Input Substitution in Irrigated Agriculture in the High Plains of Texas, 1970–80

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The adaptability of irrigated agriculture in the High Plains region of Texas in the 1970–80 period is analyzed by estimating Allen partial elasticities of substitution for five key inputs (water, labor, center pivot, furrow, and wheel roll systems) used to produce two crops (cotton and grain sorghum). The results indicate that farmers have adapted to changes in a manner generally consistent with prior expectations concerning complementarity and substitutability among inputs. The output-constant price elasticity of water demand was statistically significant but relatively small (−.25).

Key words: elasticity of substitution, irrigation technology, pump cost, Texas.

Irrigated agriculture in the western United States has experienced tremendous changes in the past three or more decades. It appears that many more dynamic adjustments will occur in the future. Rising (real) prices for key inputs (water, labor, and capital) and falling crop prices represent only some of the potential problems that must be confronted. How will farmers adapt to these new constraints? The recent advances in irrigation technology provide reasons to be somewhat sanguine. But, more important, it is essential to understand the flexibility of farmers in adapting to dynamic changes in irrigated agriculture. Unfortunately, knowledge in this area is sparse. As Frederick and Hanson have observed, "Less may be known about the impact of irrigation on the overall performance of U.S. agriculture than is known about the impact of any of the other principal inputs" (p. 3). One way to anticipate farmers' future adaptability is to analyze how they have adjusted to changes in the recent past. Several studies have analyzed the adjustment in water usage due to rising pumping costs and the benefits from groundwater management (Feinerman and Knapp; Gisser and Sanchez; Nieswiadomy; Shipley and Goss). Recently, Caswell and Zilberman used historical data to determine the likelihood of adopting furrow, sprinkler, or drip irrigation in California. However, no rigorous analysis of the changes in the usage of all irrigation inputs has been conducted.

To this end, this paper analyzes the adaptability of irrigated agriculture in the High Plains of Texas in the 1970–80 period by using a dual cost function to estimate Allen partial elasticities of substitution for five key inputs (water, labor, center pivot, furrow, and wheel roll systems) that are used to produce two crops (cotton and grain sorghum). The 1970–80 period is significant because 1970 was the first year in which the center pivot, a significant advancement in irrigation technology, came into use.[1] The results indicate that farmers have adapted to changes in a manner consistent with most a priori agricultural engineering expectations concerning relative complementarity and substitutability among inputs. Although these results are based on cost-minimizing adjustments to past input price changes, the re-

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[1] The study period ends in 1980 because of the lack of data on irrigation equipment usage. TAES's *High Plains Irrigation Survey* was unfortunately discontinued after 1977. Three additional years of data were gathered via personal communication with extension agents. See appendix for further details.

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sults may give some evidence of the ability which farmers might have to adjust to future changes.

The paper is organized as follows. Changes in irrigated agriculture in the study area are first reviewed. This is followed by a description of the translog cost function along with a discussion of the estimation procedure. Then the parameter estimates and the elasticities of substitution are presented and analyzed. The paper concludes with a summary and a discussion of the limitations of the study. The appendix includes a description of the variables used in the study.

A Review of Changes in Irrigated Agriculture

Irrigation systems have undergone major quantitative and qualitative changes in the past three decades. In the initial stages, irrigation was performed using furrow flooding methods on "hardland soil." However, furrow flooding could not be used easily on sandy soils because of water losses from deep percolation. In the 1950s, aluminum pipe sprinkler systems came into widespread use in Texas counties having sandy soil or rolling topography. Early sprinkler units were very labor intensive because the pipe had to be moved and assembled by hand. In the early 1960s technological improvements resulted in motorized wheel roll systems, which reduced labor requirements by 50% (Lacewell and Hughes). But an even greater technological implementation came in the late 1960s with the introduction of center pivots, perhaps prompted by the tight labor supply conditions at that time.

