An Analysis of the Feasibility of Carbon Management Policies as a Mechanism to Influence Water Conservation Using Optimization Methods

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Abstract

Studies that focus on the effect that carbon reducing policies would have on agriculture have revealed a strong connection between carbon emissions and irrigation. In light of the recent debate about how to regulate the use of the Ogallala Aquifer by landowners on the Texas High Plains, this connection poses an interesting question. Could water conservation be realized through carbon policy? This study seeks to answer this question by using optimization methods to examine the effect of both a tax on carbon emissions and a subsidy for emissions reduction on the Texas High Plains. The results show that a tax or subsidy that reduces carbon emissions to 15% of a baseline estimate also reduces the amount of water used for irrigation by about 20%; however, the amount that must be paid in either taxes or subsidies may be too high for such policies to be feasible.

Introduction

The concern about the effect of man-made carbon emissions has led to concerns about how we interact with the environment. The predicted effects of large scale changes in the earth's climate are many and include changes in water availability, changes in ecosystem structures, changes in agricultural productivity, and changes in sea level, as well as various impacts on the human population (United Nations, 2007). There appears to be little debate on the contribution of carbon emissions to climate change, but there is uncertainty about the severity of the changes listed above (McKibben and Wilcoxen, 2002); as such, there is an ongoing debate about whether or not anything should be done to change how we live our lives in order to mitigate the problem. This debate, however, has not prevented governments from attempting to curb the emission of carbon by humans.

In the United States, the most recent of these efforts was the American Clean Energy and Security Act of 2009 (the "Waxman-Markey" bill) in the House of Representatives. This bill is important not only for its proposed changes in how the nation deals with carbon emissions, such as setting up a cap and trade scheme for carbon regulation, but also for the fact that it passed in House before stalling in the Senate. No other bill regulating carbon emissions in America had gone so far through the legislative process. Along with this legislative effort, the Environmental Protection Agency (EPA) claims that it already has the right to regulate carbon emission via the Clean Air Act and has created new regulations regarding carbon emissions; although the EPA's authority to do so is being challenged in federal court. While neither of these attempts to regulate carbon would affect agricultural production, the willingness of policymakers to confront the issue of climate change in the United States has drawn the interest of researchers and industries alike.

Researchers at the University of Arkansas have sought to determine how a cap and trade policy would affect agricultural production in different parts of the nation. The first step was to develop a method by which emissions could be calculated at the farm level using Life Cycle Analysis (Popp, et. al, 2010). Using the calculations from this approach, an optimization model was developed that maximized net farm income while including the additional revenue from trading carbon credits in a carbon offset market, like the type of market that would have been established for other industries by Waxman-Markey (Nalley and Popp, 2010). Scenarios that calculated both gross and net carbon emissions were considered and produced different results. The study showed that whether gross or net carbon emissions are considered is important to who benefits from trading carbon credits in a carbon offset market. Areas in the study that were high emitters of carbon were also high sequesterers of carbon; thus, when only gross carbon emissions are considered in emission calculations these areas do not benefit from trading in an offset market, but when net emissions are considered these areas can benefit from selling carbon credits. The same is true of certain crops, such as corn, that were found to be both high emitters and sequesterers of carbon.

Studies of how carbon reduction policies would affect agricultural production have also found that there is a connection between carbon emissions and irrigation. The carbon calculations used by Popp, et. al (2010), and Nalley and Popp (2010) show that center pivot irrigation is a large contributor to carbon emissions in agriculture due to the energy involved in pumping water from the ground. Wright and Hudson (2011) estimate the impact on farmer's net revenue on the Texas High Plains of a 95% and 85% reduction on carbon emissions compared to a baseline scenario with no constraint on emissions. The study calculated carbon in a manner similar to that of Popp et al., but allows for the amount of water as an input in the production process to vary as a choice variable in the model. The result is that the choices of what crop to plant and how many acres to plant tended to remain constant while the number of acre-inches applied to a crop is reduced to meet the constraint.

The connection between carbon reduction and water use reduction found by Wright and Hudson implies that in agriculture a carbon reduction policy is a restriction on water use. In light of the recent debate about how to regulate the use of the Ogallala Aquifer by landowners on the Texas High Plains, this result poses an interesting question. Could water conservation be realized through carbon policy? This study seeks to answer this question by examining the effect of both a tax on carbon emissions and a subsidy for emissions reduction on the Texas High Plains. Specifically, optimization methods will be used to determine what level of tax or subsidy is necessary to influence a reduction in carbon emissions, and to determine the effect these policies have on farmers' net revenue, crop and acreage choices, and water usage.

