Forecasting the Use of Irrigation Systems with Transition Probabilities in Texas

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ABSTRACT

An irrigation system transition probability matrix and a forecast of irrigation system adoption are estimated for Texas using the probability-constrained minimum absolute deviation (MAD) modeling approach. The results show that the adoption of advanced irrigation systems is slow, and that a transition from irrigated to dryland crop production is expected in the future.

KEY WORDS: irrigation system adoption, probability-constrained modeling.

Water availability is one of the most limiting factors of irrigated agricultural production in Texas. For example, the Ogallala aquifer provides 80% of the irrigation water in the Southern High Plains of Texas. Insignificant annual recharge, and continued mining of the Ogallala have resulted in declines of the aquifer's water table. As water levels decline, irrigation well yields decline, pumping costs increase, and the profitability of irrigated crop production is reduced. The depletion of the aquifer threatens the long-term stability of irrigated crop production and the agricultural economy of the Southern High Plains of Texas.

The adoption of water conserving irrigation systems and water conserving tillage technologies have been the common strategies followed to reduce irrigation water use. An alternative strategy for stabilizing the irrigated agricultural economy, may be to moderate the rate of ground water use and stabilize the ground water level by reducing irrigated acreage to acceptable levels. In fact, the trends of water table changes published by Musick et al. (1990) indicate that the rate of decline of ground water tables have been reduced in most areas of the Southern High Plains of Texas. In general, farmers seem to be moving away from wasteful irrigation practices or irrigated crop production due to low farm profits and high water pumping costs. However, individual users have little incentive to consider the effects of their withdrawals on future water table levels. Their actions could result in unacceptable ground water depletion rates. The transition from irrigated crop production to dryland crop production can be important to policy-makers considering alternative water conservation strategies. This information can also be valuable to those individuals interested in predicting expected depletion rates of ground water resources. The objective of this paper is to estimate irrigation systems adoption and the expected transition from irrigated to dryland crop production in Texas.

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BACKGROUND

Irrigation practices in Texas increased during the 1930s. Rapid irrigation development began in the late 1940s and peaked during the late 1970s. Thereafter, irrigated cropland declined due to ground water depletion (Lee, 1987). Irrigated cropland in Texas declined from a peak of 8.95 million acres in 1978 to 5.72 million acres in 1988 (Irrigation Association, 1988), a 36% reduction. The transition from irrigated to dryland crop production has been the major factor for the recent slow-down of ground water use (Lee, 1987).

The adoption of highly efficient irrigation systems has been another factor affecting the reduction of ground water use. Initially, irrigation systems were primarily gravity systems, including: gated pipe direct from source, open ditch, siphon tube, underground with valves, and flooding from ditches. The percentage of gravity irrigated acreage declined from 95% of the irrigated acreage in the mid-1950s to 40% in 1988. The decline in gravity irrigated acreage is primarily associated with the low water application efficiency of the gravity irrigation systems. The adoption of sprinkler irrigation systems in the 1960s greatly improved water conservation through better irrigation management and higher water application efficiencies. The use of conventional sprinkler systems, which include hand move, gun, side roll, and traveller, increased through the 1960s, thereafter their use declined due to the expansion of center pivot systems. In 1988, 19% of the irrigated acreage was irrigated by center pivot systems. There is also a small percentage of the irrigated acreage irrigated with newer irrigation systems such as low-energy precision application (LEPA) system, low-pressure sprinkler, and surge or cablegation techniques. These irrigation systems are not included in this investigation.

The transition from irrigated to dryland crop production and the adoption of more efficient irrigation systems have contributed to the reduction in the depletion rate of ground water resources. The estimation of a transition probability matrix provides useful information about the dynamic nature of irrigation system transition and the potential for water conservation.

A transition probability matrix was used by Schaible and Kim (1989) to forecast irrigation system transition in the Pacific Northwest. They estimated a transition probability matrix using the probability-constrained minimum absolute deviations (MAD) estimator (Buccola, 1982; Charnes, 1963; Charnes and Cooper, 1959; Johnson and Boehlje, 1981). Schaible and Kim (1989) showed that the probability-constrained MAD estimator is superior to the probability-constrained quadratic programming estimator when estimating transition probability with limited aggregate time series data.

