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Economic Efficiency of Short-Term Versus Long-Term Water Rights Buyouts

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Because of the decline of the Ogallala Aquifer, water districts, regional water managers, and state water officers are becoming increasingly interested in conservation policies. This study evaluates both short-term and long-term water rights buyout policies. This research develops dynamic production functions for the major crops in the Texas Panhandle. The production functions are incorporated into optimal temporal allocation models that project annual producer behavior, crop choices, water use, and aquifer declines over 60 years. Results suggest that long-term buyouts may be more economically efficient than short-term buyouts.

Key Words: dynamic production function, nonlinear optimization, Ogallala Aquifer, water rights buyout

JEL Classifications: Q30, Q32, Q38

Agriculture in the Great Plains is heavily dependent on groundwater supplies from the Ogallala Aquifer. Over 70% of the total value of crop production in the area comes from irrigated acreage overlying the aquifer, which encompasses 174,000 square miles and underlies parts of eight states: Texas, New Mexico, Oklahoma, Colorado, Kansas, Nebraska, South Dakota, and Wyoming (Alley, Reilly, and Franke). The abundant supply of feed grains produced with water from the Ogallala Aquifer fuels the livestock, meatpacking, and ethanol industries. Additionally, the area produces approximately 32% of the national production of cotton (National Agricultural Statistics Service [NASS]). Many of these industries are vertically integrated so that changes in one industry will impact the others, having a ripple effect on the economy. The unfortunate consequence of this integration is that regional economies have become precariously water dependent.

The Ogallala Aquifer has very little recharge and is essentially a finite resource. In portions of the Ogallala Aquifer, up to 40% of the predevelopment storage has already been depleted (Feng and Segarra), and the overdraft continues to take place. Current aquifer decline rates foretell the eventual demise of irrigated agriculture and conversion to dryland production, which may have a significant long-term negative economic impact on the area. Faced with this situation, policymakers, state water managers, and other stakeholders are investigating conservation policy alternatives aimed at reducing current levels of groundwater consumption and extending the economic life of the aquifer. In order to extend the economic life of the aquifer and maintain the economic base of the region, both voluntary and mandated policy intervention may need to be considered.

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The development and implementation of effective water management strategies for irrigation in the Great Plains is a multidimensional problem and may be more important there than anywhere else in the United States. Policymakers must weigh not only the potential water savings that may be generated through a particular water conservation strategy but also the implementation costs and the potential impacts on the regional economy (Amosson et al.). Other considerations include the incentives that may be required for producer adoption and the regulations and monitoring that may be necessary to ensure that water savings are realized. Failure to address the aforementioned factors can lead to the development and implementation of water conservation strategies that may not reach the goals or may not have the impacts originally intended by water policymakers.

The public policy debate over the sustainability of the aquifer is significant. Several policy alternatives have been suggested, including water taxes, mandatory reductions in current water allocations, voluntary water retirement programs, incentive programs aimed at reducing the planted acreage of water intensive crops, incentive programs aimed at increasing irrigation efficiency, and incentive programs aimed at temporarily converting irrigated land to dryland production. In order to make informed decisions, policymakers need accurate information concerning the economic impacts of these various policies.

This research considers two policy scenarios as well as a status quo scenario for nine counties of the southern High Plains of Texas: Cochran, Floyd, Gaines, Hale, Hockley, Lamb, Lubbock, Terry, and Yoakum. These are relatively high-water-use counties that accounted for 1,243,800 irrigated cotton acres, 25,800 irrigated grain sorghum acres, and 38,400 irrigated wheat acres in 2006 (NASS). The three scenarios include 1) a status quo scenario in which no change is made to current water policy, 2) a long-term water rights buyout program where the cropland is permanently converted to dryland production, and 3) a short-term water rights buyout program where the cropland is converted to nonirrigated production but allowed to resume irrigated production after 15 years. Therefore, the objective of the study is to evaluate the efficiency of both long-term and short-term water rights buyout policies.