Data & Methods

Study Area and Data Sources

The study area chosen for this project was the Texas High Plains, an area of forty counties in the northwest part of the state. The total shaded area in Figure 1 illustrates the layout of these counties. The blue shaded area depicts the Northern High Plains and the red shaded area depicts the Southern High Plains. For each of these counties, a representative farm was established where corn, cotton, peanuts, sorghum, and wheat were grown. Only irrigated production was considered for corn and peanuts, while for cotton, sorghum, and wheat both dryland and irrigated production was allowed; thus, there were eight different crops considered in the study.

Information for the crops and counties came from three primary sources. First, crop budgets published by the Texas A&M Extension Service for the years 2008 to 2010 provided information on crop prices, per acre costs, and per acre input quantities.[1] For the price and input cost data, the average over all three budgets was used. Second, to calculate per acre yield for irrigated crops, functions were obtained from previous studies that had been performed on the High Plains (Wheeler et al., 2006; New, 2010). Finally, NASS statistics for planted acres, harvested acres, and yields for the years 2000 to 2009 for each crop in each county were used to provide realistic bounds for the model.

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[1] It should be noted that Zivkovic and Hudson have questioned the validity of using crop budgets to develop carbon emissions estimates, but a calibration method has yet to be developed. We use the budgets here, but the reader should note that the resulting total carbon emissions estimates are likely high relative to actual farm emissions.

The Model

Using the above information, the same non-linear programming model used in Wright and Hudson (2011) was used to maximize net revenue for each county. To estimate the model, the Excel Premium Solver program developed by Frontline Systems was used.

The objective function of the model is specified as:

$$(1)\quad Max\ NR = \sum_j [(h_{ij} y_{ij} p_j) - a_{ij}(c_{ij} + r_i x_{ij})].$$

In the revenue function, h_{ij} is the number of acres of crop *j* harvested in county i, y_{ij} is per acre yield for crop j in county i, and p_j is the unit price for crop *j*. In the cost function, a_{ij} is defined as the number of acres of crop *j* planted in county i, c_{ij} is the per acre specified costs, excluding irrigation costs, for crop *j* in county *i* according to the extension service budgets, r_i is the cost associated with pumping from the aquifer in each county, and x_{ij} is the number of acre inches from the aquifer in county i applied to crop j. For the purpose of this study all irrigation is assumed to come from center pivot systems.

In this model, the decision variables are a_{ij} and x_{ij}, the acres planted and amount of water applied to each crop. Harvested acreage is a function of planted acres such that $h_{ij} = k_{ij} a_{ij}$ where k_{ij} is defined as the ratio of the average harvested acreage to the average planted acreage for each crop and county. For irrigated crops, y_{ij} is a quadratic function of the amount of water applied, x_{ij}, while for dryland crops the yield is set at the ten year average yield according to the NASS data. Finally, per acre specified costs for each crop were adjusted to 60% of the value in the budgets for two reasons. First, the calculations do not include government supports and reducing the costs account for this. Second, the extension service budgets tend to overestimate the amount of inputs that farmers will use during production; therefore, reducing the specified cost more accurately represents the actual costs faced by the producer.

The constraints of the model are as follows:

(2) $y_{ij} \geq y_{ij\,min}$,

(3) $0 \leq a_{ij} \leq a_{ij\,max}$,

(4) $0 \leq x_{ij\,irr} \leq 23$, and

(5) $x_{ij\,dry} = 0$.

Equations 2 and 3 are meant to constrain acreage and yield to amounts that would be reasonable for the Texas High Plains according to historical data. Equation 2 states that per acre crop yield in a county is at least the minimum yield reported by NASS for the county. Equation 3 states that the amount of acres of a crop planted in a county cannot exceed the maximum amount that is historically planted. Equations 4 and 5 constrain water use in each county so that for irrigated crops (4) the amount of water used cannot exceed twenty-three acre-inches and for the dryland crops (5) the amount of water that can be applied is zero.