In this paper, the transition probabilities of irrigation systems, and of irrigated to dryland crop production are estimated using the probability-constrained MAD estimator. A continuous series aggregate data for the state of Texas for the 1974 to 1988 period are used in this study. The transition probabilities of three irrigation systems and dryland farming are estimated. The states used in the transition probability matrix were gravity, conventional sprinkler, center pivot sprinkler, and dryland farming. The unique nature of this study is the introduction of dryland farming as a state. Schaible and Kim made the assumption that total irrigated cropland remained constant through time. This is a rather restrictive assumption, because total acreage of irrigated cropland changes due to the exit and the entry of dryland. The exclusion of dryland farming may cause the estimation of the transition probabilities to be biased, as the changes in the proportion of irrigation systems used may not represent the transition from one state to another.

THEORETICAL MODEL

The discrete-time stochastic process of finite Markov chain can be written as:

(1) $$P[Xj,t+1:Xi,t, Xi\text{-}1,t\text{-}1,\ldots,Xo,o] = P[Xj,t+1:Xi,t].$$

Equation (1) implies that the probability distribution of the state at time t+1, depends only on the state at t and does not depend on the states of the chain passed through on the way to Xi at time t.

Given the assumption that for all states i and j and all time t, P[Xj,t+1:Xi,t] is independent of t, we have:

(2) $$P[Xj,t+1:Xi,t] = Pij,$$

where Pij is the transition probability from state i at time t to state j at time t+1. Equation (2) implies that the transition probability remains stationary over time, and Pij has the following properties:

(3) $$Pij \geq o \quad \text{for all i and j}$$
and
(4) $$\Sigma_j\, Pij = 1 \text{ for all i.}$$

Given the above information, the joint probability of Xj,t+1 and Xi,t can be written as:

(5) $$P[Xj,t+1,Xi,t] = P[Xi,t]*P[Xj,t+1:Xi,t] = P[Xi,t]*Pij.$$

Summing both sides of Equation (5) over all possible outcomes of the states Xi, the stochastic process then can be written as follows:

(6) $$P[Xj,t+1] = \Sigma_i\, P[Xi,t]*Pij.$$

Replacing P[Xj,t+1] and P[Xi,t] with the observed proportions Yj,t+1 and Xi,t, Equation (6) can be written in the form:

(7) $$Yj,t+1 = \Sigma_i\, Xi,t*Pij + ej, \quad \text{for all i and j},$$

where Yj,t+1 is the observed proportion of state j at time t+1, Xi,t is the observed proportion of state i at time t, and ej is a random error term. Given Equation (7) and the time series data the Pij's can be estimated by appropriate regression techniques. The use of ordinary least squares estimators is not permissible due to the heteroskedasticity of the error terms. Kim and Schaible (1988) showed that the probability-constrained MAD estimator, P, is superior to the probability-constrained quadratic programming estimator. Thus, the probability-constrained minimum absolute deviations estimator is used to estimate Pij's in this study. A linear programming problem of absolute deviation minimization was set up as follows:

(8) $$\text{Minimize } \Sigma_j \Sigma_t (Zj,t + Z'j,t),$$

Subject to:

(9) $$\Sigma_i \, Pij = 1 \quad \text{for all i},$$

(10) $$\Sigma_i \, Xi,t * Pij + Zj,t - Z'j,t = Yj,t+1$$
$$\text{for all j and t, and } Zj,t,\ Z'j,t, \text{ and } Pij \geq 0.$$

Where Zj,t and Z'j,t are the absolute value of positive and negative deviations, respectively.

The assumption for the stationary Markov chain and the transition probability matrix is that the transition probability does not change over time. This assumption implies no new irrigation system inventions, no dramatic change in the pumping cost, no major droughts, and no significant changes in government programs.

ESTIMATION AND RESULTS

The total acreage of irrigated cropland in Texas increased to a peak of 8.95 million acres in 1978. Thereafter, as pointed out earlier, it decreased to 5.72 million acres in 1988. The irrigation acreage data were classified into four states: gravity irrigation, conventional sprinkler irrigation, center pivot irrigation, and dryland farming. For 1978 and earlier, the data for the irrigation states of gravity, conventional sprinkler, and center pivot were expressed as a percentage of the total irrigated acreage. The value for the dryland farming state was zero. For 1979 and thereafter, the value for each year's dryland farming was expressed as the difference between the total irrigated acreage in that year and 8.95 million acres. The data for all the states were expressed as the percentage of 8.95 million acres (the peak value of total irrigated acreage appeared in 1978). The data used is presented in Table 1.