The concept of purchasing and permanently retiring water rights is relatively new. Ise and Sunding evaluated the state-sponsored purchase of agricultural water rights in the Lahontan Valley of Nevada. Golden evaluated the water rights buyout program in the Rattlesnake Subbasin of Kansas. Supalla, Buell, and McMullen compared the state's cost of purchasing water rights to the state's cost of leasing water rights in Nebraska. The concept of a short-term water rights buyout program is also relatively new. The Environmental Quality Incentives Program (EQIP) provides a voluntary conservation program for farmers and ranchers. Within Kansas, EQIP funds from the Natural Resources Conservation Service are used to suspend irrigated production for four years. The Conservation Reserve Enhancement Program is being used in Nebraska and Idaho to suspend irrigated crop production 14 to 15 years.

Literature Review

In order to accomplish the goals of this research, a variety of economic and hydrological models will be required. The study will require the development of two broad classes of economic models. For simplicity purposes, they will be referred to as models of "production" and models of "temporal allocation." The models of production are necessary to provide the required input for the model of temporal allocation. The models of temporal allocation will provide the required time series forecast on water use, irrigated acreage, and economic productivity for the alternative policy scenarios.

The development of economic models that predict the future are, by their very nature, subject to error, and the results are most appropriately viewed as a "best guess." From a policy analysis perspective, it is not imperative that the predictions be perfectly accurate. It is important to focus on the "difference" between scenarios and not the scenario itself. As long as consistency is maintained between methodology and assumptions, comparisons of different scenarios are appropriate to evaluate water management options.

Models of Production

A production function is a mathematical equation that relates the quantity of output produced to the quantity of inputs used in the production process. As an example, the production function for irrigated corn would quantify the relationship between the bushels of corn produced per acre to the amount of irrigation water applied. There is extensive literature on the shape of crop production functions. Research by Frank, Beattie, and Embleton; Kastens, Schmidt, and Dhuyvetter; Llewelyn and Featherstone; Moore, Gollehon, and Negri; and Paris suggest that crop production functions are curvilinear in nature. As a result, most economic research assumes a polynomial or other curvilinear functional form. The relevance of the shape of production functions is that curvilinear production functions imply diminishing marginal returns to the quantity of irrigation water applied. Simply stated, the yield increase per acre-inch of water applied diminishes as the amount of water applied increases.

Past research has shown that irrigated agriculture is best viewed in a dynamic framework. As an example, choices of technology, crop choice, crop yields, and water use per acre may change over time. Future trends in these variables will impact the status quo and alternative scenarios. Peterson and Bernardo suggest that the ability to predict the future revenues, to a large extent, depends on the ability to predict future yields. As such, this research develops dynamic production functions that account for growth in crop yields as well as gains in water use efficiency.

Models of Temporal Allocation

The models of temporal allocation will provide a 60-year planning horizon representation of water use, aquifer levels, irrigated acreage, and economic productivity. For a confined aquifer, the economic community typically uses the concept of a "single-cell aquifer" as the hydrological model that is incorporated into the temporal allocation model. Within this framework, the aquifer is viewed as being strictly homogeneous on the spatial scale being analyzed. In other words, if analysis is performed on a subarea level, then the aquifer is assumed to be uniform across that subarea.

There are two methods of generating the temporal allocation solution: 1) the competitive market solution and 2) the optimal temporal allocation solution. Gisser and Mercado were among the first to integrate economic theory and the hydrological theory of groundwater flow into a single model. They conceptualized the single-cell aquifer, defined the appropriate equations of motion, and provided the theoretical basis for evaluating the competitive market solution. Within the competitive market framework, a producer maximizes profit by choosing the optimal allocation of water on an annual basis. While a producer may realize that the choice of water use today impacts the aquifer decline and thus the future value of water, this factor is not taken into consideration because of the common property characteristic of the aquifer. Typically, the producer's decisions are simulated on a yearly basis without regard for the future. Comparable models have been developed and applied to groundwater policy management scenarios by Feinerman and Knapp; Gisser; and Gisser and Sanchez.