Calculating Carbon Emissions

Carbon emissions in the model were calculated using the method used by Popp, et. al (2010) in which each unit of input in the extension service budget is equated to a number of units of carbon emitted. For example, if one lb. of fertilizer is equivalent to 0.2 lbs. of carbon emitted, then applying twenty five pounds of fertilizer to an acre of a crop is equivalent to that acre emitting five pounds of carbon. Adding up the calculated emissions for each input results in the per acre carbon emission for the crop in question. This study makes use of gross carbon emissions and makes no attempt to calculate net carbon emissions.

Figures 2 and 3 show per acre carbon emissions estimated from the extension service budgets for dryland and irrigated crops respectively. Emissions for dryland crops range between about sixty and one hundred pounds of carbon per acre. Emissions for irrigated crops are much higher, ranging in the mid five hundreds for cotton, sorghum, and wheat and in the eight hundreds for corn and peanuts. These emission calculations assume that producers apply to a crop the amount of each input specified in its budget. To evaluate how water use might change under different carbon reducing policies, this study differs from Popp et. al by allowing the amount of water applied to each crop to vary as a decisions variable, thus the carbon emissions calculated in the model will vary depending upon how much water is applied to each crop.

Evaluating Carbon Policies

Using the above model and method of calculation carbon, two policies were considered to encourage carbon reduction: a per unit tax on emissions and a per unit subsidy for carbon abatement. First, an initial run for each county was performed with no restriction placed on carbon, the results of which provided baseline estimates of net revenue, acreage, water usage, and carbon emissions. The model was then estimated a second time with carbon emissions restricted to 85% of the baseline. The shadow price of this restriction for each county became the amount of the tax or subsidy per unit of carbon emitted or abated in subsequent runs of the model.

The shadow price of the constraint on carbon can be interpreted as how much the farmer would be willing to pay to emit one more pound per acre of carbon beyond the restriction. By charging a per unit tax equal to the shadow price for each pound of carbon emitted above the policy goal, the farmer could be forced to reduce his or her carbon emissions down to the point where the tax equals his willingness to pay to emit. Similarly, paying the farmer a per unit subsidy equal to the shadow price for each pound of carbon not emitted, the farmer could be convinced to reduce his or her emissions down to the point where the subsidy equals how much he or she values one more pound of carbon.

To evaluate the effect of a tax, the original model was modified to include a new term:

$$(6)\quad Max\ NR = \sum_j [(h_{ij} y_{ij} p_j) - a_{ij}(c_{ij} + r_i x_{ij})] - (E_i - .85B_i)T_i.$$

In this new specification, E_i is defined as the total emissions for county i, B_i is the total emissions calculated in the baseline, and T_i is the per unit tax on emissions. According to this specification, farmers in the county are taxed for any emissions above a goal emission of 85% of the baseline. To avoid a negative tax and new constraint was added:

$$(7)\ \ E_i - .85B_i \geq 0.$$

Similarly, a subsidy for carbon emission reduction was evaluated using the specification:

$$(8)\ \ Max\ NR = \sum_j [(h_{ij} y_{ij} p_j) - a_{ij}(c_{ij} + r_i x_{ij})] + (B_i - E_i) S_i,$$

where S_i is the subsidy per unit of carbon reduced from the baseline. In this specification a farmer is paid a subsidy for each pound of carbon under the baseline they choose not to emit. The same constraint specified in (7) was used to constrain the reduction in emissions to 85% of the baseline. Both of these alternate models were estimated for each county and the results compared to the results from the baseline and 85% constrained runs of the original model.

After running the model using equations (6) and (8) and the individual shadow prices for each county, the tax and subsidy models were estimtaed a second time using the average shadow price. Using the individual county shadow price assumes that whatever agency implements these policies would charge a different tax or pays a different subsidy for each farm. Averaging the shadow price from each county provides a single tax or subsidy amount for the region. The results using this average can be compared to the results using the individual shadow price to determine how effective a single tax or subsidy would be at reducing carbon emissions across the region.

Results

County Shadow Prices

The shadow prices estimated by the model are reported in tables 1 and 2. Shadow prices in the Northern High Plains (NHP) have an average value of 0.27, or $.27 per pound of carbon, with a high of 0.4 and a low of 0.1. In the Southern High Plains (SHP), the average shadow price is .67, or $.67 per pound of carbon, with a high of 2.6 and a low of 0.2. District 2 shadow prices are higher because there is more irrigated agriculture practiced in this area. Farmers in these counties require more water for production and, therefore, place a higher value on the ability to emit carbon in the form of energy expenditures for irrigation. The average shadow price across all counties in the region is 0.435, or $.44 per pound.