The center pivot system became extremely popular, probably because it required only one-fourth the amount of labor that a furrow or hand move system needed (Hughes). The center pivot has several other advantages over conventional furrow systems because it can be used on hillier land and sandier soil with higher application efficiency.[2] One drawback of the center pivot was its relatively high energy requirements. Energy use comparisons between these systems must be based on the costs of delivering a given amount of water to the root zone of the plants. According to Frederick and Hanson, the total energy cost of a gravity distribution system with a 50% application efficiency exceeds that of a center pivot system with an 80% application efficiency for pumping depths of 250 feet or more. Thus, center pivots were more likely to be water saving rather than energy saving.[3]

Tables 1 and 2 summarize some of the major changes that have occurred in the study area. The study area consists of seven counties covering 4,304,640 acres in the southern portion of the High Plains of Texas: Cochran, Dawson, Gaines, Hockley, Lynn, Terry, and Yoakum. The region was chosen because of the approximate homogeneity of the production process across counties. Each county grows primarily two crops, cotton and grain sorghum, and the counties' soils have a similar sandy composition. Because many of the price and quantity variables were constructed from primary data, a description of the construction techniques is presented in the appendix.

From table 1 it is apparent that there was substantial volatility in real input and output prices in the 1970–80 period. In particular, the increase in pumping cost stands out as the most significant change. There were also large changes in input usage and crop output, as shown in table 2. Although pumpage and surface irrigation declined greatly, the most remarkable change was the tremendous rise in center pivot usage in the 1970s. On the output side, grain sorghum output decreased as cotton output rose. Because most agricultural studies indicate that grain sorghum is the more water intensive crop,[4] these results would be expected as water became relatively more expensive, *ceteris paribus.*

Theoretical and Statistical Models

The models that follow are grounded on principles of duality developed by Samuelson,

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[2] Application efficiency is defined as the ratio of the amount of water that is retained in the root zone divided by the amount of water delivered to the soil surface.

[3] Note that the technological characteristics described here pertain to the 1970–80 study period. Many technical advances have occurred for both center pivots (e.g., low pressure) and furrow systems (e.g., surge techniques) in the 1980s which are not accounted for in this study. The data for 1981 forward is not available.

[4] Heimes and Luckey's study (p. 9) calculated the irrigation requirements for various crops using the Blaney-Criddle formula. For a representative county in the High Plains of Texas, the annual irrigation demand is 14.1 inches for sorghum and 11.8 inches for cotton.

Table 1. Changes in Input and Output Prices in a Seven County Area of the Texas High Plains

Variable	1970	1980	%Δ 1970–80
Pump cost[a] ($/acre foot)	1.71	3.58	+109.4
Center pivot[b] cost ($user cost/system)	2,113	2,207	+4.4
Furrow cost ($user cost/acre)	1.71	2.16	+26.3
Wheel roll cost ($user cost/system)	1,202	1,019	−15.2
Wage ($/hour)	1.16	1.26	+8.6
Cotton price ($/lb.)	0.21	0.23	+9.5
Grain sorghum ($/bushel)	0.94	1.04	+10.6

Note: The seven counties are Cochran, Dawson, Gaines, Hockley, Lynn, Terry and Yoakum, covering 4,304,640 acres.

[a] Pump cost is the cost of the energy needed to pump one acre foot of water per foot of lift times the average lift, expressed in 1967 dollars.

[b] See the appendix for a discussion of the calculation of all input user costs and output prices. All costs and prices are expressed in 1967 dollars.

Shephard, Uzawa, and Diewert. They are used to estimate elasticities of substitution from cost-minimizing factor demand equations. To this end, assume that for each farm there exists a cost function:

$$C = C(P_i, q) \qquad i = 1, \ldots, 5, \tag{1}$$

where q is the vector of outputs and P_i is the price of the ith input. Uzawa showed that, under the postulate of cost minimization, the partial elasticity of substitution between inputs i and j is

$$\sigma_{ij} = C(\partial^2 C/\partial P_i \partial P_j)/((\partial C/\partial P_i)(\partial C/\partial P_j)). \tag{2}$$