Within the optimal temporal allocation framework, a single "social planner" determines both current and future water use. The social planner is forward looking and chooses the optimal time path of water use based on the discounted value of future profits considering the marginal benefit of future water consumption. The optimal temporal allocation solution yields an optimal time path for water use. Burt is often credited with developing the decision rules for the optimal temporal allocation of groundwater stocks. Comparable models have been developed and applied to groundwater policy management scenarios by Ding; Gisser; Gisser and Sanchez;

Johnson; and Wheeler. Feinerman and Knapp; Gisser; and Nieswiadomy evaluated both models and suggest that there is very little difference between the competitive market solution and the optimal temporal allocation solution. This research will incorporate the optimal temporal allocation framework.

Analysis of Net Present Value

Net present value comparison is a standard method used to compare long-term projects. The calculation discounts future cash flows to present values and sums the resulting income stream. The use of net present value is a reasonable method for long-lived entities to use when comparing investments and/or project costs. However, it often has been argued that measures of welfare based on the discounted value of the future benefit stream are inappropriate. Ferejohn and Page argued that the use of the discounted present value metric is inappropriate when dealing with welfare maximization over an infinite horizon because it implies that the underlying social preference ranking remains constant over time. Gisser indicates that there is a philosophical problem of the inappropriateness of welfare maximization over an infinite horizon. He argues that the only justification for the application of net present value theory is the assumption that the present generation feels altruistic toward future generations and will represent their best interest.

An additional concern raised by the economic literature is the reliance on net present value as a metric of comparison and the failure to include measures of social welfare loss in the analyses. There probably is no justification for excluding social welfare losses due to the social cost of water in economic analysis. The existence value that society places on the remaining stock of water in the Ogallala Aquifer should not be neglected.

Net present value calculations require a "discount rate" that transforms future values into present values. The use of a positive discount rate would imply the conventional view that profits today are more valuable than profits in the future. A positive discount rate might be chosen by a producer that focuses on the near-term cash flows necessary to meet current obligations, such as land and equipment payments. A 0% discount rate would imply neutrality as to the timing of cash flows. The use of a negative discount rate would imply that profits and, by extension, water are valued more highly in the future than today. Such a stance might be taken by a producer that wants to ensure that water resources are conserved today so that his children might enjoy the stability of irrigated production in the future.

For this research, it is appropriate to use net present value analysis to compare and choose between policy alternatives since all polices were developed to yield similar relatively short-term water savings; therefore, for the purposes of this study, a discount rate of 3% will be used.

Mathematical Model

The effects of the short-term and long-term water buyout policies were evaluated for the purposes of this study using county-level dynamic optimization models for nine relatively high-water-use counties in the Texas High Plains. General Algebraic Modeling System, a computer software optimization program (Brooke et al.), was used in the study to solve the optimization models formulated and to evaluate the respective policy scenarios. The framework of the optimization model used in this study was originally developed by Feng and has been expanded and modified by Arabiyat; Das; Johnson; Terrell; and Wheeler.

The objective of the county-level optimization models is to maximize net present value of net returns to land, management, and groundwater over a 60-year planning horizons for a given county as a whole for both short-term and long-term water rights buyout policies.

The objective function is

$$(1)\quad \text{Max NPV} = \sum NR_t * \left[(1+\Omega)^t/(1+r)^t\right]$$

where NPV represents the net present value of net returns, r represents the discount rate, Ω represents the average rate of technological advancement through time based on historical data, and NR_t represents net revenue at time t. NR_t is defined as

$$NR_t = \sum_i \sum_k \Theta_{ikt}\{P_i Y_{ikt}(WA_{ikt}, WP_{ikt}) - C_{ik}(WP_{ikt}, X_t, ST_t)\}, \quad (2)$$

where i represents crops grown; k represents irrigation technologies used; Θ_{ikt} represents the percentage of crop i produced using irrigation technology k in time t; P_i represents the output price of crop i; WA_{ikt} and WP_{ikt} represent per acre irrigation water applied and water pumped per acre, respectively; $Y_{ikt}[\cdot]$ represents the per acre yield production function; C_{ikt} represents the costs per acre; X_t represents pump lift at time t; and ST_t represents the saturated thickness of the aquifer at time t.