Net Revenue

Table 3 reports the total net revenue for the entire Texas High Plains (THP), the Northern High Plains, and Southern High Plains. Comparing the baseline run of the model to the constrained run reduces net revenue by about 9% for the region as a whole. The NHP sees about a 6% decrease in net revenue, and the SHP sees about a 10% decrease.

Using each county's individual shadow price as the tax rate results in an 8.3% decrease in net revenues compared to the baseline. For many counties, the model was able to reduce carbon to the goal level of emissions while maintaining higher net revenue than was estimated in the constrained run of the model. When restricting carbon through a constraint, the model would generally maintain a county's baseline acreage and reduce the amount of water applied; but, when using a tax to restrict carbon, the model would reduce acreage so that more water could be applied to irrigated crops. As a result, per acre profit increased and the total net revenue estimated for the area is slightly greater than the amount estimated in the constrained model.

Using the average tax rate reduces net revenue for the area by about 14% compared to the baseline, and by about 6.5% compared to a specific county tax; however, there was one county for which the model could not find an optimal solution using the average tax rate. The lack of data for this county makes comparisons between the two tax scenarios difficult; however, it is reasonable to assume that the difference between the scenarios can be explained at least in part by the absence of the missing county from the aggregate results. The net revenue for the missing county using its individual shadow price was about $115 million, which accounts for most of the total difference between the scenarios. The shadow price for the missing county was estimated at 1.2, which is about three times the average value, so it is likely that using the average shadow price as a tax rate would not completely reduce carbon emissions to the goal level and the county would incur some tax. Based on the results from the model, using an average tax rate for the region would reduce net revenue compared to a scenario where an individual tax rate for each county is used; however, the amount of the difference is unclear.

When considering a subsidy as a means to reduce carbon emissions, using each county's individual shadow price compensates producers so that net revenue remains close to the level found in the baseline. In fact, the net revenue for the entire region slightly increases when a subsidy is offered for carbon reduction; however, when using the average shadow price as the subsidy level net revenue for the region decreases by 3.7%. Similar to the case of an average tax, there was one county in the south for which an optimal solution using the average subsidy amount could not be found. Including this county in a real world subsidy would increase producer net revenue in this scenario closer to the baseline.

Acreage

The total acres of each crop planted in the Northern High Plains and in the Southern High Plains are listed in Tables 4 and 5, respectively. NHP acreage shows little variation across the various scenarios. While there are slight changes in sorghum, wheat, and corn, the amount of acreage gained or lost is generally too small to be economically meaningful, and cotton acreage stays constant throughout. SHP acreage saw more variability in acreage, especially in the case of irrigated wheat, peanuts, and cotton. The variability of cotton is especially interesting considering its real world importance to the area and the fact that in the northern region cotton acres remained constant. The fact that cotton acres are reduced in the southern region could mean that managing carbon emissions in this area could have impacts beyond the High Plains in the global cotton market.

Carbon Emissions

Total carbon emissions for the region in each scenario are shown in Table 6. In every tax and subsidy scenario, carbon emissions are close to the 85% constraint. Interestingly, this holds true in the Southern High Plains despite the fact that many of the counties in the southern region had a shadow price greater than the average. Further study of each individual county revealed that the model was able to find a solution in many of these counties that reduces emissions to 85% of the baseline even with a lower tax or subsidy than dictated by the shadow price. This result indicates that using the average shadow price as the tax or subsidy amount would be effective as an incentive for reducing carbon emissions even in areas that exhibit a very high value for carbon emissions.

Water Use

The total amount of water allocated to each crop in the northern and southern regions is shown in Tables 7 and 8. In the northern counties the majority of water pumped from the aquifer is applied to corn while cotton and wheat are allocated similar amounts; however, NHP wheat acreage is twice that of cotton acreage so the amount of water applied per acre to cotton is higher. In the southern counties cotton receives the vast majority of the water pumped from the aquifer; possibly part of the reason that cotton acreage reduces so much when carbon emissions are constrained. While the water applied to all of the crops decreases when carbon is constrained, the percent change in the amount of water applied to wheat, and sorghum is much higher than the change in the amount applied to corn, cotton or peanuts.

