Selected Presentation at the 2022 Agricultural and Applied Economics Association Annual Meeting, Anaheim, California, July 31-August 2

Evidence of the social cost of agricultural greenhouse gas mitigation: A national optimization model of United States crop production[1]

Kent Kovacs[2]

USDA Economic Research Service

[1] The findings and conclusions in this manuscript are those of the authors and should not be construed to represent any official USDA or U.S. government determination or policy.
[2] Kovacs is a research agricultural economist and corresponding author (kent.kovacs@usda.gov) with the USDA Economic Research Service, Resource and Rural Economics Division.

Abstract

We consider the social costs associated with a second best policy for the mitigation of greenhouse gas from field crop agriculture in the United States. We utilize a price-endogenous, partial equilibrium model, known as the Regional Environmental and Agricultural Programming (REAP) model, to solve for the intersection of national supply and demand while accounting for heterogeneity in the resource endowments, inputs, and production. The reference allocation of row crops within the U.S. corresponds to an overall net sequestration of 98,006 million tons, attributable to the net sequestration of widely cultivated corn. A policy that requires a 30% increase in net sequestration above the 98,006 million tons raises social costs (loss of consumer and producer surplus relative to the status quo) by $56 million for each percentage, and a 50 to 70% increase in net sequestration raises social costs by $254 million for each percentage. The rising social costs occurs as field crops shift to rotations less effective at GHG mitigation. Most increases in acreage occurs for the continuous corn rotation, since corn has the largest net sequestration of GHG of any crop and the enterprise is profitable. Most decreases in acreage occur for the rotations with rice, soybeans, and cotton, since these crops are all net emitters of GHGs.

Keywords: Social costs, Greenhouse gases, National optimization model, REAP

Introduction

We investigate the social costs of a second-best policy for the mitigation of agricultural greenhouse gases (GHG). A national optimization model of crop production with calibration to economic and agronomic data explores how land use margins adjust to policy. In the U.S., the agricultural sector accounts for about 9% of total GHG emissions, mainly in the form of nitrous oxide (N2O) and methane (CH4). The majority of the GHG emissions from agriculture in the U.S. come from N2O emissions associated with soil management. Agricultural soils can also store carbon, thereby contributing negatively to GHG emissions. A growing body of literature suggests that, owing to its GHG mitigation potential, the agricultural sector could be part of a multi-faceted GHG mitigation strategy (McCarl and Schneider, 2001; Pautsch et al., 2001; Antle et al., 2007).

We empirically address the social costs of a second-best policy of GHG mitigation associated with field crop agriculture in the United States. We use a national optimization model, related to the Regional Environment and Agriculture Programming (REAP), of U.S. production for field crops calibrated to the available economic and agronomic information. The disaggregation into farm production regions capture part of the heterogeneity in soil and climatic conditions over space in addition to regional differences in crop choice and resource constraints. The model allows for crop substitution, and we validate our calibrated model by predicting crop allocation and output under out-of-sample economic conditions and compare the results to observed patterns. The model performs reasonably well, suggesting that relevant tradeoffs at the national scale are captured.

We simulate U.S.'s marginal abatement cost curve assuming a regulating agency requires increases GHG net sequestration relative to a baseline. The requirements mean that actual net emissions have to be measured, but more realistically a regulator could instead just observe management practices. Biophysical models would then be relied upon to determine the relationship between various management practices and GHG emissions. Given that GHG emissions arise from numerous adjustment margins that are location specific, allocative efficiency would require a sophisticated (and costly) series of emission factors linked to management practices.

Modeling framework

The Regional Environmental and Agricultural Programming (REAP) model is one of the core models used by USDA’s Economic Research Service to analyze the intersection of agriculture and the environment for policy applications (Johansson et al. 2007). ERS has been the home to REAP since the 1980s, and the model is used to inform reports, journal publications, and important policy discussions. Recent examples include applications to on climate change and crop insurance, and nutrient losses from cropland.