The constraints of the model are

$$ST_{t+1} = ST_t - \Big[\Big(\sum_i \sum_k \Theta_{ikt} \times WP_{ikt}\Big) - R\Big]A/s, \quad (3)$$

$$X_{t+1} = X_t + \Big[\Big(\sum_i \sum_k \Theta_{ikt} \times WP_{ikt}\Big) - R\Big]A/s, \quad (4)$$

$$GPC_t = (ST_t/IST)^2 \times (4.42 \times WY/AW), \quad (5)$$

$$WT_t = \sum_i \sum_k \Theta_{ikt} \times WP_{ikt}, \quad (6)$$

$$WT_t \leq GPC_t, \quad (7)$$

$$PC_{ikt} = \{[EF(X_t + 2.31 \times PSI)EP]/EFF\} \times WP_{ikt}, \quad (8)$$

$$C_{ikt} = VC_{ik} + PC_{ikt} + HC_{ikt} + MC_k + DP_k + LC_k, \quad (9)$$

$$\sum_i \sum_k \Theta_{ikt} \leq 1 \text{ for all } t, \quad (10)$$

$$\Theta_{ikt} \geq 0. \quad (11)$$

Equations (3) and (4) represent the two equations of motion included in the model that update the two state variables, saturated thickness and pumping lift, ST_t and X_t, respectively, where R represents the annual recharge rate in feet, A represents the percentage of irrigated acres expressed as the initial number of irrigated acres in the county divided by the area of the county overlying the aquifer, and s represents the specific yield of the aquifer. Constraints (5), (6), and (7) are the water application and water pumping capacity constraints, respectively. In Equation (5), GPC represents gross pumping capacity, IST represents the initial saturated thickness of the aquifer, and WY represents the average initial well yield for the county. Equation (6) represents the total amount of water pumped per acre, WT_t, as the sum of water pumped on each crop. Constraint (7) requires WT_t to be less than or equal to GPC.

Equations (8) and (9) represent the cost functions in the model. In Equation (8), PC_{cit} represents the cost of pumping, EF represents the energy use factor for electricity, EP is the price of energy, EFF represents pump efficiency, and 2.31 feet is the height of a column of water that will exert a pressure of 1 pound per square inch. Equation (9) expresses the cost of production, C_{ikt} in terms of VC_{ik}, the variable cost of production per acre; HC_{ikt}, the harvest cost per acre; MC_k, the irrigation system maintenance cost per acre; DP_k, the per acre depreciation of the irrigation system per year; and LC_k, the cost of labor per acre for the irrigation system. Equation (10) limits the sum of all acres of crops i produced by irrigation systems k for time period t to be less than or equal to 1. Equation (11) is a nonnegativity constraint to ensure that all decision variables in the model take on positive values.

Data Collection

Specific data were compiled for each county within the study region. The county-specific data included a 4-year average (NASS 2003–2006) of planted acreage of cotton, grain sorghum, wheat, and peanuts and 4-year average crop prices (NASS 2003–2006), total acreage under subsurface drip irrigation (SDI), low-application spray application (LEPA), and dryland.

Operating costs for 2007 associated with the most commonly used crop production practices was also collected for specific crops, including fertilizer, herbicide, seed, insecticide, fuel, irrigation technology maintenance, irrigation, labor, and harvesting costs (Texas Agricultural Extension Service). An electricity price of $.09 per kilowatt-hour, which was gathered by research on the Texas Alliance for Water Conservation in Floyd and Hale counties, was used in the model (Kellison).

Finally, hydrologic data were collected, including the area of each county overlying the aquifer (U.S. Census Bureau), average recharge (Stovall), total crop acres per irrigation well (Texas Water Development Board [TWDB] 2001), average saturated thickness of the aquifer, average pump lift, specific yield (Texas Tech Center for Geospatial Technology), and initial well yield (TWDB 1976).