A translog cost function (Christensen, Jorgenson, and Lau) pertaining to five inputs (water, center pivot, furrow, wheel roll, and labor) and two outputs (cotton and grain sorghum) and a fixed factor (rainfall [R]) may be written

$$\begin{aligned} \ln C = \alpha_0 &+ \sum_{k=1}^{2} \alpha_i \ln Y_k \\ &+ \sum_{i=1}^{5} \beta_i \ln P_i + \theta_r \ln R \\ &+ \tfrac{1}{2}\left(\sum_{k=1}^{2}\sum_{l=1}^{2} \delta_{kl} \ln Y_k \ln Y_l\right) \\ &+ \tfrac{1}{2}\left(\sum_{i=1}^{5}\sum_{j=1}^{5} \gamma_{ij} \ln P_i \ln P_j\right) \\ &+ \tfrac{1}{2}(\theta_{rr}(\ln R)^2) \\ &+ \sum_{k=1}^{2}\sum_{i=1}^{5} \rho_{ik} \ln Y_k \ln P_i \\ &+ \sum_{k=1}^{2} \epsilon_k \ln Y_k \ln R \\ &+ \sum_{i=1}^{5} \phi_i \ln P_i \ln R, \end{aligned} \tag{3}$$

Table 2. Changes in Input Usage and Crop Output in a Seven County Area of the Texas High Plains

Variable	1970	1980	%Δ 1970–80
Pumpage[a] (acre feet)	168,795	83,324	−50.6
Center pivot (systems)	6	164	+2,633
Surface irrigation (acres)	42,714	25,917	−39.3
Wheel roll (systems)	378	375	−1
Labor (+180 day workers)	423	460	+8.7
Cotton (million lbs.)	29.138	35.292	+21.1
Grain sorghum (100,000 bushels)	13.824	2.986	−78.4

Note: All measurements are averages per county.

[a] Pumpage, cotton and grain sorghum measurements are two-year averages to partially smooth for seasonal variation in weather. See the appendix for an explanation of variable calculations.

where α_0, α_i, β_j, θ_r, δ_{ij}, γ_{ij}, θ_{rr}, ρ_{ij}, ϵ_k, and ϕ_i are parameters determined by the technology. (Note that weak separability is assumed to eliminate all other inputs such as fertilizer and other capital inputs. No data is available on the use of these inputs in irrigated agriculture. However, it seems likely that the levels of usage of fertilizer and herbicide, for example, do not affect the ratio of the marginal products of the inputs under consideration. Thus, these other input prices are not shown because they will not appear in the share equations—since the derivatives of the logged prices of interest do not involve the prices of the separable inputs. Of course, this is primarily a short-run, not a long-run, argument.[5]) To ensure $\sigma_{ij} = \sigma_{ji}$, a symmetry condition is imposed: $\gamma_{ij} = \gamma_{ji}$, for $i \neq j$. The linear homogeneity assumption in factor prices entails the restrictions:

$$\text{(4a)} \qquad \sum_{i=1}^{5} \beta_i = 1$$

$$\text{(4b)} \qquad \sum_{i=1}^{5} \rho_{ik} = 0 \qquad k = 1, 2$$

$$\text{(4c)} \qquad \sum_{i=1}^{5} \gamma_{ij} = 0 \qquad j = 1, \ldots, 5$$

$$\text{(4d)} \qquad \sum_{i=1}^{5} \phi_i = 0.$$

Assuming the appropriate conditions on the underlying technology and producer behavior, Shephard's lemma shows that

$$\text{(5a–e)} \quad \partial \ln C/\partial \ln P_i = \beta_i + \sum_{j=1}^{5} \gamma_{ij} \ln P_j + \sum_{k=1}^{2} \rho_{ik} \ln Y_k + \phi_i \ln R \qquad i = 1, \ldots, 5$$

where $\partial \ln C/\partial \ln P_i = M_i = P_iX_i/C$.

In estimating the system (5a–e), the usual problem of overidentification must be addressed. One may incorporate the a priori restrictions by writing (5a–e) as

$$\text{(6)} \quad M_i = \beta_i + \sum_{j=1}^{4} \gamma_{ij} \ln(P_j/P_5) + \sum_{k=1}^{2} \rho_{ik} \ln Y_k + \phi_i \ln R + e_i \qquad i = 1, \ldots, 4$$

and restricting $\gamma_{ij} = \gamma_{ji}$ (for $i \neq j$) in a systems estimation procedure. The parameters of the fifth equation can be obtained using the restrictions (4a)–(4d). The parameters are estimated by the iterative Zellner-efficient (IZEF) method (which has been shown by Kmenta and Gilbert to yield maximum likelihood estimates), which are invariant to the four equations chosen. The data consist of seven individual county observations for each year of the eleven-year period ($n = 77$).