REAP is a partial equilibrium, price endogenous model that solves for the intersection of supply and demand at the national level, allowing for regional variation according to differing resource endowments, inputs, and production. Agricultural production in REAP is assigned to regions, crop rotations and production methods (tillage and irrigation options). An important and distinguishing feature of REAP is an accounting of environmental impact drivers and outcomes.

Nested constant elasticity of transformation model

Production responds to changes in crop price, and the supply of crops is implicitly determined by the allocation of land to rotation and technique. Aggregate acreage employed is determined in equilibrium, and the choice problem is represented by two-stage budgeting. Farmers first assess the profitability of tillage practices to choose the optimal allocation to each rotation option for conventional and reduced till practices. Next, given the value of each rotation option, the farmer allocates land to rotations to maximize the aggregate value of land.

When looking at the allocation of agricultural land to crops (such as corn and soybeans) and cropping methods (crop rotation or tillage method) and increase in the supply of one crop may imply increases or decreases in the supply of another crop, depending on whether the crops are complements or substitutes in production. Many fields in the Midwest have soybeans alternated with corn. An increase in the supply of corn might then increase the supply of soybeans due to complementarity in the products.

The constant elasticity of transformation (CET) function represents the trade-off between the movement of land across rotational choices and the aggregate land for cultivation,

$$1 = \left(\sum_r \theta_r \left(\frac{N_r}{\bar{n}_r}\right)^{\rho}\right)^{1/\rho} \quad (1)$$

where N_r is the farmer's choice of land allocation to rotation r, $\bar{n}_r$ is the reference allocation of land to rotation r, θ_r is the value share of rotation r in the aggregate rental value of land, and ρ is a parameter to represent the elasticity of transformation. The value share of rotation r in aggregate profit is $\theta_r = \frac{\sum_t \bar{\pi}_{rt} \bar{l}_{rt}}{\sum_{r't} \bar{\pi}_{r't} \bar{l}_{r't}}$.

The farmer's allocation of land solves max $\sum_r \pi_r N_r$ subject to Eq. (1). The profit of an acre of land in rotation r is shown in Eq. (2),

$$\pi_r = \max \sum_t X_{rt} \sum_c p_c y_{crt} - C_{rt} \tag{2}$$

with the price of crop c given by p_c, the yield of crop c for rotation r and tillage practice t given by y_{crt} , and C_{rt} is the cost per acre of land in rotation r and tillage practice t. The profit for rotation r is subject to the CET function for the movement of land across tillage practices represented by

$$1 = \left(\sum_t \alpha_{rt} \left(\frac{X_{rt}}{\bar{x}_{rt}}\right)^{\gamma_r}\right)^{1/\gamma_r}. \tag{3}$$

Maximization of π_r (Eq. 2) reveals the amount of land used by rotation and tillage practice, X_{rt}, and the reference allocation of land to a rotation and tillage practice is $\bar{x}_{rt}$. The elasticity of transformation across tillage practices is characterized by γ_r. The value share for the benchmark allocation is α_{rt} with,

$$\alpha_{rt} = \frac{\sum_c \bar{p}_c y_{crt} - C_{rt}}{\bar{\pi}_r}$$

where the reference price of crop c is $\bar{p}_c$ and $\bar{\pi}_r = \sum_{ct} \bar{p}_c y_{crt} - C_{rt}$.

Objective

The objective is to maximize the sum of producer and consumer surplus relative to the reference allocation of land to crops and tillage practices. Assuming a linear supply schedule and an elasticity of supply η, the maximization of the change in producer surplus relative to the benchmark point yields:

$$\max \quad \bar{p}(S-\bar{S})\left(1+\frac{1}{2\eta}\left(\frac{S}{\bar{S}}-1\right)\right)-pS$$, where the model yields $\bar{S}=S$ when $p=\bar{p}$.