The crop simulation software CropMan was used to estimate county production function parameters by crop and system (Gerik and Harman). The most prevalent soil types along with the weather data from the closest weather stations were used for each county. Yields were obtained from CropMan for LEPA and SDI for varying water application rates. Regressions for each crop and system were then estimated in Microsoft Excel where Y will be calculated as the CropMan yield minus the actual NASS 2003–2006 average dryland yield, X was water application rate, and X^2 was water application rate squared. The regression was estimated setting the intercept to zero, then adding back the dryland intercept.

The technological advancement coefficient, Ω, was estimated for each county by averaging the respective crop and system 26-year historical yield data. The respective yield average was then multiplied by 1.67%, which is the most recent Economic Research Service (ERS) estimated rate of growth in agricultural output from 1948–2006 (Fugile, MacDonald, and Ball). By multiplying a county's respective average yield by the ERS estimated growth rate, the technological parameter used in the nonlinear models is based on the historic productivity of the crop and system in a county instead of a blanket rate of technological progress.

Results

The optimal levels of saturated thickness, annual net revenue per acre, pump lift, water applied per cropland acre, cost of pumping, and net present value of net returns per acre (NPV) were derived using the nine-county nonlinear dynamic optimization models for the status quo scenario and both the long-term and the short-term (15-year) water rights buyout policies for a 60-year planning horizon. As mentioned previously, the status quo scenario assumes no change to current water policy. The short-term water right buyout policy assumes that 25% of a respective county is converted to dyland for 15 years. At the end of the 15-year buyout term, the acres can be converted back to irrigated production. The long-term water right buyout policy assumes that 25% of a respective county is permanently converted to dryland production for the entire 60-year planning horizon. The results are similar across the nine-county region. Results will be discussed for two counties: Floyd, a northern county with a relatively diverse crop mix, and Terry, a southern county that is primarily cotton production.

Floyd County Results

The status quo scenario in which no change is made to current water policy shows a significant decline in saturated thickness over the 60-year planning horizon. The results show a decline in the saturated thickness level from 76 ft. to 23.5 ft., a depletion of 52.5 ft. The estimated NPV for the status quo scenario is $7,753.43. Similarly, the short-term water right buyout estimates a decline in saturated thickness from 76 ft. to 27 ft., a decline of 49 ft., or approximately 7% less than the status quo saturated thickness depletion. The corresponding NPV for the scenario is $7,278.48, which is about 6% less than the status quo NPV.

Finally, the long-term water right buyout policy estimates the saturated thickness depletion to drop from 76 ft. to 53 ft. over the 60 years. This level of depletion is considerably less than the previous scenarios discussed at only 23 ft., which is approximately 56% less than the aquifer depletion under the status quo scenario. The NPV for the long-term policy is about 21% less than the status quo scenario at $6,157.41.

Terry County Results

The status quo scenario for Terry County also shows a relatively significant decline in saturated thickness over the planning horizon. The model estimated that the saturated thickness would decline from 84 ft. to 47 ft., or 37 ft., over 60 years. The NPV for the status quo scenario is $9,558.37. The short-term water right buyout policy showed similar results with the saturated thickness declining from 84 ft. to 51 ft., or 33 ft. over the planning horizon. The decline of 33 ft. is approximately 4 ft., or 11% less than the status quo scenario depletion. The corresponding NPV for the short-term buyout policy is 8% less than the status quo at $8,797.77.

Finally, the long-term water right buyout policy for Terry County shows a decline in saturated thickness from 84 ft. to 63 ft. with a depletion of 21 ft. The lower depletion rate for the long-term policy is significant at approximately 43% less than the status quo scenario forecasted aquifer drawdown. The NPV for the long-term water right buyout is $7,610.56, which is 20% lower than the status quo scenario.

Conclusions

The decline of the Ogallala Aquifer has been a growing concern for over 40 years. In the Texas High Plains, groundwater conservation districts have had an instrumental role in dampening this decline through innovative conservation rules since their establishment in the 1950s. Because over 50% of the original water stock has been consumed in some areas, more restrictive water conservation rules are being discussed. This study has added information to the discussion concerning the economic impacts of two of the possible policy alternatives.