The probability-constrained MAD modeling approach described above was applied to the irrigated acreage data using the General Algebraic Modeling System (World Bank, 1982). The transition probability matrix obtained was:

(11)

	GR	SP1	SP2	DR
GR	0.938	0.011	0.028	0.023
SP1	0.108	0.892	0	0
SP2	0	0	0.937	0.063
DR	0	0	0	1

Where GR represents the gravity irrigation system, SP1 represents the conventional sprinkler irrigation system, SP2 represents both the center pivot sprinkler and the drip/trickle irrigation systems, and DR represents dryland farming.

The transition probability matrix above traces the transition of irrigation systems and dryland farming among the four states. Information contained in Matrix (11) can be interpreted as follows. Going across the GR row, the transition probability matrix indicates that: (1) 93.8% of the current cropland under gravity irrigation will remain under gravity irrigation; (2) it is expected that 1.1% of the current cropland under gravity irrigation will be transferred to conventional sprinkler irrigation; (3)

it is expected that 2.8% of the current cropland under gravity irrigation will be transferred to center pivot and/or drip/trickle irrigation; and (4) it is expected that 2.3% of the current cropland under gravity irrigation will be transferred to dryland farming.

The diagonal coefficients in Matrix (11) confirm Schaible and Kim's finding that farmers tend to remain with their initial investment. It seems that Texas irrigators using conventional sprinkler irrigation systems are more likely to change their irrigation system than irrigators using other irrigation systems. Also, as can be seen in Matrix (11), dryland farmers are not likely to adopt any irrigation system. In other words, if irrigators transfer to dryland farming, they are likely to remain with dryland farming. The transition from relatively inefficient irrigation systems to more efficient systems is slower than had been anticipated. As pointed out above, approximately 94% of irrigators using the gravity irrigation system are likely to remain with the gravity irrigation system, only 1.1% of those irrigators will adopt center pivot sprinkler irrigation systems, and 2.33% will transfer to dryland farming. Farmers using conventional sprinkler irrigation will not switch to center pivot sprinkler irrigation and dryland farming systems. About 6.3% of center pivot sprinkler users will be transferring to dryland farming. Overall, 8.6% of irrigated acreage is expected to be transferred to dryland farming.

Table 1. Irrigation data for the period of 1974-1988.

Year	System Proportion Acreage[1]				Total irrigated acreage
	GR	SP1	SP2	DR	
1974	0.7706	0.1878	0.0416	0	8500000
1975	0.7774	0.1756	0.0469	0	8618000
1976	0.7591	0.1749	0.0659	0	8200000
1977	0.7595	0.1634	0.0771	0	8900000
1978	0.7575	0.1624	0.0801	0	8950000
1979	0.6280	0.1575	0.0905	0.1265	7817681
1980	0.5994	0.1405	0.1050	0.1503	7604669
1981	0.5756	0.1313	0.1955	0.1741	7391660
1982	0.5540	0.1369	0.1145	0.1946	7208600
1983	0.5153	0.0603	0.1821	0.2217	6965636
1984	0.5127	0.0485	0.1832	0.2455	6752625
1985	0.4927	0.0481	0.1877	0.2679	6752000
1986	0.4559	0.0481	0.1922	0.3017	6750000
1987	0.4319	0.0469	0.1933	0.3267	6025745
1988	0.4079	0.0469	0.1933	0.3604	5724458

[1]GR = Gravity, SP1 = Conventional Sprinkler, SP2 = Center Pivot and drip/trickle, and DR = Dryland farming.

The transition matrix estimated in this study, also confirms Schaible and Kim's result that irrigators will not necessarily replace their aging irrigation systems with higher efficiency irrigation systems. This is because almost 11% of conventional sprinkler users will switch to gravity systems. Texas irrigators are different from Pacific Northwest irrigators, because no Texas irrigators using center pivot sprinkler irrigation systems will shift to gravity and conventional sprinkler irrigation systems. The switch back from conventional sprinklers to gravity irrigation may be explained due to the lack of the capital needed to replace fully depreciated irrigation systems, lack of management skills, or due to soil and topographic characteristics.