Likewise, maximizing the change in consumer surplus assuming a linear demand and an elasticity of demand ϵ, relative to the benchmark point:

$$\max \quad \bar{p}(D-\bar{D})\left(1+\frac{1}{2\epsilon}\left(\frac{D}{\bar{D}}-1\right)\right)-pD$$

yields $D=\bar{D}$ when $p=\bar{p}$. In equilibrium, the supply of crop *(c)* from all rotations *(r)* and tillage practices *(t)* equals aggregate demand. Equation (4) denotes an acreage allocation as *X*, yield as *y*, and a market demand as *D*:

$$D_c = \sum_{rt} X_{rt} y_{crt}. \tag{4}$$

Data

REAP quantifies agricultural production and the associated environmental impacts for 273 production regions within the United States. REAP includes 10 major commodity crops (corn, sorghum, oats, barley, wheat, rice, cotton, soybeans, hay, and silage). Each REAP model region includes a set of production activities comprising crop rotation and tillage practice (i.e. no-till, reduced till, or conventional tillage). The combination of rotation and tillage practice referred to as a production enterprise and represents the basic unit of crop production economic activity in the REAP model. The selection of available production enterprises for each region was derived from the 2007 National Resources Inventory (NRI) data. When REAP solves for agricultural production patterns under a climate mitigation policy, acreage in each region is distributed among available production enterprises based on an assessment of relative rates of return arising from differences in yields, costs, and returns, and is further constrained by acreage distribution parameters that capture historically observed patterns of production (Tables 1 and 2).

To form a reference against which climate mitigation policy is measured, we designed a set of caps on GHGs that reflect how patterns of production might change relative to historically observed dynamics, but always compare to a reference scenario without a climate mitigation policy. The reference scenario reflects one set of plausible expectations about how prices, acreages, and yields might exist in the absence of a climate policy. Such a reference scenario is sensitive to many assumptions about uncertain policy dynamics and farmer behavior. The results relating to climate policy impacts should therefore be interpreted not as predictions of absolute impact under any given policy scenario but as indicative as the relative direction and magnitude of impact.

REAP's acreage distribution parameters and the crop yield from the EPIC model are calibrated to the reference scenario such that the portrait of agriculture emerging from the model's reference optimization—average yields, production level, crop production acreage, and prices—matches that specified by the reference projection for that time period. Calibration of REAP's reference acreage, production, and GHG impacts incorporates information on cropping rotations from the NRI as well as supporting data on tillage and fertilizer use (ARMS). The impacts of climate policy on agricultural production are then assessed by substituting into REAP the regional yield, crop-water requirements, and cost estimates for production enterprises for 2007. The REAP modeling framework reallocates production acreage under each of the climate policy scenarios to optimize the sum of producer and consumer surplus given the changes in regional yield and crop water use. As prices vary, consumer and producer surplus are also endogenous and are explored separately across the climate policy scenarios.

While yield and water use are fixed by production activity for any given climate policy, endogenous changes in aggregate production, production acreage, and tillage emerge as a result of reallocation of cropland acreage across production activities. In addition to the drivers of land use re-allocation listed above, acreage reallocation under climate policy may also be constrained by the regional availability of resources such as productive land and water.

Results and Discussion

The change in land use and the rise in social cost in response to a national GHG policy that enforces 30%, 50%, and 70% greater carbon sequestration on crop producers is shown in Table 2. The most significant increase in acreage occurs for the continuous corn rotation (RCCC) followed by a continuous wheat rotation (RWWW). The continuous corn rotation provides the largest amounts of sequestration since corn has the largest net sequestration of GHG of any crop, and the enterprise is profitable. The reason for the large increase in continuous wheat is that the enterprise is widely available in many regions, and there is above average profitability and sequestration potential. The most significant decrease in acreage occurs for the rotations with rice, soybeans, and cotton (RBBB, RTTT and RWT). While the enterprises that decrease in acreage have above average profitability, the rice and cotton crops emit more GHGs to the atmosphere than any of the other crops.

The social costs that rise with the percent increase in net sequestration required of the GHG mitigation policy do so at an increasing rate. The added social cost for the first 30% increase in net sequestration is $1,669 million, and this corresponds to an average $56 million for each percentage between 0-30%. Going from a 30% to 50% increase in required net sequestration increases social cost by an additional $3,127 million, and this corresponds to $156 million for each percentage. Finally, going from a 50% to 70% increase in required net sequestration raises social costs by $5,079 million, meaning each percentage increase corresponds to $254 million.