Of the two policies evaluated, the long-term water rights buyout policy saves more water in the aquifer but at a higher cost to the economy than the short-term water rights buyout policy. One method to evaluate the policies is to calculate the costs per foot of saturated thickness saved for each policy. The cost is the present value of the forgone net income experienced with each policy. For Floyd County, the 15-year water rights buyout policy cost $475 per acre and saved 3.5 ft. of saturated thickness, so the incremental cost is $136 per foot of saturated thickness saved. In like manner, the long-term policy cost $1,596 per acre and saved 29.5 ft. of saturated thickness, resulting in a calculated cost $54 per foot of saturated thickness saved. Terry County showed similar results of $190 per foot of saturated thickness saved for the short-term policy and $122 per foot of saturated thickness saved for the long-term policy.

Although the long-term policy has a higher cost per acre resulting in a greater negative impact on the regional economy, the cost per unit of water saved is lower than the short-term policy. Another conclusion that may be drawn from this study is that counties with more available crop alternatives due to soil type and climate may have a lower economic cost associated with imposing more restrictive water conservation policies. This type of analysis allows policymakers to have additional information concerning the costs associated with alternative conservation policies aimed at conserving water in the Ogallala Aquifer.

References

Alley, W.M., T.E. Reilly, and O.L. Franke. *Sustainability of Groundwater Resources*. USGS Circular 1186. Denver, CO: U.S. Geological Survey, 1999.

Amosson, S., L. Almas, F. Bretz, D. Gaskins, B. Guerrero, D. Jones, T. Marek, L. New, and N. Simpson. *Water Management Strategies for Reducing Irrigation Demands in Region A*. Prepared for Agricultural Sub-Committee, Panhandle Water Planning Group. Amarillo, Texas: Texas A&M University Agricultural Research and Extension Center, 2005.

Arabiyat, T.S. "Agricultural Sustainability in the Texas High Plains: The Role of Advanced

Irrigation Technology and Biotechnology.'' Unpublished master's thesis, Texas Tech University, 1998.

Brooke, A., D. Kendrick, A. Meerdus, R. Raman, and R.E. Rosenthal. *GAMS: A User's Guide*. Washington, DC: GAMS Development Corporation, 1998.

Burt, O.R. ''Temporal Allocation of Groundwater.'' *Water Resources Research* 1,1(1967):45–56.

Das, B. ''Towards a Comprehensive Regional Water Policy Model for the Texas High Plains.'' Ph.D. dissertation, Texas Tech University, 2004.

Ding, Y. ''The Choices of Irrigation Technologies and Groundwater Conservation in the Kansas High Plains: A Dynamic Analysis.'' Ph.D. dissertation, Kansas State University, 2005.

Feinerman, E., and K.C. Knapp. ''Benefits from Groundwater Management: Magnitude, Sensitivity, and Distribution.'' *American Journal of Agricultural Economics* 65(November 1983): 703–9.

Feng, Y. ''Optimal Intertemporal Allocation of Ground Water for Irrigation in the Texas High Plains.'' Ph.D. dissertation, Texas Tech University, 1992.

Feng, Y., and E. Segarra. ''Forecasting the Use of Irrigation Systems with Transition Probabilities in Texas.'' *Texas Journal of Agriculture and Natural Resources* 5,1(1992):59–66.

Ferejohn, J., and T. Page. ''On the Foundation of Intertemporal Choice.'' *American Journal of Agricultural Economics* 60(May 1978):269–75.

Frank, M.D., B.R. Beattie, and M.E. Embleton. ''A Comparison of Alternative Crop Response Models.'' *American Journal of Agriculture Economics* 72(1990):597–603.

Fugile, K., J. MacDonald, and E. Ball. *Productivity Growth in U.S. Agriculture*. USDA ERS Economic Brief Number 9. September 2007.

Gerik T., and W. Harman. Crop Production and Management Model (CropMan Version 3.2). Temple, TX: Blackland Research Center.

Gisser, M. ''Groundwater: Focusing on the Real Issue.'' *Journal of Political Economy* 91,6(1983): 1001–27.

Gisser, M., and A. Mercado. ''Economic Aspects of Ground Water Resources and Replacement Flows in Semiarid Agricultural Areas.'' *American Journal of Agricultural Economics* 5,3(August 1973):461–66.

