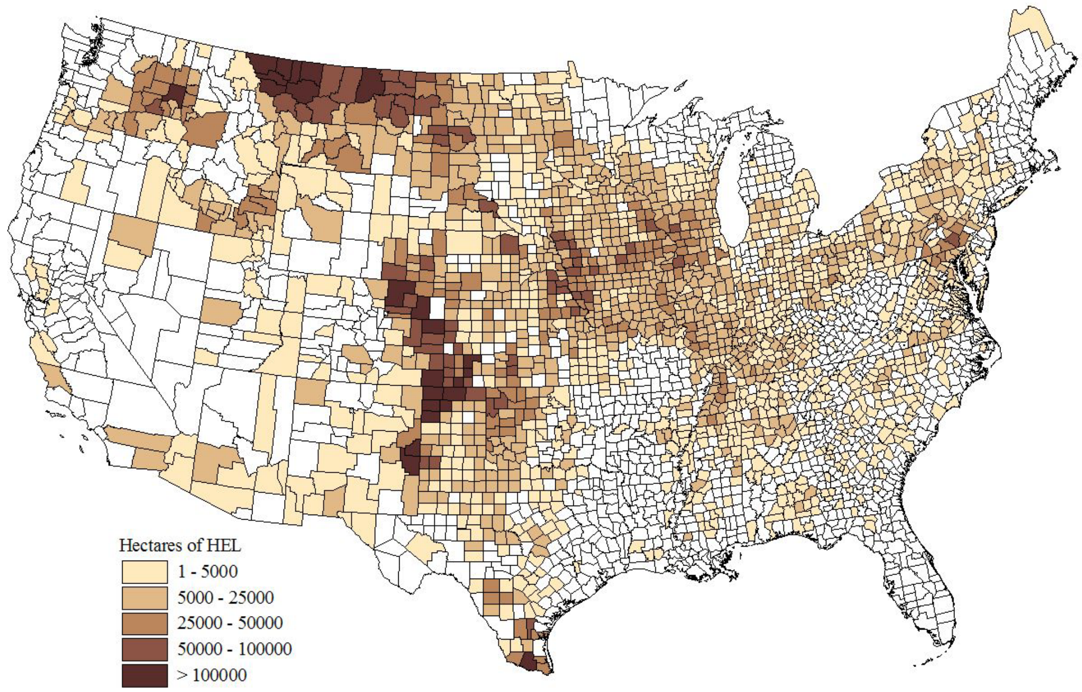

Figure 1. Area of HEL under crop production by U.S. county.