Table 9 shows the change in total water use for the region. Constraining carbon by any means produces similar water savings. For the region as a whole, constraining carbon to 85% of the baseline would result in about 22.3% less water applied to crop production. The northern and southern regions would see similar reductions in water use. These results suggest that constraining carbon emissions could significantly reduce water use in the region.

Discussion and Conclusions

The results of this study indicate that by either taxing carbon emissions above a certain threshold or by subsidizing the reduction of carbon emissions, the Texas High Plains could indeed see reductions in the amount of water pumped from the Ogallala Aquifer. When aiming to reduce emissions by 15% the model showed that more than 20% less water was applied to crop production. Achieving these savings resulted in net revenue decreasing to about 90% of the baseline in the case of a tax, and net revenue remaining at a level similar to the baseline in the case of a subsidy

While such policies may seem to achieve the stated goal, there are still some questions about their feasibility. One question that still needs to be answered is whether or not the price of either of these policies is too high. One might argue that charging $.44 per pound of carbon is too much. At this price per pound, farmers would pay a total of $5 million in taxes to the government or the government would be paying about $200 million in subsidies to farmers. Whether either of these parties could afford to pay, or should pay, the related amount is questionable. One way to evaluate the price of carbon estimated in this study would be to compare it to the market price of carbon; however, at this time there is no market for carbon in the United States, so determining if the value of carbon estimated in this study is too high is difficult.

A second question regarding the feasibility of these policies is what unintended consequences they might have with regard to production practices. This entire study is based on the premise that linkages between carbon emissions and water can lead to water conservation, but what other linkages might exist that disrupt this relationship? This study assumes the use of center pivot technology, but would imposing carbon restrictions spur a shift to alternate irrigation systems such as drip irrigation? Drip irrigation emits a significantly smaller amount of carbon that center pivot irrigation, and the higher yields realized with drip systems actually tend to encourage water use. The implication is that enacting carbon restrictions in irrigation might actually increase water use in the long run.

Further research along the lines of this study is needed before any type of carbon reduction policy is actually considered. The above questions are obvious candidates for future projects, and the consideration of net carbon emissions is another. Previous studies show that considering net emissions does have an effect on the results of the model. Currently the calculations necessary to include sequestration in model for the Texas High Plains are not far enough along to use; however, it would be appropriate to include sequestrations in later versions of this project once the methods are available.

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Figure 1. The Texas High Plains

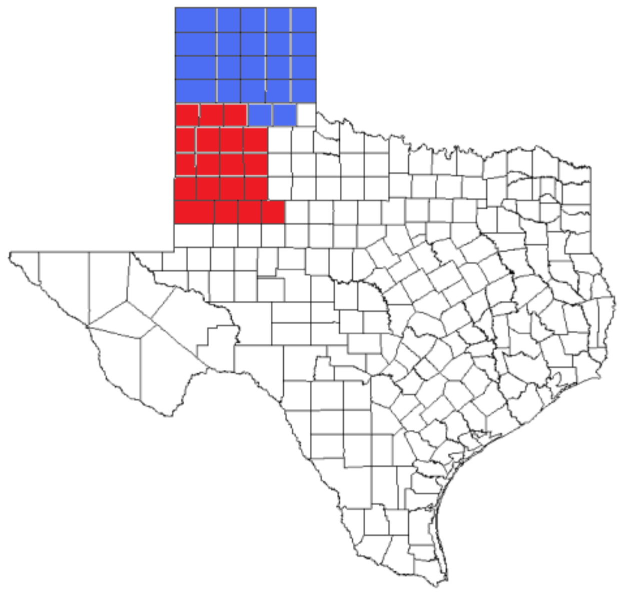

Figure 2. Texas High Plains carbon emissions for dryland crops (lbs/acre)