Gisser, M., and D.A. Sanchez. ''Competition Versus Optimal Control in Groundwater Pumping.'' *Water Resource Research* 16,4(1980):638–42.

Golden, B. ''The Value of Water Rights in the Rattlesnake Sub-Basin: A Spatial-Hedonic Analysis.'' Ph.D. dissertation, Kansas State University, 2005.

Ise, S., and D.L. Sunding. ''Reallocating Water from Agriculture to the Environment Under a Voluntary Purchase Program.'' *Review of Agricultural Economics* 20,1(1998):214–26.

Johnson, J.W. ''Water Conservation Policy Alternatives for the Southern Portion of the Ogallala Aquifer.'' Ph.D. dissertation, Texas Tech University, 2003.

Kastens, T.L., J.P. Schmidt, and K.C. Dhuyvetter. ''Yield Models Implied by Traditional Fertilizer Recommendations and a Framework for Including Nontraditional Information.'' *Soil Science Society of America Journal* 67(January–February 2003):351–63.

Kellison, R. *An Integrated Approach to Water Conservation for Agriculture in the Texas Southern High Plains*. Texas Alliance for Water Conservation 2nd Annual Report submitted to the Texas Water Development Board under project number 141G-44-B819. Lubbock: College of Agricultural Sciences and Natural Resources, Texas Tech University, April 2007. 2007.

Llewelyn, R.V., and A.M. Featherstone. ''A Comparison of Crop Production Functions Using Simulated Data for Irrigated Corn in Western Kansas.'' *Agricultural Systems* 54(1997):521–38.

Moore, M.R., N.R. Gollehon, and D.H. Negri. ''Alternative Forms for Production Functions of Irrigated Crops.'' *Journal of Agricultural Economics Research* 44,3(1992):16–32.

National Agricultural Statistics Service. Quick Stats: Agricultural Statistics Data Base. http://www.nass.usda.gov/QuickStats, 1999 and 2006.

Nieswiadomy, M. ''The Demand for Irrigation Water in the High Plains of Texas, 1957–80. *American Journal of Agricultural Economics* 67,3(1985):619–26.

Paris, Q. ''The von Liebig Hypothesis.'' *American Journal of Agricultural Economics* 74(1992): 1020–28.

Peterson, J., and D. Bernardo. *A Review of Economic Analyses of Water Policies and Irrigation Issues in the High Plains: 1980–2000*. Research Report No. 36. Manhattan: Kansas Agricultural Experiment Station, Kansas State University, 2003.

Stovall, J.N. ''Groundwater Modeling for the Southern High Plains.'' Ph.D. dissertation, Texas Tech University, 2001.

Supalla, R., T. Buell, and B. McMullen. ''Economic and State Budget Cost of Reducing the Consumptive Use of Irrigation Water in the Platte and Republican Basins.'' Unpublished research report prepared by the University of Nebraska–Lincoln, Department of Agricultural Economics, for the Nebraska Department of Natural Resources, August 2006.

Terrell, B. "Economic Impacts of the Depletion of the Ogallala Aquifer: An Application to the Texas High Plains." Unpublished master's thesis, Texas Tech University, 1998.

Texas Agricultural Extension Service. *2007 Texas Crop and Livestock Budgets*. Districts 1 and 2. http://agecoext.tamu.edu/budgets/district/1and2/2007/index.php.

Texas Tech Center for Geospatial Technology. Atlas of the Ogallala Aquifer Program. gis.ttu.edu/ogallalaatlas (Accessed June 15, 2007).

Texas Water Development Board. *Analytical Study of the Ogallala Aquifer*. Various counties. Report 204. May 1976.

———. *Survey of Irrigation in Texas*. Report 347. August 2001. http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/R347.pdf.

U.S. Census Bureau http://quickfacts.census.gov/qfd/states/48000.html (Accessed May 2005).

Wheeler, E.A. "Policy Alternatives for the Southern Ogallala Aquifer: Economic and Hydrologic Implications." Unpublished master's thesis. Texas Tech University, 2005.