The time path of the irrigation and dryland states transition for the period 1989 to 2000 was predicted using the estimated transition probability matrix. Letting W(0) be the initial vector of proportions at time 0, the conditional expectation W(t:0) is given as:

$$W(t{:}o) = W(0)*P(n), \tag{12}$$

where n is the number of time periods, and P(n) is the n-step probability transition matrix. Given the initial transition probability matrix P, the n-step transition probability matrix can be obtained by:

$$P(n) = P^n. \tag{13}$$

Using the observed proportions in 1988 as W(0), the predicted proportions of the irrigation and dryland states were derived for the period 1989 to 2000, and are listed in Table 2.

Table 2. Predicted proportions of irrigation technologies for Texas[1].

Year	GR	SP1	SP2	DR
1989	0.3877	0.0463	0.1925	0.3738
1990	0.3686	0.0456	0.1913	0.3948
1991	0.3507	0.0447	0.1895	0.4135
1992	0.3338	0.0438	0.1874	0.4354
1993	0.3178	0.0427	0.1850	0.4548
1994	0.3027	0.0416	0.1822	0.4738
1995	0.288[illegible]	0.0404	0.1792	0.4922
1996	0.2749	0.0392	0.1760	0.5102
1997	0.2622	0.0380	0.1726	0.5276
1998	0.2499	0.0368	0.1691	0.5445
1999	0.2385	0.0356	0.1654	0.5609
2000	0.2275	0.0344	0.1617	0.5768

[1]GR = Gravity, SP1 = Conventional Sprinkler, SP2 = Center Pivot and drip/trickle, DR = Dryland Farming.

In 1988, approximately 36% of the total acreage was in dryland production, and the total irrigated acreage was 5.72 million (Table 1). Of the total irrigated acreage in 1988, approximately 61% was irrigated by gravity systems, 6% by conventional sprinkler systems, and about 30% by center pivot systems. By the year 2000, compared to 1988 it is expected that acreage under dryland farming will increase 21 %, the total acreage of irrigated land will be 3.75 million, and approximately 51% of the irrigated acreage land will be irrigated by gravity systems, 7% by conventional sprinkler systems, and 37% by center pivot systems. Thus, for the period 1988 to 2000, most of the changes are expected to occur in the transition from irrigated to dryland crop production.

To determine the validity of the estimated proportions in Table 2, the information expectation statistical test for a measure of badness of fit, as used by Schaible and Kim, was carried out. The information expectation test was calculated as:

$$I(P:P') = (N(t)/2)^* \Sigma_j [Pi(t) - P'i(t)]^2 / P'i(t) \text{ for all t,} \quad (14)$$

where Pi(t) and P'i(t) are the observed and predicted proportions of the ith irrigation system and dryland state at time t, respectively. N(t) is the sample size in thousands of acres. The information expectation, I(P:P') approximately follows the Chi-Square distribution with (r-1) degrees of freedom, where r is the number of states. The test results are presented in Table 3 and indicate that for most of the years the computed statistic is less than the Chi-Square value at 0.05 probability level (7.85). This implies that for most of the years there is no significant difference between the observed and the predicted proportions.

Table 3. Computed test statistics between observed and predicted proportions.

Year	Computed test statistic[1]
1975	19.9167
1976	3.0877
1977	7.8159
1978	1.1507
1979	65.2794
1980	2.5102
1981	0.3571
1982	9.4154
1983	29.1903
1984	13.9561
1985	1.6105
1986	2.5699
1987	1.0286
1988	0.9199

[1]Chi-Square value 3, 0.05 = 7.85

CONCLUSIONS

An irrigation system transition probability matrix and a forecast of irrigation systems and dryland farming adoption are estimated for Texas. The probability-constrained MAD modeling approach was used in this study. The results indicate that most of the changes in irrigated cropland in Texas are expected to occur in the transition from irrigation to dryland crop production, while the transition from relative inefficient irrigation systems to more advanced irrigation systems is slow. Assuming that the stationary Markov process holds, it is estimated that in the year 2000, approximately 65% of currently irrigated land will remain in irrigation, and 51% of that will be irrigated by gravity systems. That rapid ground water depletion and the apparent benefits from the adoption of more advanced irrigation systems have not influenced farmers away from inefficient irrigation systems, may suggest the existence of institutional and/or economic barriers that limit the adoption of advanced irrigation technologies.

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