Parameter Estimates

The estimates and asymptotic t ratios appear in table 3. In assessing the estimates it may be helpful to note the following points. First, substituting the translog derivatives into equation (2) yields the usual own- and cross-elasticities of substitution:

$$\text{(7)} \qquad \sigma_{ii} = (\gamma_{ii} + M_i^2 - M_i)/M_i^2$$

$$\text{(8)} \qquad \sigma_{ij} = (\gamma_{ij}/M_iM_j) + 1 \qquad i \neq j.$$

Second, because the constant-output elasticity of demand for input i is $E_{ii} = M_i\sigma_{ii}$, each σ_{ii} must be nonpositive as a stability condition. None of the estimates is statistically significantly positive. Testing other stability conditions is difficult (Moroney and Toevs), so these tests were not performed. Third, the mean values of relative shares are treated as constants in estimating the asymptotic variances of the elasticities.

The estimated elasticities, evaluated at sample means, and their asymptotic standard errors appear in table 4. Many of the results are statistically significant and consistent with a priori agricultural engineering assumptions concerning relative substitutability and complementarity, as described earlier. Starting with the water equation, water's own elasticity ($\sigma_{11} = -.95$) is significantly negative. This result is evidence of the adjustments farmers made to rising pump costs in the 1970s. In this study period, the furrow system and labor appear to be substitutes for water because both σ_{13} and σ_{15} are significantly positive. On the other hand,

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[5] Sufficient data on the prices of hand move pipe were not available. The separability argument must be made to justify the omission of hand move systems. Also, hand move systems irrigated only 12.6% of all acres served by sprinkler systems as opposed to 87.4% for center pivots and wheel roll systems in 1979 (TDWR 1981). For a discussion of separability of cost functions, see Blackorby, Primont, and Russell, especially theorems 3.4 and 7.1.

Table 3. Translog Cost Function Estimates

Parameter	Estimate	Parameter	Estimate
β_1	4.675 (6.70)	γ_{35}	−0.393 (−4.16)
β_2	2.074 (1.75)	γ_{44}	0.200 (1.23)
β_3	−3.934 (−3.00)	γ_{45}	0.412 (3.37)
β_4	2.833 (1.85)	γ_{55}	−0.226 (−1.75)
β_5	−4.641 (−3.48)	ρ_{11}	−0.141 (−4.59)
γ_{11}	0.127 (3.32)	ρ_{12}	0.017 (0.32)
γ_{12}	−0.062 (−2.05)	ρ_{21}	0.043 (2.15)
γ_{13}	0.044 (1.21)	ρ_{22}	−0.001 (−0.33)
γ_{14}	−0.215 (−4.18)	ρ_{31}	0.053 (2.39)
γ_{15}	0.106 (2.79)	ρ_{32}	−0.004 (−0.97)
γ_{22}	0.018 (0.14)	ρ_{41}	−0.042 (−1.10)
γ_{23}	0.376 (3.79)	ρ_{42}	0.013 (1.99)
γ_{24}	−0.433 (−4.30)	ρ_{51}	0.086 (3.63)
γ_{25}	0.101 (1.05)	ρ_{52}	−0.010 (−2.38)
γ_{33}	−0.063 (−0.49)		
γ_{34}	0.037 (0.32)		
ϕ_1	−0.103 (−3.06)		
ϕ_2	−0.002 (−0.91)		
ϕ_3	0.046 (1.97)		
ϕ_4	−0.001 (−0.03)		
ϕ_5	0.060 (2.30)		

Notes: The subscript numbers represent for inputs: water 1, center pivot 2, furrow 3, wheel roll 4, and labor 5; for outputs: cotton 1, grain sorghum 2. Asymptotic t-statistics for testing the null hypothesis that a parameter is zero are listed in parentheses beneath the parameter estimates.