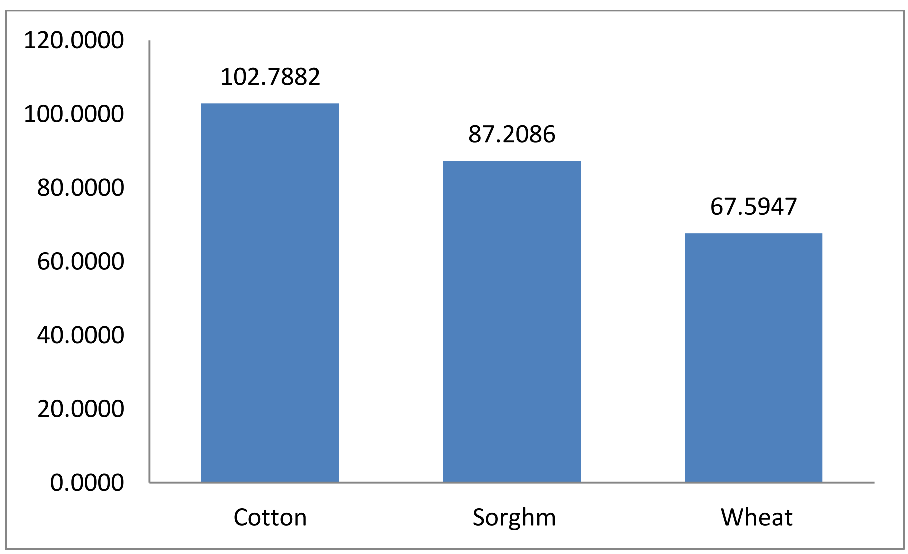

Figure 3. Texas High Plains carbon emissions for irrigated crops (lbs/acre)

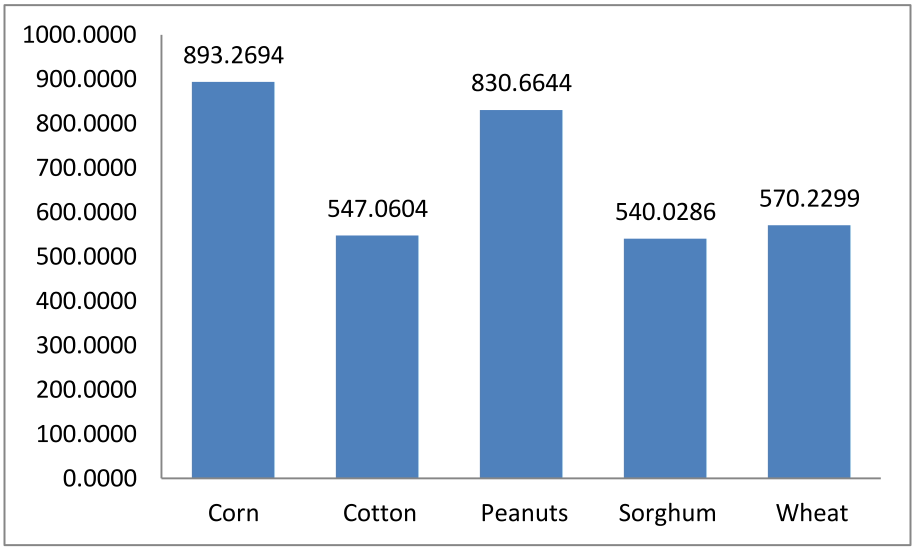

Table 1. Shadow prices for NHP counties

County	Shadow Price	County	Shadow Price
Armstrong	0.4	Hemphill	0.2
Briscoe	0.3	Hutchinson	0.4
Carson	0.3	Lipscomb	0.2
Collingsworth	0.3	Moore	0.3
Dallam	0.4	Ochiltree	0.2
Deaf Smith	0.2	Oldham	0.1
Donley	0.3	Potter	0.1
Gray	0.2	Randall	0.2
Hall	0.4	Roberts	0.2
Hansford	0.2	Sherman	0.4
Hartley	0.3	Wheeler	0.3

Table 2. Shadow prices for SHP counties

County	Shadow Price	County	Shadow Price
Bailey	0.3	Hockley	0.3
Borden	0.4	Lamb	0.2
Castro	0.2	Lubbock	0.4
Cochran	2.6	Lynn	1.0
Crosby	No Results	Parmer	0.3
Dawson	0.6	Scurry	1.3
Floyd	0.2	Swisher	0.2
Gaines	0.5	Terry	1.2
Garza	1.1	Yoakum	0.5
Hale	0.2		