We expect social costs to rise as the land use that provides the greatest sequestration for the least loss of social surplus are exhausted.

Conclusion

Our national analysis of the social costs of a second-best policy for the mitigation of agricultural greenhouse gases (GHG) suggest that the costs to increase sequestration rise with the stringency of the policy requirement. The national scale allows us to highlight the efficiencies that come from considering a broad geographic area with the aim to achieve more sequestration. Considering only the losses of producer and consumer surplus associated with the changes in crop rotation from the policy, the social cost for a reduction in carbon range from a low of $0.05 per ton for the first 30% increase in net sequestration to $0.26 per ton for sequestration between 50 to 70%. While this illustrates the potential that row crop agriculture has for achieving GHG sequestration at a low cost, there are many monitoring and enforcement costs still unaccounted to achieve the low cost of GHG reductions associated with the policy.

References

Antle, J.M., Capalbo, S.M., Paustian, K., Ali, M.K. 2007. Estimating the economic potential for agricultural soil carbon sequestration in the Central United States using an aggregate econometric-process model. Climatic Change 80: 145–171.

Johansson, Robert, Mark Peters, and Robert House. Regional Environment and Agriculture Programming Model, TB-1916. U.S. Dept. of Agriculture, Econ. Res. Serv. March 2007.

McCarl, B.A., Schneider, U.A. 2001. Greenhouse gas mitigation in U.S. agriculture and forestry. Science 294(5551): 2481–2482.

Pautsch, G., Kurkalova, L., Babcock, B.A., Kling, C. 2001. "The efficiency of sequestering carbon in agricultural soils." Contemporary Economic Policy 19 (2): 123–134.

Table 1. Initial acres, prices, and net greenhouse gas emissions by crop

Crop	**Initial acres (Millions)**	**Crop price ($ per crop unit)**	**Crop yield (Crop unit per acre)**	**Net GHG emission (Carbon equivalent)**
Corn (Label "C")	93.6	4.2 per bushel	135.28	-368
Sorghum (Label "S")	7.7	4.08 per bushel	58.91	-268
Barley (Label "L")	4	4.02 per bushel	64.85	-268
Oats (Label "O")	1.6	2.63 per bushel	63.40	-268
Wheat (Label "W")	60.4	6.48 per bushel	49.72	-180
Rice (Label "R")	2.75	12.8 per cwt	67.67	1806
Soybeans (Label "B")	63.7	10.1 per bushel	46.28	24
Cotton (Label "T")	10.6	331.2 per ton	1.76	259
Hay (Label "H")	62.5	135 per ton	2.45	-20
Silage (Label "G")	7.5	35 per bushel	16.95	-368

Table 2. Rotation specific initial acres and costs

Rotation	**Initial acres (Millions)**	**Variable costs ($ per acre)**	**Land costs per acre ($ per acre)**
RCH	41.2	1111	1029
RCB	39.12	1810	1427
RCBW	35.52	1482	1118
RCCC	34.57	2580	1538
RWWW	31.67	609	409
RHHH	16.17	2399	2382
RBBB	13.57	1449	1679
RBW	12.49	1654	1613
RCBH	7.66	2396	2595
RCW	7.57	6393	4010
RGGG	7.26	6558	4218
RTTT	6.57	4130	1032
RCBWH	4.79	2453	2788
RBH	4.65	2178	2637
RCS	3.54	2736	971
RCBS	3.39	2838	2530
RBWO	3.3	171	158
RCBL	3.03	981	828
RSH	3.02	898	640
RWT	2.42	3325	964
RCBWL	2.28	343	307
RCBT	2.28	5039	2069
RLH	2.19	3031	2587
RSSS	2.14	2359	1527
RCF	1.8	2616	1997
RBT	1.77	6154	2669
RWLH	1.74	977	709
RBST	1.73	1387	768
RRRR	1.63	4949	2493
RCWH	1.55	6923	6301
RWL	1.5	4026	3281
RBR	1.26	4113	2257
RBWT	1.17	4359	1982
RWS	1.02	6445	3217
RCL	1	3850	2340
RCBO	1	11106	12464