Table 4. Cross- and Own-Substitution Elasticities Estimates from the Translog Cost Function

Elasticity of Substitution	Estimate	Elasticity of Substitution	Estimate
σ_{11}	−0.950 (−1.78)	σ_{33}	−29.30 (−0.95)
σ_{12}	−1.092 (−1.08)	σ_{34}	3.05 (0.47)
σ_{13}	3.54 (1.71)	σ_{35}	−21.06 (−4.02)
σ_{14}	−1.90 (−2.71)	σ_{44}	−0.01 (−0.01)
σ_{15}	2.42 (4.75)	σ_{45}	6.31 (4.01)
σ_{22}	−6.55 (−0.61)	σ_{55}	−5.49 (−3.31)
σ_{23}	53.11 (3.87)		
σ_{24}	−13.03 (−3.98)		
σ_{25}	4.26 (1.36)		

Notes: See table 3 for subscript notation and t-test description. These elasticities can be converted into cost-minimizing elasticities of demand using equation (2) and the mean cost share values: water 0.267, center pivot 0.111, furrow 0.065, wheel roll 0.278, labor 0.279.

the wheel roll system (and perhaps center pivots, although the t-statistic is not large) is a complement with water, since σ_{14} is significantly negative. The lower energy requirements of the furrow system evidently more than offset its lower application efficiency, which made it a better substitute for water than any of the sprinkler systems studied in this period.[6]

In the center pivot equation, the center pivot's own elasticity is statistically insignificant. The center pivot is definitely substitutable with the furrow system ($\sigma_{23} = 53.11$)—and possibly with labor ($\sigma_{25} = 4.26$), although the t-statistic is not large—and complementary with the wheel roll ($\sigma_{24} = -13.03$). These results are expected, given the relative labor requirements of the systems. As described earlier, the wheel roll uses half as much labor as furrow systems, and the center pivot uses one-fourth as much labor. The complementarity between the wheel roll and the center pivot may be due to their similar technologies (e.g., relatively high pressure requirements, capital intensive) which allow them to share similar maintenance equipment, for example.

With respect to the furrow system, its own elasticity is negative but statistically insignificant. However, there is strong evidence of complementarity between the furrow system and labor ($\sigma_{35} = -21.06$), as is expected, because the furrow system is a labor intensive method.

With respect to the wheel roll system, its own elasticity is statistically insignificant. But

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[6] Please recall footnote 3.

there is strong evidence of substitutability between wheel rolls and labor ($\sigma_{45} = 6.31$), as is expected, because the wheel roll system is a relatively capital intensive system. Finally, labor's own elasticity is statistically negative.

A few of the results in table 3 deserve comment. First, notice that cotton output has a statistically negative effect on water's cost share ($\rho_{11} = -.141$), while grain sorghum output has a statistically insignificant effect on water's cost share. This is expected because grain sorghum is relatively more water intensive.[7] As the relative amount of cotton to grain sorghum output increases, *ceteris paribus,* water's share of total cost should decrease, and vice versa.

Finally, note that an increase in rainfall significantly decreases water's share of cost ($\phi_1 = -.103$), as is expected. Further, $\phi_5 = .060$ shows that as rainfall increases, producers are able to take advantage of this free substitute for all other forms of irrigation; thus, the relative cost share of labor increases. This result gives some evidence that the method used to calculate annual water pumpage, described in the appendix, is reasonably accurate and warrants consideration for use in future research.

Summary and Conclusions

This paper has shown that farmers exhibited adaptability to the economic changes of the 1970s. Most of the elasticities of substitution estimates (9 of 15) were statistically significant and intuitively plausible in terms of relative substitutability and complementarity. Water's own elasticity is significantly negative, indicating that farmers did reduce their water usage in response to the shock in pump costs. However, because the output-constant water demand elasticity is only $-.25$, the responsiveness was relatively small. Water appeared to be substitutable with labor and furrow systems and complementary with wheel rolls (and perhaps center pivots). The lower energy requirements for furrow versus wheel roll and center pivot sprinkler systems is a possible explanation for this result. The center pivot was strongly substitutable with furrow systems, and perhaps labor, as is expected based on the relatively low labor requirements of center pivots and wheel rolls. For the same reason the furrow system is strongly complementary with labor, and the wheel roll system is strongly substitutable with labor. Finally, the own-elasticity of labor was significantly negative.