Table 3. Summary of Net Revenue

	THP	NHP	SHP
Baseline	$ 1,952,081,104	$ 491,976,297	$ 1,460,104,807
Constraint	$ 1,773,410,162	$ 462,552,545	$ 1,310,857,617
County Tax	$ 1,790,285,216	$ 461,395,874	$ 1,328,889,343
Average Tax	$ 1,673,773,248	$ 460,306,566	$ 1,213,466,682
County Subsidy	$ 1,969,651,078	$ 516,634,855	$ 1,453,016,224
Average Subsidy	$ 1,880,582,535	$ 537,712,321	$ 1,342,870,215

Table 4. NHP Acreage

			Tax		Subsidy	
	Baseline	**Constraint**	**County**	**Average**	**County**	**Average**
Corn	622,587	617,690	598,610	620,841	598,610	620,841
Dry Cotton	209,500	209,500	209,500	209,500	209,500	209,500
Irr. Cotton	231,500	231,500	231,500	231,500	231,500	231,500
Peanuts	0	0	0	0	0	0
Dry Sorghum	102,084	102,084	103,882	102,084	103,882	102,084
Irr. Sorghum	0	0	0	0	0	0
Dry Wheat	224,106	257,313	259,489	218,270	259,489	218,270
Irr. Wheat	582,347	606,171	582,347	580,847	582,347	580,847
Total	**1,972,124**	**2,024,258**	**1,985,329**	**1,963,042**	**1,985,329**	**1,963,042**

Table 5. SHP Acres

			Tax		Subsidy	
	Baseline	**Constraint**	**County Tax**	**Average Tax**	**County**	**Average**
Corn	231,078	228,536	224,100	228,812	224,100	228,812
Dry Cotton	949,445	940,742	901,528	789,892	901,528	789,892
Irr. Cotton	1,842,806	1,840,408	1,839,300	1,711,606	1,839,300	1,711,606
Peanuts	108,254	108,254	64,262	77,554	64,263	85,187
Dry Sorghum	198,090	198,067	194,472	198,090	194,473	198,090
Irr. Sorghum	402,575	402,574	396,712	402,575	396,712	402,575
Dry Wheat	214,800	214,800	209,800	209,800	209,800	209,800
Irr. Wheat	120,000	120,000	106,019	120,000	106,020	120,000
Total	**4,067,048**	**4,053,380**	**3,936,194**	**3,738,329**	**3,936,195**	**3,745,962**

Table 6. Total Carbon Emissions

	THP	**NHP**	**SHP**
Baseline	3,294,722,331	1,192,002,455	2,102,719,877
Constraint	2,801,810,477	1,014,498,582	1,787,311,895
County Tax	2,823,411,274	1,030,038,461	1,793,372,813
Average Tax	2,721,828,781	1,014,498,582	1,707,330,199
County Subsidy	2,823,411,274	1,030,038,461	1,793,372,813
Average Subsidy	2,659,669,107	1,014,498,582	1,645,170,525

Table 7. NHP Water Use per Crop (ac-in)

	Corn	Cotton	Peanuts	Sorghum	Wheat
Baseline	14,319,490	4,797,044	0	0	7,882,355
Constraint	12,179,561	4,043,599	0	0	4,689,193
County Tax	12,460,704	4,196,964	0	0	5,089,567
Average Tax	12,429,024	4,068,930	0	0	4,598,628
County Subsidy	12,460,704	4,196,964	0	0	5,089,567
Average Subsidy	12,429,024	4,068,930	0	0	4,598,627

Table 8. SHP Water Use per Crop (ac-in)

	Corn	Cotton	Peanuts	Sorghum	Wheat
Baseline	4,209,405	32,187,579	2,489,849	6,177,123	1,487,182
Constraint	3,681,260	27,068,221	1,970,295	2,569,809	886,261
County Tax	3,632,541	28,335,422	1,445,246	2,755,649	887,683
Average Tax	3,687,625	26,563,040	1,750,959	2,565,283	886,261
County Subsidy	3,632,539	28,335,421	1,445,246	2,755,649	887,683
Average Subsidy	3,687,625	26,483,169	1,834,492	2,565,283	886,261

Table 9. Total Water Use

	THP	NHP	SHP
Baseline	73,550,026	26,998,889	46,551,137
Constraint	57,088,199	20,912,353	36,175,846
County Tax	58,803,776	21,747,235	37,056,541
Average Tax	56,549,751	21,096,582	35,453,169
County Subsidy	58,803,773	21,747,235	37,056,538
Average Subsidy	56,553,412	21,096,582	35,456,830