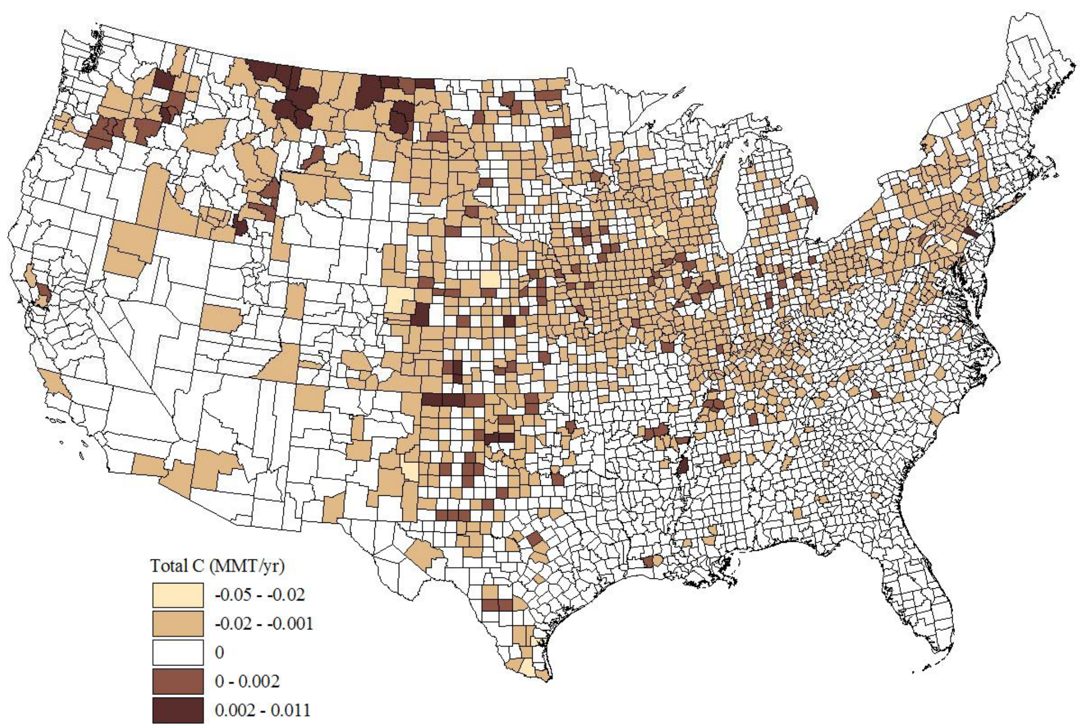

Figure 2. Annual rate of soil C sequestration from crop production on HEL by U.S. county.

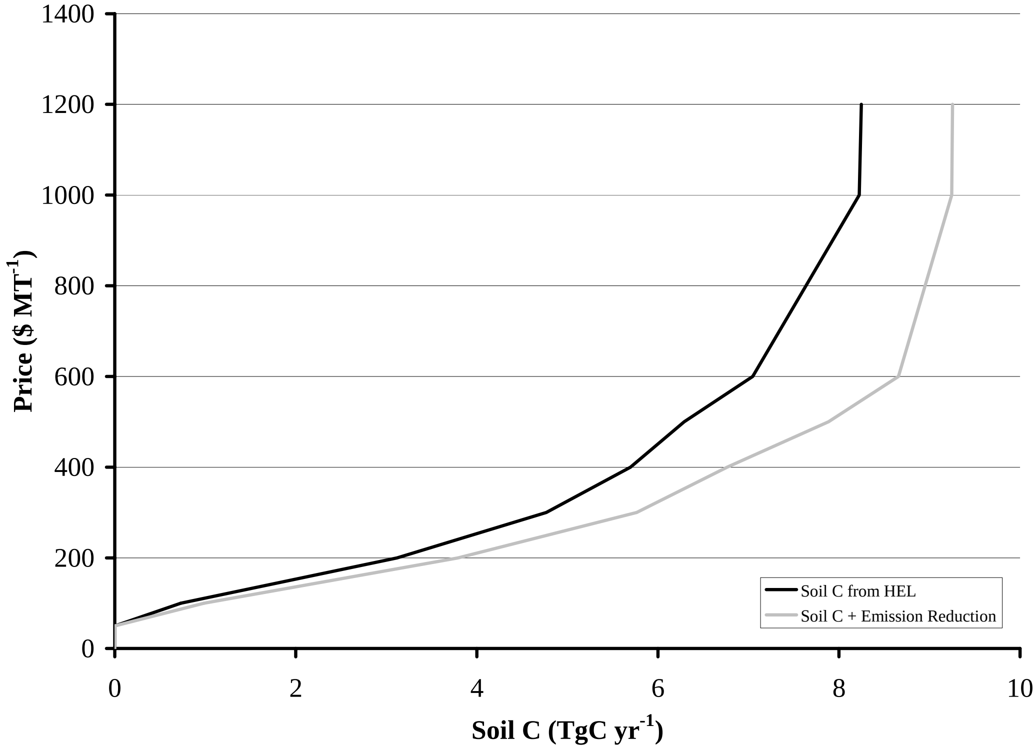

Figure 3. Supply curves for soil C (dark line) and combined soil C and C from emission reduction (grey line).