Some of the limitations of the study need mentioning. First, even though this study attempts to decompose aggregate technology, the individual technologies themselves (e.g., center pivots) were not perfectly homogenous. Innovations were made over time in center pivots, for example. Unfortunately, there is no further detailed data available. Second, as with other translog cost studies, the adjustment to price changes are modeled as though nearly perfect adjustment occurs instantaneously. Obviously, many lagged effects as the result of price changes (and tax changes) could be considered. Unfortunately, the data are not rich enough to describe the ages and types of equipment used each year to permit a more detailed analysis. Third, the separability argument is crucial. Since several inputs such as fertilizer, chemicals and other capital inputs were not measured, the results may be biased if the level of usage of these inputs affects the ratios of marginal products of the inputs included in the study.

With these caveats in mind, this study is the first to analyze the use of several different irrigation technologies over a significant time period in irrigation history. It has shown that farmers in irrigated agriculture have exhibited some flexibility, which appears intuitively plausible, in confronting dynamic conditions. However, since the output-constant demand elasticity for water is only $-.25$, the degree of flexibility exhibited in the 1970s was relatively small. It would be useful to conduct more research in another area of the High Plains where data for the 1980s are available to determine if farmers are becoming more adaptable to scarce water conditions. Finally, although the data set ends in 1980, it is interesting to note that the Ogallala aquifer in the study area did not decline in 1985 or 1986, for the first time in at least thirty-six years. Obviously many factors are involved in this possible stabilizing of the aquifer, but the adjustment in irrigation technology may have played a role.

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[7] Please recall footnote 4.

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Appendix

Calculation of Variables

Expected crop prices, outputs, and the wage rate. The expected prices of cotton and grain sorghum were chosen to be the higher of the lagged price or the effective support price, as has been done by other researchers (Shumway and Chang). These prices, as well as the hourly farm wage and crop outputs, were obtained from the Texas Department of Agriculture. All prices in this study are expressed in 1967 dollars.

Pump cost. Because both natural gas and electricity are used, a weighted pump cost was calculated based on the estimates of the percentage of wells using these two energy sources given by the Texas Agricultural Experiment Service. The pump cost formulas are based on Sloggett's formulas (p. 5). The energy prices were provided by local energy suppliers: Energas and the South Plains Electric Cooperative.

User costs. The annual cost of the flow of services from the stock of capital was assumed to be the product of the purchase price of the system and the sum of the nominal interest rate and a 5% depreciation rate. The purchase prices of the center pivot, wheel roll, and furrow systems were obtained from local retailers. Costs are expressed in

1967 dollars. The furrow cost per acre was based on the assumption that a system covered 160 acres. This assumption was needed because the TAES measured furrow usage in acres, while measuring center pivot and wheel roll usage in number of units.

Pumpage. Water pumpage is calculated using a method introduced by Nieswiadomy. Essentially, the TDWR and HPUWCD's water level measurements are used to determine the change in pumping depths and pumpage, using the formula $W = \{[(\Delta D \times S) + R] \times A\}/(1 - \alpha)$, where W is water pumpage in acre feet per year, ΔD is the change in depth to the saturated thickness of the aquifer per year, S is the storativity coefficient, R is the recharge rate in feet per year, A is the area of the aquifer in acres, and α is the return flow coefficient.

Irrigation equipment. The annual usage of center pivot and wheel roll systems and the number of surface irrigated acres are tabulated annually in the TAES's *High Plains Irrigation Survey* for 1970–77. Three additional years of data were obtained via communication with county extension agents.

Labor. County employment of farm workers (working more than 150 days) was obtained from the U.S. Department of Commerce, Bureau of Economic Analysis unpublished data, 1969–80. Irrigation labor was estimated as the percentage of total planted acres irrigated each year in each county multiplied by the number of farm workers in each county. This averaged approximately 47% over the 1970–80 period. These data were obtained from *County Statistics,* Texas Department of Agriculture, for these counties.

Rainfall. Rainfall is treated as a fixed factor, not in a stochastic sense, but in the sense of an endowment. Peak growing season rainfall (June–August) data were obtained from the NOAA for each county.