RBS	0.93	5872	6563
RHF	0.91	1641	1682
RCBR	0.9	3107	1475
RBWF	0.79	531	1065
RWF	0.77	12713	10069
RWH	0.72	15927	16662
RGH	0.68	7585	7110
RCLH	0.66	673	765
ROH	0.41	13027	14301
RCT	0.4	18988	5330
RRF	0.36	1505	895
RCBWS	0.31	4512	5051
RCWF	0.25	5205	3147
RCWL	0.21	2129	1351
RCWS	0.05	4016	1833
RBWH	0.03	4688	6010
RCOH	0.01	8928	9349
RBWS	0.01	5956	6306
RCBOH	0.01	4866	6444
RCO	0.01	9951	8167

Table 3. Land allocation by rotation in response to GHG policy

Rotation	Initial acres (millions)	Difference in acreage with GHG policy (millions)		
		30% greater sequestration	50% greater sequestration	70% greater sequestration
RCH	41.2	0.06	0.12	0.24
RCB	39.12	3.13	5.44	8.45
RCBW	35.52	1.64	3.32	4.17
RCCC	34.57	6.39	10.78	16.07
RWWW	31.67	5.96	9.94	16.68
RHHH	16.17	0.36	0.64	0.98
RBBB	13.57	-1.2	-2.01	-2.68
RBW	12.49	-0.27	-0.38	-1.55
RCBH	7.66	-0.11	-0.2	-0.28
RCW	7.57	3.41	5.89	8.51
RGGG	7.26	1.76	2.93	4.26
RTTT	6.57	-0.93	-1.28	-1.7
RCBWH	4.79	-0.11	-0.18	-0.3
RBH	4.65	-0.03	-0.05	-0.06
RCS	3.54	1.12	1.94	3.03
RCBS	3.39	-0.23	-0.44	-0.67
RBWO	3.3	0.23	0.42	0.49
RCBL	3.03	-0.27	-0.49	-0.69
RSH	3.02	-0.33	-0.61	-0.96
RWT	2.42	-0.59	-1.14	-1.33
RCBWL	2.28	-0.23	-0.31	-0.37
RCBT	2.28	0.31	0.41	0.5
RLH	2.19	0	0	0.01
RSSS	2.14	-0.29	-0.16	0.09
RCF	1.8	-0.38	-0.63	-0.87
RBT	1.77	0.1	0.13	0.16
RWLH	1.74	-0.09	-0.16	-0.27
RBST	1.73	0.02	-0.01	-0.03
RRRR	1.63	-0.2	-0.27	-0.7
RCWH	1.55	-0.06	-0.1	-0.17
RWL	1.5	0.79	1.31	1.78
RBR	1.26	-0.57	-1.14	-1.16
RBWT	1.17	0.33	0.49	0.49
RWS	1.02	2.25	3.67	5.15
RCL	1	0.12	0.22	0.35
RCBO	1	0.06	0.1	0.16

RBS	0.93	-0.2	-0.4	-0.6
RHF	0.91	-0.01	-0.01	-0.02
RCBR	0.9	-0.03	-0.05	-0.08
RBWF	0.79	-0.28	-0.49	-0.79
RWF	0.77	0.39	0.67	0.68
RWH	0.72	0.14	0.25	0.34
RGH	0.68	0.01	0.01	0.02
RCLH	0.66	-0.02	-0.04	-0.05
ROH	0.41	0.07	0.12	0.18
RCT	0.4	-0.01	-0.02	-0.04
RRF	0.36	0.13	0.21	0.29
RCBWS	0.31	-0.09	-0.15	-0.18
RCWF	0.25	-0.02	-0.04	-0.07
RCWL	0.21	-0.04	-0.07	-0.11
RCWS	0.05	0.05	0.07	0.1
RBWH	0.03	0	0	0
RCOH	0.01	0	0	0
RBWS	0.01	-0.01	-0.01	-0.01
RCBOH	0.01	0	0	-0.01
RCO	0.01	0	0	0
GHG emission (tons)	-98,006	-127,408	-147,009	-166,610
Net social costs ($ millions)	103,180	104,849	107,976	113,055